Human Health & Support Systems
Capability Roadmap
Progress Review

Dennis Grounds
Al Boehm
March 17, 2005
Draft Agenda

8:00 a.m.  Welcome & Review Process  Panel Chair & NRC Staff
8:15-8:30 a.m.  Introduction by APIO to CRM  Jan Aikins
8:30-9:00 a.m.  Human Health & Support Systems CRM Overview  Dennis Grounds
9:00 a.m.-10:30 p.m.  Human Health & Performance  Dennis Grounds
10:30 a.m.  Break
10:45 a.m.-12:15 p.m.  Life Support & Habitation  Dan Barta
12:15-1:00 p.m.  Lunch
1:00-2:30 p.m.  Extra-Vehicular Activity  Kerri Knotts
2:30-3:30 p.m.  Open Discussion/Q&A with NRC Panel  All
3:30 p.m.  Break/NRC panel meets in closed session
4:15-5:00 p.m.  NRC panel discussion with NASA  All
5:00 p.m.  Adjourn
## Capability Roadmap Team

### Co-Chairs
- NASA: Dennis Grounds, JSC
- External: Al Boehm. Retired Hamilton Sundstrand

### Team Members

<table>
<thead>
<tr>
<th>Government</th>
<th>Industry</th>
<th>Academia</th>
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<tr>
<td>J. Charles, JSC</td>
<td>B. Harris</td>
<td>J. Becker, NSBRI</td>
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<tr>
<td>R. Carrasquillo, MSFC</td>
<td>R. Poisson, Ham.Sunstrand</td>
<td>D. Akins, Univ. Maryland</td>
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<td>G. Jahns, ARC</td>
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<td>R. Schlegel, Univ. Oklahoma</td>
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<td>G. Lutz, JSC</td>
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### NASA Technical Leads
- D. Barta, JSC
- K. Knotts, JSC

### Other/Independent Coordinators
- G. Miller, Lockheed Martin
- APIO: J. Aikins, JPL

- Directorate: E. Trinh, HQ ESMD; D. Craig, HQ ESMD
The Human Health & Support Systems Capability Roadmap focuses on research and technology development and demonstration required to ensure the health, habitation, safety, and effectiveness of crews in and beyond low Earth orbit. It contains three distinct sub-capabilities:

- Human Health and Performance
- Life Support and Habitats
- Extra-Vehicular Activity
The Human Health and Performance area guides the research and countermeasure development to reduce the risks to humans in space flight, as well as define the technology necessary for maintenance of the daily functional requirements of the human system.

- Space Radiation
- Medical Care
- Human Health Countermeasures
- Behavioral Health & Performance
- Space Human Factors

Life Support and Habitation focuses on the research and technology development to sustain the life of the human system during transit and planetary phases of exploration.

- Life Support Systems (air, thermal, water, food)
- Environmental Monitoring and Control
- Contingency Response Technologies
- Exploration Habitats

The Extra-Vehicular Activity project develops the technology required to sustain the life of humans outside of the life support systems of the vehicle and surface habitats, as well as the tools required to perform exploration and contingency EVA.

- EVA suit
- Pressurized volumes
- EVA tools
- Ground support equipment
Roadmap Process and Approach

- Input from internal NASA and contractor experts
- Iterative review with Roadmap team members
- Review with NASA Headquarters Exploration Systems Mission Directorate
- Interim NRC review
- Updates based on the NRC review
- Updates based on Strategic Roadmaps
- Final review with NRC
- Final product updated as required during NASA planning phases
Requirements/Assumptions

- The following Design Reference Missions were used as guidance in some instances:
  - *Human Exploration of Mars: Artificial-Gravity Nuclear Electric Propulsion Option*
  - *Reference Mission Version 3.0 Addendum to the Human Exploration of Mars*
  - *Mars 98 Reference mission: Reference Mission of the NASA Mars Exploration Study Team*
  - *Lunar Surface Reference Missions: A Description of Human and Robotic Surface Activities*
  - *The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities*

- Potential mission timeframes follow the Document: *ESMD-RQ-0019 Preliminary Title: CEV Concept of Operations Effective Date: 1 September 2004*

- Additional requirements/assumptions are detailed within the sub capability charts
A Capability is defined as a set of systems with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

- **Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified**
- **Sub-Capabilities* Demonstrated in a Laboratory Environment**
- **Integrated Capability Demonstrated in a Relevant Environment**
- **Integrated Capability Demonstrated in a Laboratory Environment**
- **Integrated Capability Demonstrated in an Operational Environment**
- **Capability Operational Readiness**
- **Capability Readiness Levels**

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)
<table>
<thead>
<tr>
<th>TRL Definition</th>
<th>TRL/CMRL Score</th>
<th>CMRL Definition</th>
<th>CMRL category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic principles observed</td>
<td>1</td>
<td>Phenomenon observed and reported. Problem defined.</td>
<td></td>
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<tr>
<td>Technology concept and/or application formulated</td>
<td>2</td>
<td>Hypothesis formed; preliminary studies to define parameters. Demonstrate feasibility.</td>
<td></td>
</tr>
<tr>
<td>Analytical and experimental critical function/proof-of-concept</td>
<td>3</td>
<td>Validated hypothesis. Understanding of scientific processes underlying problem.</td>
<td></td>
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<tr>
<td>Component and/or breadboard validation in lab</td>
<td>4</td>
<td>Formulation of countermeasures concept based on understanding of phenomenon.</td>
<td></td>
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<tr>
<td>Component and/or breadboard in relevant environment</td>
<td>5</td>
<td>Proof of concept testing and initial demonstration of feasibility and efficacy.</td>
<td></td>
</tr>
<tr>
<td>System/subsystem model or prototype demonstration in relevant environment</td>
<td>6</td>
<td>Laboratory/clinical testing of potential countermeasure in subjects to demonstrate efficacy of concept.</td>
<td></td>
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<tr>
<td>Subsystem prototype in a space environment</td>
<td>7</td>
<td>Evaluation with human subjects in controlled laboratory simulating operational space flight environment.</td>
<td></td>
</tr>
<tr>
<td>System completed and flight qualified through demonstration</td>
<td>8</td>
<td>Validation with human subjects in actual operational space flight to demonstrate efficacy and operational feasibility.</td>
<td></td>
</tr>
<tr>
<td>System flight proven through mission operations</td>
<td>9</td>
<td>Countermeasure fully flight-tested and ready for implementation.</td>
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</table>
Mars Missions Decisions Related to Human Health & Support Systems

### Mission Factors

<table>
<thead>
<tr>
<th>Mission Design</th>
<th>Human Health</th>
<th>Life Support</th>
<th>Habitats</th>
<th>EVA</th>
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</thead>
<tbody>
<tr>
<td>Transit time</td>
<td>✗</td>
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<td>*Planetary stay</td>
<td>✗</td>
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<td>Precursor Robotic Missions</td>
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### Objectives

<table>
<thead>
<tr>
<th>Location - single outpost/base/ alternate outposts?</th>
<th>Human Health</th>
<th>Life Support</th>
<th>Habitats</th>
<th>EVA</th>
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<tbody>
<tr>
<td>✤</td>
<td>✗</td>
<td>✗</td>
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<tr>
<td>*Surface Mobility/Range</td>
<td>✤</td>
<td>✗</td>
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<tr>
<td>*ISRU</td>
<td>✤</td>
<td>✗</td>
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</table>

### Key Program Decisions

<table>
<thead>
<tr>
<th>Crew Size</th>
<th>Human Health</th>
<th>Life Support</th>
<th>Habitats</th>
<th>EVA</th>
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<tbody>
<tr>
<td>✗</td>
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<tr>
<td>Artificial Gravity</td>
<td>✤</td>
<td>✗</td>
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<td>Aerocapture</td>
<td>✤</td>
<td>✗</td>
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<td>Robotic Assistants</td>
<td>✗</td>
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<tr>
<td>Lunar Missions as a testbed</td>
<td>✗</td>
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<tr>
<td><em>ISS</em> as a testbed</td>
<td>✗</td>
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</table>

= Critical  = Moderate
Human Health & Performance

Presenter:
Dennis Grounds
Human Health and Performance guides the research and countermeasure development to reduce the risks to humans in space flight, and defines the technology necessary for maintenance of the daily functional requirements of the human system.

- Space Radiation
- Medical Care
- Human Health Countermeasures
- Behavioral Health & Performance
- Space Human Factors
Human Health & Performance

- Space Radiation
  - Measurement Technologies
  - Shielding Solutions
  - Risk Assessment/Projection
  - Biological Countermeasures

- Medical Care
  - Medical Devices
  - Clinical Capabilities
  - Medical Informatics

- Human Health Countermeasures
  - Artificial Gravity
  - Exercise
  - Other Physiological CM

- Behavioral Health & Performance
  - Team Cohesion & Productivity
  - Psych Health Management
  - Performance Readiness
  - Individual & Crew Selection

- Space Human Factors
  - Models & simulations
  - Design tools & requirements
  - Performance Measurements
  - Training & Decision Support Systems
Benefits of Human Health & Performance

Reduce Risk

- NASA shall implement a safe, sustained and affordable robotic and human program to explore and extend human presence across the solar system and beyond.

**Level 0 Exploration Requirements for NASA**

- For Human Explorers to undertake lengthy research trips on other worlds, they will have to maintain their health in environments that possess higher radiation and lower gravity than Earth that are far from supplies and medical expertise.

**The Vision for Space Exploration**

- The successful development of identified enabling technologies will be critical to attainment of exploration objectives within reasonable schedules and affordable costs.
- Biomedical risk mitigation – space medicine; remote monitoring, diagnosis and treatment.

Excerpt from “Report of the President’s Commission on Implementation of United States Space Exploration Policy,” June 2004

Increase Capability
Current State-of-the-Art for Human Health & Performance

- Shuttle and International Space Station (ISS) standards and practices
- Terrestrial medical capabilities
- Department of Defense (DoD) standards and practices
Requirements /Assumptions
for Human Health & Performance

• Document: ESMD-RQ-0019 Preliminary Title: CEV Concept of Operations
• Effective Date: 1 September 2004

• The Exploration Systems Mission Directorate recognizes the following major programmatic milestones and associated dates:
  – 2008: Initial flight test of a Crew Exploration Vehicle (CEV)
  – 2008: Launch first lunar robotic orbiter
  – 2009-2010: Robotic mission to lunar surface
  – 2011: First uncrewed CEV flight
  – 2014: First crewed CEV flight
  – 2014-2015: Prometheus 1 demonstration mission
  – 2015-2020: First human mission to the Moon

• Spirals 4 and 5 encompass the capabilities necessary to execute piloted missions to the vicinity of Mars as well as landed missions. The date for humans to reach the Mars vicinity is dependent on the development timeline and discoveries that result from the earlier spirals. However, 2030 is being used as a reference date for extensibility criteria and technology planning.

• For planning purposes in this roadmap, target dates were chosen from within the above time spans. These dates will be adjusted as further guidance is given by the Strategic Roadmaps and/or the Directorates.
Human Health & Performance

Space Radiation
- Measurement Technologies
- Shielding Solutions
- Risk Assessment/Projection
- Biological Countermeasures

Medical Care
- Medical Devices
- Clinical Capabilities
- Medical Informatics

Human Health Countermeasures
- Artificial Gravity
- Exercise
- Other Physiological CM

Behavioral Health & Performance
- Team Cohesion & Productivity
- Psych Health Management
- Performance Readiness
- Individual & Crew Selection

Space Human Factors
- Models & simulations
- Design tools & requirements
- Performance Measurements
- Training & Decision Support Systems

NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005
Definition

- Space Radiation addresses the risks to human exploration from exposure to space radiation, including ionizing radiation, solar particle events (SPE) and galactic cosmic rays.
  - Possible health risks include cancer, damage to the central nervous system, degenerative tissue disease (cataracts, heart disease, etc.), and acute radiation sickness.
- Components include:
  - Risk assessment/projection
  - Shielding solutions
  - Measurement technologies
  - Biological countermeasures
Benefits

- Assure that we can safely live and work in the space radiation environment, anywhere, any time.
- Assure astronauts return to Earth safely, and continue to maintain an acceptable quality of life.
Current State-of-the-Art for Space Radiation

State of the Art

- **Shuttle and ISS shielding**
  - Not inherently part of the vehicle design; some components added late in development
- **Shuttle and ISS monitoring**
  - Equipment no longer reliable
  - Lack system integration
  - Require extensive ground analysis
  - SPE early warning uses NOAA space weather satellites with Earth-based analysis and communication
  - No neutron spectrometer
- **Low Earth Orbit (LEO) exposure limits**
  - Based on LEO environment (different mix of protons and HZE particles)
- **LEO risk assessment**
  - Based on LEO environment (different mix of protons and HZE particles)
- **Space environmental models need to be validated and monitored with in-situ dosimetry**
# Space Radiation Roadmap

<table>
<thead>
<tr>
<th>Sub-Capability</th>
<th>Space Radiation</th>
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<tbody>
<tr>
<td><strong>Spiral 1: Crew Exploration Vehicle</strong></td>
<td><img src="image" alt="SRR" /></td>
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<tr>
<td><strong>Spiral 2: Extended Duration Moon</strong></td>
<td><img src="image" alt="SRR" /></td>
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<tr>
<td><strong>Spiral 3: Long Duration Moon</strong></td>
<td><img src="image" alt="SRR" /></td>
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<tr>
<td><strong>Spiral 4: Mars Vicinity</strong></td>
<td><img src="image" alt="SRR" /></td>
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<tr>
<td><strong>Spiral 5: Mars Surface</strong></td>
<td><img src="image" alt="Mars Science Lab" /></td>
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</tbody>
</table>

## Measurement Technologies
- **Sub-Capability:** Space Radiation
- **Spiral 1 Crew Selection & Constraints**
- **Spiral 2 Design Optimization**
- **Spiral 1 Design Tools**
- **Spiral 2 Design Tools**
- **Multifunctional shielding materials research**

## Shielding Solutions
- **Nuclear database**
- **Transport codes**
- **Spiral 2 SPE warning regts**
- **Spiral 2 Design Optimization**
- **Spiral 1 Design Optimization**

## Risk Assessment/ Projection
- **Radiation Research**
  - to understand acute & chronic risk
  - Radiation Research to reduce uncertainty in risk projection and develop countermeasures

## Biological Countermeasures
- **Radiation Research**
- **Spiral 1 Flight rules & operations**
- **Spiral 2 Crew Selection & Constraints**

NOTE: Milestone colors correspond to spiral color bars above.
Space Radiation Roadmap

<table>
<thead>
<tr>
<th>Sub-Capability</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
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<th>2022</th>
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<td>Spiral 5: Mars Surface</td>
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<td>Radiation Research to reduce uncertainty in risk projection and develop countermeasures</td>
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<td>Risk Assessment/ Projection</td>
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<td>Biological Countermeasures</td>
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**NOTE:** Milestone colors correspond to spiral color bars above.
Integration Approach

Ground research (NSRL) to reduce uncertainty in risk projection/Develop biological CM

Establish human exposure limits per habitable module

Establish human exposure limits per exploration mission

Maintain, improve risk assessment models/Analyze proposed mission architectures

Develop requirements for habitable volume monitoring/early warning systems

Develop operations products (flight rules, crew constraints, training, ground segment support)

Shielding

Develop design assessment tools for vehicle architecture

Evaluate candidate shielding materials (all habitable volumes) for effectiveness

Establish criteria for secondary space craft usage (material strength, properties, manufacturability)

Evaluate candidates for secondary space craft usage (structure)

Material engineering to optimize application (sandwich, impregnation)

Deliver candidate shielding technologies to space craft developer

Capability Readiness Level

2

Sub-Capabilities*

Demonstrated in a Laboratory Environment

Proof-of-Concept analyses of the Sub-capabilities are performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)
### Gaps

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inability to predict SPEs</td>
<td>Early warning system</td>
<td>1/2020</td>
</tr>
<tr>
<td>Reliable Monitoring Instruments covering most significant portions or part of spectrum</td>
<td>Operational radiation dosimetry (multiple instruments) with proven reliability and performance.</td>
<td>5/2011*</td>
</tr>
</tbody>
</table>

*Utilizes ISS as testbed
**Utilizes Moon as testbed

**Note:** Unless otherwise indicated, assumes Mars mission scenario.
<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimized shielding solutions</td>
<td>Requirements for vehicle design/materials to optimize radiation shielding</td>
<td>3/2012 (moon) 3/2020 (Mars)</td>
</tr>
<tr>
<td>Multifunctional Materials</td>
<td>Vehicle design recommendations (ALARA); Manufacturable materials w/high Radiation protection characteristics for use in vehicle structures</td>
<td>2/2008</td>
</tr>
</tbody>
</table>

Note: Unless otherwise indicated, assumes Mars mission scenario
<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk prediction tools with (&lt;2) - fold uncertainty in prediction</td>
<td>Risk Assessment and Projection tools with 95% Confidence Level</td>
<td>1/2024</td>
</tr>
</tbody>
</table>

Note: Unless otherwise indicated, assumes Mars mission scenario
### Maturity Level – Technologies for Biological Countermeasures

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biological countermeasures</td>
<td>Validated Biological countermeasures for space radiation risks</td>
<td>1/2028</td>
</tr>
</tbody>
</table>

Note: Unless otherwise indicated, assumes Mars mission scenario
• **Number of safe days in space without exceeding career limits at 95% confidence level**

  - **LEO (Spiral 1):** three 180-day missions without exceeding career limits at 95% confidence level (Solar Particle Events, Galactic Cosmic Rays, trapped radiation belts)

  - **MOON (Spirals 2-3):** six 30-90 day missions below threshold for acute effects (Solar Particle Events)

  - **MARS (Spirals 4-n):** one 1000-day mission without exceeding career limits at 95% confidence level (Galactic Cosmic Rays, Solar Particle Events)
NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005

Human Health & Performance

- Space Radiation
  - Measurement Technologies
  - Shielding Solutions
  - Risk Assessment/Projection
  - Biological Countermeasures

- Medical Care
  - Medical Devices
  - Clinical Capabilities
  - Medical Informatics

- Human Health Countermeasures
  - Artificial Gravity
  - Exercise
  - Other Physiological CM

- Behavioral Health & Performance
  - Team Cohesion & Productivity
  - Psych Health Management
  - Performance Readiness
  - Individual & Crew Selection
  - Performance Measurements
  - Training & Decision Support Systems

- Space Human Factors
  - Models & simulations
  - Design tools & requirements
  - Performance Measurements
  - Training & Decision Support Systems
Definition

• Medical Care for exploration missions must provide monitoring, diagnosis and treatment during a mission with little or no real-time support from Earth. It includes identifying, defining and monitoring health risks, establishing medical guidelines, utilizing telemedicine, and developing medical technology for exploration.
  – Medical Devices, e.g., imaging system, surgical instruments, IV fluid generation system, monitoring devices
  – Clinical Capabilities, e.g., crew selection/constraints criteria, pre-mission prevention, on-board procedures, training
  – Medical Informatics, e.g., on-board diagnosis & treatment database
Benefits of Medical Care

Benefits

• **Reduce Risk by**
  – Enhancing the prevention of medical events through selection, “vaccines,” training, and medical procedures
  – Identifying and preparing for major trauma and medical events pre-flight
  – Inflight monitoring for early detection of health conditions allowing effective, economical, early treatment

• **Increase Capability by**
  – Providing inflight medical care to ensure mission success, productive crew members and protect crew health
  – Using ISS as a testbed to determine space medical norms
  – Improving Medical Diagnostics and Therapeutics
**State of the Art**

- ISS Crew Health Care System – can provide capability to stabilize and transport crew immediately to Earth
- Terrestrial Medical Technologies – typically not designed to operate in spacecraft closed environment, in microgravity, or in a radiation environment; not designed to minimize mass/volume/power/resources
- DoD telemedicine applications – designed for extreme environments to treat multiple injuries; not constrained to spacecraft resources such as mass, volume, power, interfaces, communication latency; not designed for reduced gravity; has a backup of evacuation to definitive medical care not available for long duration missions
- Shelf life of medical supplies based on terrestrial use – not designed for space radiation environment and the length of a Mars mission
The Human System and Spiral Development for Exploration

** Includes all program requirements

03/10/05
# Medical Care Roadmap

<table>
<thead>
<tr>
<th>Spiral 1: Crew Exploration Vehicle</th>
<th>Spiral 2: Extended Duration Moon</th>
<th>Spiral 3: Long Duration Moon</th>
<th>Spiral 4: Mars Vicinity</th>
<th>Spiral 5: Mars Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRR</td>
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<td>2015</td>
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<td>Sub-Capability</td>
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<td>Clinical Capabilities</td>
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<tr>
<td>Medical Informatics</td>
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</tbody>
</table>

### Medical Devices
- In Situ IV fluid generation on ISS
- Enhanced diagnostic imaging on ISS
- Tech watch for sensors, lab tests
- CEV Crew medical reqts
- Crew Health optimization sys
- Crew/mission selection criteria
- Medical procedure development/valid - ISS
- Pharmacology tests-ISS
- Clinical watch
- Nutrition - ISS
- Lunar medical procedure development/valid
- Countermeasure effectiveness monitoring system

### Clinical Capabilities
- Risk analysis model for med events
- Master architecture for data & info comm
- Training techniques for Lunar med sys
- Med simulation model (estbed)
- ISS med decision support sys
- Sensors, lab tests integ w/ info arch
- Data mining of astronaut med data
- Lunar med training sys
- Medication delivery system
- Lunar crew select in/out criteria
- Lunar crew health optimization sys
- Nutriceutical studies

### Medical Informatics
- Enhanced Patient Condition Data Base
- Training techniques for Lunar med sys
- Risk analysis model for med events
- Data mining of astronaut med data
- Ground support med info sys
- Just-in-time training methods

### Sub-Capability Medical Care
- CEV Medical Project Plan
- CEV Medical system scarring reqts
- CEV Medical System reqts
- Med Sys reqts
- Med Data Sys
- Lunar Med Data Sys
- Lunar Med decision support sys

NOTE: Milestone colors correspond to spiral color bars above.
# Medical Care Roadmap

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## Sub-Capability Medical Care

- **SDR**
- **PDR**
- **CDR**
- **SRR**

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<td>Mars Medical System Refinement &amp; Integration</td>
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<td>Mars major illness &amp; trauma sys</td>
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<td>Space Surgeon Training prog (CMO for Mars)</td>
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<td>Integrated info arch, flight &amp; ground</td>
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<td>Identification sensors, lab tests</td>
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</tbody>
</table>

## Medical Devices

- **Blood replacement sys**
- **Identify sensors, lab tests**
- **Medical waste management**
- **Operations monitoring and intervention**
- **Pharmacology stability studies**

## Clinical Capabilities

- **Train lunar crews**
- **Train Mars crews**
- **Mars major illness & trauma sys**
- **Mars medical procedure validation**
- **Mars crew health optimization**
- **Mars crew select in/out criteria**

## Medical Informatics

- **Refresher training sys for Mars**
- **Mars decision support sys**
- **Just-in-time training sys for Mars**
Maturity Level – Capabilities
Medical Care

Integration Approach

• NASA unique technology(ies)
  Identification
  • Medical Devices
  • Clinical Care
  • Informatics

Develop & test prototype systems on ISS, in ground integration facilities, on lunar missions

Continuously evaluate & infuse new technologies until Baseline medical system per spiral

Deliver specifications & technology solutions for system development

Develop ground segment to support flight medical operations

Capability Readiness Level

2 Sub-Capabilities*
  Demonstrated in a Laboratory Environment

Proof-of-Concept analyses of the Sub-capabilities are performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)
# Maturity Level – Technologies for Medical Devices

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV fluid shelf life</td>
<td>On-board IV fluid generation</td>
<td>4/2016*</td>
</tr>
<tr>
<td>Level of care</td>
<td>Appropriate surgical instruments</td>
<td>4/2020</td>
</tr>
<tr>
<td></td>
<td>Heart, lung monitoring devices</td>
<td>5/2020</td>
</tr>
<tr>
<td></td>
<td>Pharmaceutical delivery system</td>
<td>2/2020</td>
</tr>
<tr>
<td>Limited diagnostic capability</td>
<td>Imaging system</td>
<td>5/2015**</td>
</tr>
<tr>
<td></td>
<td>Biochemical diagnostic tools</td>
<td>5/2015**</td>
</tr>
</tbody>
</table>

*Utilizes ISS as testbed  
**Utilizes Moon as testbed  

Note: Unless otherwise indicated, assumes Mars mission scenario
## Maturity Level – Technologies for Clinical Capabilities

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stabilize &amp; transport to definitive care site</td>
<td>Medical capabilities sufficient for mission concept of ops</td>
<td>6/2015</td>
</tr>
<tr>
<td>Pharmacodynamics/Pharmacokinetics Research</td>
<td>Effective pharmaceuticals/accurate prescription protocol</td>
<td>3/2016*</td>
</tr>
<tr>
<td>Environmental Hazard Knowledge (e.g., dust, radiation, toxicity, chemical properties)</td>
<td>Requirements for robotic precursor missions, including sample return</td>
<td>1/2022</td>
</tr>
<tr>
<td>Lack of Partial G procedures</td>
<td>Partial G Procedures</td>
<td>2/2020</td>
</tr>
<tr>
<td>Adequate ground and on-board training for increased autonomy</td>
<td>Training materials, methods, certification</td>
<td>2/2015 (moon) 2/2025 (Mars)</td>
</tr>
</tbody>
</table>

*Utilizes ISS as testbed

**Utilizes Moon as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario
## Maturity Level – Technologies for Medical Informatics

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependence on ground based support system</td>
<td>Semi- autonomous decision support system</td>
<td>3/2020</td>
</tr>
<tr>
<td>Lack of evidence base of medically relevant data.</td>
<td>Searchable, analyzable, structured database of medical information.</td>
<td>4/2010</td>
</tr>
<tr>
<td>Multiple system components with individual communications protocols.</td>
<td>Integrated information architecture allowing new devices to be connected in a plug and play fashion.</td>
<td>2/2015</td>
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<tr>
<td>Crewmember providing medical care with limited medical training.</td>
<td>Training system – just-in-time as well as refresher training.</td>
<td>2/2015 (moon) 2/2025 (Mars)</td>
</tr>
<tr>
<td>Use of paper-based medical procedures</td>
<td>Automated procedure assistant</td>
<td>4/2015</td>
</tr>
<tr>
<td>Reliance on microgravity for testing procedures, etc.</td>
<td>Biomedical models of human systems in microgravity</td>
<td>3/2020</td>
</tr>
</tbody>
</table>

Note: Unless otherwise indicated, assumes Mars mission scenario
• **Program Goal:**
  – Decrease in mission impacts due to medical and crew performance problems.

  *There are several metrics that can be used to assess the progress annually:

• **Annual:**
  – Progression of TRL/CMRL levels of technology components
  – Percent coverage of conditions in the Patient Condition Data Base
  – Match mass, power, volume, redundancy, modularity, resupply constraints to mission profile
  – Few resources spent redesigning (modular design)
  – High usability and integrated testing results
  – Less crew time needed for ground-based training, on-orbit training, and procedure execution
  – High reliability/maintainability (MTBF=Mean Time Between Failures, maintenance time)
Human Health Countermeasures

Definition

- Countermeasures mitigate the adverse effects of space flight to ensure that humans can function in a safe and productive manner during transit phases and planetary stays required in exploration missions. Sub-capabilities include:
  - Artificial Gravity, continuous or intermittent
  - Exercise
  - Other Countermeasures to address:
    - Musculoskeletal Alterations (Bone and Muscle)
    - Cardiovascular Alterations
    - Sensory motor and neurological changes (e.g., balance and coordination)
    - Immunology, infection, hematology
    - Environmental Physiology (e.g., Decompression Sickness, toxicity, microbiology)
Benefits:

• Reduce Risk by
  – Developing and maintaining permissible exposure limits to the adverse affects of space flight on humans

• Increase Capability by
  – Providing validated Countermeasure Suites for Moon and Mars to manage or prevent:
    • Bone and muscle loss
    • Cardiovascular alterations
    • Sensory motor problems
    • Immunology, infection, and hematology problems
    • Environmental physiology conditions
Currently used countermeasures have been shown to be effective for flight durations up to 180 days.

<table>
<thead>
<tr>
<th>Development</th>
<th>Evaluation</th>
<th>Validation</th>
<th>Operations</th>
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<tbody>
<tr>
<td>Pharmacologics</td>
<td>Vibration Plate Protocols</td>
<td>Potassium Citrate (kidney stones)</td>
<td>Exercise</td>
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<tr>
<td>Gaze, Spatial Orientation Protocols</td>
<td>Artificial Gravity</td>
<td>Midodrine (orthostatic intolerance)</td>
<td>TVIS</td>
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<td>Cognitive Tools</td>
<td>Ultrasound Bone Stimulation</td>
<td>Bisphosphonates (Bone Loss)</td>
<td>BD-1</td>
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<tr>
<td>Immune Regulation</td>
<td>Enhanced nutrition &amp; exercise protocols</td>
<td>EVA Pre-Breathe Reduction Protocols (decompression sickness)</td>
<td>CEVIS</td>
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<td>Gait Adaptability Training Program</td>
<td>Exercise prescriptions evaluation &amp; optimization</td>
<td>Exercise hardware devices and prescriptions validation</td>
<td>SchRED</td>
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<td>Next generation exercise devices</td>
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<td>Fluid Loading</td>
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<td>Re-entry Anti-G suit</td>
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<td>Liquid Cooling Garment (LCG)</td>
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<td>Vitamin D and Caloric Counseling</td>
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<td>Acoustics CM Kit</td>
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<td>Prebreathe Protocol</td>
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<td>Circadian Shifting</td>
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NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005
The Human System and Spiral Development for Exploration

** Includes all program requirements
## Human Health Countermeasures Roadmap

### Sub-Capability

**Human Health Countermeasures**

<table>
<thead>
<tr>
<th>Sub-Capability</th>
<th>Validated Ground Analog</th>
<th>Spacecraft resource requirements</th>
<th>Candidate Countermeasure Suite</th>
<th>Validated Countermeasure Suite</th>
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<tr>
<td><strong>Test individual system countermeasures</strong></td>
<td>Test candidate countermeasure suites</td>
<td>Validate integrated countermeasure suite</td>
<td>ISS Flight Test Exercise Devices</td>
<td>ISS Flight Test Exercise Devices</td>
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<td>Next generation device evaluations</td>
<td>ISS Reliable Exercise Systems</td>
<td>Validated Exercise Model</td>
<td>Operations planning</td>
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<td>Ground Studies for exercise Rx</td>
<td>Bedrest Baseline</td>
<td>Bedrest Optimized Rx</td>
<td>Lunar CM Hardware Development &amp; Validation</td>
<td>Lunar CM Hardware Development &amp; Validation</td>
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<td>AG Pilot Study</td>
<td>AG – optimize Rx</td>
<td>AG – Clinical Studies</td>
<td>AG Decision Support Package</td>
<td>AG Decision Support Package</td>
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<td>AG – Clinical Studies</td>
<td>Directed Studies (52’ &amp; 20G Centrifuges)</td>
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### Milestones

- **SRR**: System Requirements Review
- **SDR**: System Design Review
- **PDR**: Preliminary Design Review
- **CDR**: Critical Design Review
- **1st Human Mission**: Mars Science Lab

### Milestone Colors

- **Yellow Triangle**: Milestone
- **Red Bar**: Timeframe
- **Green Bar**: Operations planning

### Timeline

- **2005 - 2017**: Dates for each milestone

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**NOTE:** Milestone colors correspond to spiral color bars above.
# Human Health Countermeasures Roadmap

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<td>Spiral 4: Mars Vicinity</td>
<td></td>
<td></td>
<td>SDR</td>
<td>PDR</td>
<td>CDR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spiral 5: Mars Surface</td>
<td></td>
<td></td>
<td>SRR</td>
<td>SDR</td>
<td>PDR</td>
<td>CDR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Sub-Capability**

**Human Health Countermeasures**

- Operations planning, monitoring and intervention
- Long duration Lunar countermeasure suite decision
- Long Duration Lunar CM Hardware Development & Validation
- Mars countermeasure suite decision
- Mars CM Hardware Development & Validation
- Spacecraft resource requirements

**NOTE:** Milestone colors correspond to spiral color bars above.
Benefits:

- Physiological adaptation in-transit (bone, muscle, cardio, neuro, …)
- Human factors in-transit (spatial orientation, WCS, galley, …)
- Medical equipment/operations (countermeasures, surgery, CPR, …)
- Environmental (particulates, liquids, …)

Risks/Uncertainties:

- Engineering (requirements, design: truss, fluid loops, propulsion…)
- Human factors during spin-up/down
- Physiological adaptation during spin-up/down (neuro, cardio, …)
Evidence Base to Guide Program Decisions

Transit Vehicle

- Continuous AG
  - Trade Space
  - $g$, $r$, $\omega$
  - spin up/down req'ts
  - human factors

- Intermittent AG
  - Trade Space
  - $g$, $r$, $\omega$, duty cycle
  - exercise req'ts
  - optimal prescription

Surface Ops

- 3/8 g enough?
  - yes
  - no

- human factors
Integration Approach

**Maturity Level – Capabilities for Human Health Countermeasures**

- **Individual Investigators:**
  - Understand scientific basis of problem: Formulate countermeasure concept

- **Focused research teams:**
  - Demonstration of CM efficacy
  - Laboratory/clinical testing

- **CM evaluation with human subjects in simulated spaceflight environment**

- **CM validated with human subjects in Actual Spaceflight environment**

- **Countermeasure operational**

---

**Capability Readiness Level**

- **Sub-Capabilities**
  - Demonstrated in a Laboratory Environment

  Proof-of-Concept analyses of the Sub-capabilities are performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.

  * Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)
## Maturity Level – Technologies for Artificial Gravity

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential ameliorative and/or adverse effects from A/G (spin vehicle)</td>
<td>Decision support from long radius centrifuge research studies</td>
<td>1/2016</td>
</tr>
<tr>
<td>Trade Space for Spacecraft Designers (radius, angular velocity, spin down rates)</td>
<td>Decision support from long radius centrifuge research studies</td>
<td>1/2016</td>
</tr>
<tr>
<td>Potential ameliorative and/or adverse effects from on-board centrifugation</td>
<td>Decision support from long radius centrifuge research studies</td>
<td>1/2016</td>
</tr>
<tr>
<td></td>
<td>Design Options for Short Radius Centrifuge (flight)</td>
<td>2/2011</td>
</tr>
<tr>
<td>Fitness for duty after spin down</td>
<td>Decision support from long radius centrifuge research studies</td>
<td>1/2016</td>
</tr>
</tbody>
</table>

Note: Unless otherwise indicated, assumes Mars mission scenario
### Maturity Level – Technologies for Exercise

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliable, instrumented exercise equipment for evaluation on ISS</td>
<td>Robust exercise equipment for validation on ISS</td>
<td>5/2010*</td>
</tr>
<tr>
<td>Optimized exercise prescriptions</td>
<td>Optimized &amp; validated exercise prescriptions for use for all phases of exploration missions</td>
<td>5/2012*</td>
</tr>
<tr>
<td>Validated exercise equipment requirements for use for all phases of exploration missions</td>
<td>Validated h/w &amp; medical requirements for next generations systems</td>
<td>5/2013 (moon) 1/2023 (Mars)**</td>
</tr>
</tbody>
</table>

*Utilizes ISS as testbed

**Utilizes Moon as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario
### Maturity Level – Technologies for Other Countermeasures

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inadequate knowledge of countermeasures for bone, muscle, cardiovascular, and sensory motor</td>
<td>Optimized, validated countermeasure suite</td>
<td>4-5/2016*</td>
</tr>
<tr>
<td>Inadequate knowledge of immunology, infection &amp; hematology risks associated with space flight</td>
<td>Definitive knowledge of IIH risk in space flight If risk, then adequate treatment</td>
<td>2/2016*</td>
</tr>
<tr>
<td>Inefficient protocols for decompression sickness (probably too conservative)</td>
<td>Safe, effective protocols to prevent DCS Recommendation for cabin pressure</td>
<td>7/2011</td>
</tr>
<tr>
<td>Inadequate standards for air contaminants (180 days)</td>
<td>1000 day standards for air contaminants</td>
<td>6/2008</td>
</tr>
<tr>
<td>Lack of knowledge of Mars dust chemical composition, toxicity and volatility</td>
<td>Requirement for Mars dust analysis on precursor missions</td>
<td>N/A / SRR for Mars Science Lab</td>
</tr>
</tbody>
</table>

*Utilizes ISS as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario
## Metrics for Human Health Countermeasures

<table>
<thead>
<tr>
<th>TRL Definition</th>
<th>TRL/CMRL Score</th>
<th>CMRL Definition</th>
<th>CMRL category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic principles observed</td>
<td>1</td>
<td>Phenomenon observed and reported. Problem defined.</td>
<td></td>
</tr>
<tr>
<td>Technology concept and/or application formulated</td>
<td>2</td>
<td>Hypothesis formed; preliminary studies to define parameters. Demonstrate feasibility.</td>
<td></td>
</tr>
<tr>
<td>Analytical and experimental critical function/proof-of-concept</td>
<td>3</td>
<td>Validated hypothesis. Understanding of scientific processes underlying problem.</td>
<td></td>
</tr>
<tr>
<td>Component and/or breadboard validation in lab</td>
<td>4</td>
<td>Formulation of countermeasures concept based on understanding of phenomenon.</td>
<td></td>
</tr>
<tr>
<td>Component and/or breadboard in relevant environment</td>
<td>5</td>
<td>Proof of concept testing and initial demonstration of feasibility and efficacy.</td>
<td></td>
</tr>
<tr>
<td>System/subsystem model or prototype demonstration in relevant environment</td>
<td>6</td>
<td>Laboratory/clinical testing of potential countermeasure in subjects to demonstrate efficacy of concept.</td>
<td></td>
</tr>
<tr>
<td>Subsystem prototype in a space environment</td>
<td>7</td>
<td>Evaluation with human subjects in controlled laboratory simulating operational space flight environment.</td>
<td></td>
</tr>
<tr>
<td>System completed and flight qualified through demonstration</td>
<td>8</td>
<td>Validation with human subjects in actual operational space flight to demonstrate efficacy and operational feasibility.</td>
<td></td>
</tr>
<tr>
<td>System flight proven through mission operations</td>
<td>9</td>
<td>Countermeasure fully flight-tested and ready for implementation.</td>
<td></td>
</tr>
</tbody>
</table>

**TRL/CMRL Definition**

**CMRL Definition**

**CMRL category**
Definition

- Behavioral Health & Performance addresses the human performance-related challenges associated with space flight due to isolation, confinement and potential hazards. These challenges are characterized by:
  - Team cohesion and productivity
  - Psychological health management
  - Performance readiness
  - Individual and crew selection
Benefits

- Mitigation of risk of human performance failures through in-flight monitoring and early detection of conditions interfering with behavioral performance and health
- Selection of individuals and crews to match mission requirements and team compatibility
- Performance readiness assessments of individuals and crews
- Mitigation and management of risks related to team cohesion and productivity, individual behavioral health, mission safety and mission success
State of the Art

- Anecdotal information from Shuttle, Mir and ISS crews
- Preliminary predictive models for fatigue-related performance deficits based on ground studies
- Dependence on pharmacological aids for sleep management and improvement
- Select-in criteria for astronaut candidate applicants, but no validation with training or performance data
- New select-out criteria and standards developed based on Diagnostic Statistical Manual of Mental Disorders IV; awaiting headquarters approval
The Human System and Spiral Development for Exploration

** Includes all program requirements

03/10/05
### Behavioral Health & Performance Roadmap

#### Shuttle & ISS
- **SRR**: SRR
- **SDR**: SDR
- **PDR**: PDR
- **CDR**: CDR
- **Un-crewed Flight**: Un-crewed Flight
- **Crewed Flight**: Crewed Flight

#### Spiral 2: Extended Duration Moon
- **SRR**: SRR
- **SDR**: SDR
- **PDR**: PDR
- **CDR**: CDR

#### Spiral 3: Long Duration Moon

#### Spiral 4: Mars Vicinity

#### Spiral 5: Mars Surface

### Sub-Capability

#### Behavioral Health & Performance

### Team Cohesion & Productivity
- Computerized conflict mgmt training
- Tech watch for sensors, lab tests
- Partnerships for Tech (DoD, NSBRI, other)

### Psychological Health Management
- Enhance data capture from ISS
- Prototype depression mgmt trg
- Clinical watch
- Lunar BHP intervention procedures developed/validated
- BHP pharmacology tests (earth, ISS)

### Performance Readiness
- Identify sensors, tests for cognitive readiness
- Blue light and other circadian rhythm entrainment
- Verifying individualized predictive models for fatigue (ISS)
- Predictive models for lunar-cognitive & fatigue related decrements

### Individual & Crew Selection
- Current astronaut select-in/select-out criteria validated
- Just-in-time training methods
- Lunar crew select-in/select-out criteria

---

**NOTE**: Milestone colors correspond to spiral color bars above.
Maturity Level – Capabilities
Behavioral Health & Performance

Integration Approach

- Mission Concept of Operations
- Develop predictive models of individual & team performance
- Validate models
- Develop ground and flight support system
- In-flight monitoring and intervention
- Refine mission operations tools

Capability Readiness Level

1

Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

The Capability is defined in written form. The uses and/or applications of the Capability are described and an initial Proof-of-Concept analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)
### Maturity Level – Technologies for Team Cohesion & Productivity

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify standards/operating limits for team cohesion and productivity</td>
<td>Standards, operating limits, guidelines</td>
<td>2009</td>
</tr>
<tr>
<td>Sensors, unobtrusive monitoring capabilities</td>
<td>Assessment technologies for team cohesion and productivity</td>
<td>3/2009</td>
</tr>
<tr>
<td>Predictive models for team cohesion/productivity*, **</td>
<td>Computer Models, simulations</td>
<td>3/2012</td>
</tr>
<tr>
<td></td>
<td>Later refinement for Mars</td>
<td>3/2018</td>
</tr>
</tbody>
</table>

*Utilizes ISS as testbed  
**Utilizes Moon as testbed  

Note: Unless otherwise indicated, assumes Mars mission scenario.
<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standards, requirements, operating bands for behavioral health (mood, anxiety)</td>
<td>Standards/requirements/operating bands for mood and anxiety for CEV, lunar, and Mars</td>
<td>2007 (CEV) 2012 (Lunar) 2020 (Mars)</td>
</tr>
<tr>
<td>Unobtrusive, ongoing monitoring capabilities</td>
<td>Requirements and validated technologies for unobtrusive monitoring (e.g., optical computer recognition of facial features/voice analysis; smart clothing or variation thereof)</td>
<td>2/2008</td>
</tr>
<tr>
<td></td>
<td>Refinements (lunar, Mars)  Biomarkers that are easily obtained and do not require astronaut initiation</td>
<td>2014—2025</td>
</tr>
<tr>
<td>Biomarker sentinels of mood and anxiety degradation; stress reactions</td>
<td>Refinements for lunar, Mars  Computerized, modular systems/decision trees</td>
<td>2/2012</td>
</tr>
<tr>
<td></td>
<td>Refinements for lunar, Mars  Requirements and validated technologies for unobtrusive monitoring (e.g., optical computer recognition of facial features/voice analysis; smart clothing or variation thereof)</td>
<td>2014/2022</td>
</tr>
<tr>
<td>Just in time training/education for astronaut, ground, flight surgeon</td>
<td>Refinements for lunar, Mars  Requirements and validated technologies for unobtrusive monitoring (e.g., optical computer recognition of facial features/voice analysis; smart clothing or variation thereof)</td>
<td>2/2012</td>
</tr>
<tr>
<td></td>
<td>Refinements for lunar, Mars  Requirements and validated technologies for unobtrusive monitoring (e.g., optical computer recognition of facial features/voice analysis; smart clothing or variation thereof)</td>
<td>2014/2022</td>
</tr>
<tr>
<td>Risk mitigation and countermeasures</td>
<td>Tele behavioral health therapy, on-board pharmaceuticals and other countermeasures</td>
<td>2/2012</td>
</tr>
<tr>
<td></td>
<td>Refinements for lunar, Mars  Requirements and validated technologies for unobtrusive monitoring (e.g., optical computer recognition of facial features/voice analysis; smart clothing or variation thereof)</td>
<td>2015/2025</td>
</tr>
</tbody>
</table>

Note: Unless otherwise indicated, assumes Mars mission scenario
## Maturity Level – Technologies for Performance Readiness

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Readiness to perform standards/ operating bands/requirements</td>
<td>Standards/requirements/operating bands for cognitive, sleep and circadian elements</td>
<td>2007</td>
</tr>
<tr>
<td>Readiness to perform predictors</td>
<td>Individualized model for sleep-related fatigue</td>
<td>4/2007</td>
</tr>
<tr>
<td></td>
<td>Individualized model for cognitive decrements</td>
<td>3/2009</td>
</tr>
<tr>
<td>Countermeasures for cognitive decrements</td>
<td>Environmental supports (SHF)</td>
<td>3/2012</td>
</tr>
<tr>
<td></td>
<td>Pharmaceutical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Refresher training</td>
<td>2020</td>
</tr>
<tr>
<td>Risk mitigation for sleep-related fatigue</td>
<td>Pharmaceuticals for Mars</td>
<td>3-5/2009</td>
</tr>
<tr>
<td></td>
<td>Rest schedules</td>
<td>4/2009</td>
</tr>
<tr>
<td></td>
<td>Developed blue light / other light tools</td>
<td>3/2010</td>
</tr>
<tr>
<td></td>
<td>Refinements for Mars</td>
<td>2020</td>
</tr>
</tbody>
</table>

Note: Unless otherwise indicated, assumes Mars mission scenario
### Maturity Level – Technologies for Individual & Crew Selection

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/ Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirements for individual select-in for a mission across spirals</td>
<td>Validated requirements - CEV select-in</td>
<td>2010</td>
</tr>
<tr>
<td></td>
<td>Validated requirements - lunar select-in</td>
<td>2015</td>
</tr>
<tr>
<td></td>
<td>Validated requirements - Mars select-in</td>
<td>2025</td>
</tr>
<tr>
<td>Validation of current select in procedures for astronaut candidacy</td>
<td>Validated select in procedures for astronaut candidacy</td>
<td>2010</td>
</tr>
<tr>
<td>Revise astronaut candidacy select-in based on validation</td>
<td>Improved select-in procedures</td>
<td>2010</td>
</tr>
<tr>
<td>Lunar</td>
<td></td>
<td>2015</td>
</tr>
<tr>
<td>Mars</td>
<td></td>
<td>2025</td>
</tr>
<tr>
<td>Development of criteria for crew select-in for CEV, Lunar, Mars</td>
<td>System of selecting team members based on group compatibility, productivity and mission scenario</td>
<td>2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2015 (Lunar)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2025 (Mars)</td>
</tr>
</tbody>
</table>

Note: Unless otherwise indicated, assumes Mars mission scenario.
Program Goal

- Reduction in human error due to lack of readiness to perform, behavioral health dysfunction, imprecise selection, or poor team compatibility / productivity

Annual Metrics

- Progression through TRL levels of technology components
- Percent coverage of the gaps across years
- Validation across lab, earth analog, ISS, and lunar testbeds
Space Human Factors

Human Health & Performance

- Space Radiation
  - Measurement Technologies
  - Shielding Solutions
  - Risk Assessment/Projection
  - Biological Countermeasures

- Medical Care
  - Medical Devices
  - Clinical Capabilities
  - Medical Informatics

- Human Health Countermeasures
  - Artificial Gravity
  - Exercise
  - Other Physiological CM

- Behavioral Health & Performance
  - Team Cohesion & Productivity
  - Psych Health Management
  - Performance Readiness
  - Individual & Crew Selection

- Space Human Factors
  - Models & simulations
  - Design tools & requirements
  - Performance Measurements
  - Training & Decision Support Systems
Definition

- Space Human Factors addresses the human performance-related challenges associated with space flight due to vehicle and habitat design, tool and task design. Space Human Factors mitigates these challenges through the use of:
  - Models and simulations
  - Design tools and requirements
  - Performance measurements
  - Training and decision support systems
Benefits

- Enhanced human performance through incorporation of human factors into vehicle, task and equipment design
- Increased mission success due to well-designed tasks and matching skills and tools to task requirements
- Expanded Non-intrusive performance measures to enable real-time assessment of readiness
- Utilization of appropriate automation to reduce crew workload
- Improved training and decision support systems for greater crew autonomy to enable missions with large communications lags and blackouts
State of the Art

- Anecdotal information from Shuttle, Mir and ISS crews
- Commercial models of 1-g physical performance
- Research models of human cognitive performance
- Commercial CAD design tools do not interface with Human Factors (HF) requirements
- External non-NASA, including DoD, HF knowledge about training, performance measurement, simulations is potentially applicable to some space applications (launch, entry) but not all (microgravity, partial gravity)
NASA-STD-3000: Human-Systems Integration Standards (HSIS)
• Created by an inter-disciplinary team including NASA, aerospace industry, and academia.
• Agency-wide standard replacing Marshall Space Flight Center and Johnson Space Center Human Factors Standards
• Adopted by the International Standards Organization as ISO 17399:2003
• Includes:
  – Volume: Data for sizing the vehicle
  – Anthropometry & Biomechanics: Data for sizing & operating the vehicle
  – Acceleration Limits: Data for defining the ascent/descent acceleration regimes
  – Radiation: Dose mitigation requirements on a radiation protection system
  – Human/Computer Interaction: Data appropriate to current interface technologies
  – Maintainability/Commonality/Sustainability: Limits to operational overhead
  – EVA: Supporting data appropriate to the top-level EVA requirement for the vehicle
• Document is iterated with supplemental volumes specific to each vehicle or habitat
Space Human Factors Roadmap

Shuttle & ISS
- 2005: SPIRAL 1: Crew Exploration Vehicle (CEV) - SRR
- 2006: SPIRAL 2: Extended Duration Moon - SRR
- 2007: SPIRAL 3: Long Duration Moon - SRR
- 2008: SPIRAL 4: Mars Vicinity - SRR
- 2009: SPIRAL 5: Mars Surface - SRR
- 2010: ISS End of US commitment - SRR
- 2011: Retirement of Shuttle - SRR
- 2012: Mars Science Lab - SRR

Sub-Capability
Space Human Factors

Models & Simulations
- Digital anthropometry models
- Physical model - CEV crew
- Cognitive models - CEV launch
- Part-task cognitive modeling
- Physical model - lander

Design Tools & Requirements
- NASA-STD-3000 CEV Requirements
- NASA-STD-3000 Vol I. Revision
- Design tool- cockpit volume reqts
- Design tool- lander volume reqts
- Design tool- habitat volume reqts

Performance Measurements
- Physical performance, 0-g
- Cognitive performance, operational

Training & Decision Support Systems
- CEV Training reqts & guidelines
- Lunar lander Training reqts & guidelines

NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005
NOTE: Milestone colors correspond to spiral color bars above
<table>
<thead>
<tr>
<th>Sub-Capability Space Human Factors</th>
<th>Models &amp; Simulations</th>
<th>Design Tools &amp; Requirements</th>
<th>Performance Measurements</th>
<th>Training &amp; Decision Support Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars Habitat, Transfer Vehicle Design Rqmts</td>
<td>Models of human-automation performance</td>
<td>Habitat, transfer vehicle design Rqmts</td>
<td>Tools for partial-g performance measurement</td>
<td>Training system requirements</td>
</tr>
<tr>
<td>Training requirements &amp; guidelines</td>
<td>Models of human teams</td>
<td>Tools for Team Design</td>
<td>Partial-g data collection</td>
<td>Training system requirements</td>
</tr>
<tr>
<td>Models of partial-g physical performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE: Milestone colors correspond to spiral color bars above.
Integration Approach

- Human System Integration Standards
- Research to update contents and fill missing elements
- Evaluate models
- Modify and validate models for NASA applications
- Predict, monitor and assess readiness to perform
- Refine operational tools and capabilities

Capability Readiness Level

2 Sub-Capabilities*

Demonstrated in a Laboratory Environment

Proof-of-Concept analyses of the Sub-capabilities are performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)
### Maturity Level – Technologies for Team Models & Simulations

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human size data for input to spacecraft designs</td>
<td>Digital anthropometry models</td>
<td>3/2007</td>
</tr>
</tbody>
</table>
| Physical performance models for 0-g (time to perform, strength, fatigue) | Model time to do physical tasks  
Model strength in different positions | 3/2016  
3/2016 (end of ISS) |
| Predictive models of cognitive performance       | Part task models – cockpit-type tasks  
Integrated cognitive models as function of task design, aids | 2/2011  
2/2017 |
| Predictive models of team performance            | Models of human/automation perf.  
Models of teams of humans                                                      | 1/2020  
1/2022 |
| Physical performance models for partial-g         | Model time to do physical tasks  
Model strength in different positions | 2/2027 |

*Utilizes ISS as testbed

**Utilizes Moon as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario
### Maturity Level – Technologies for Design Tools & Requirements

Note: Unless otherwise indicated, assumes Mars mission scenario

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human-centered design requirements</td>
<td>Updated HSIS standards that are verifiable</td>
<td>5/2009</td>
</tr>
<tr>
<td></td>
<td>Design tools for habitable environment: lander</td>
<td>3/2013</td>
</tr>
<tr>
<td></td>
<td>Design tools for habitable environment: habitat</td>
<td>3/2015</td>
</tr>
<tr>
<td>Team design requirements &amp; guidelines, including multi-agent teams</td>
<td>Tools for team design</td>
<td>8/2023</td>
</tr>
<tr>
<td></td>
<td>Task allocation analysis</td>
<td></td>
</tr>
</tbody>
</table>
### Maturity Level – Technologies for Performance Measurements

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantitative performance measurement tools</td>
<td>Validated real-time physical performance measurement tools in zero-g</td>
<td>4/2009</td>
</tr>
<tr>
<td></td>
<td>Validated real-time cognitive performance measurement tools</td>
<td>3/2011</td>
</tr>
<tr>
<td></td>
<td>Validated real-time physical performance measurement tools in partial-g</td>
<td>6/2018</td>
</tr>
</tbody>
</table>

Note: Unless otherwise indicated, assumes Mars mission scenario
### Maturity Level – Technologies for Training & Decision Support Systems

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive skill-based training systems</td>
<td>Gap analysis and trade studies</td>
<td>3/2010</td>
</tr>
<tr>
<td></td>
<td>Lunar lander guidelines and requirements</td>
<td>3/2015</td>
</tr>
<tr>
<td>Decision support systems (DSS) with high reliability</td>
<td>Gap analysis and trade studies</td>
<td>8/2021</td>
</tr>
<tr>
<td></td>
<td>Requirements for DSS</td>
<td>3/2024</td>
</tr>
</tbody>
</table>

Note: Unless otherwise indicated, assumes Mars mission scenario
Metrics for Space Human Factors

• **Program Goal**
  – Decrease task time
  – Decrease errors, error rate and the effects of errors
  – Decrease engineering design time
  – Increased usability of equipment and procedures

• **Annual**
  – Progression of TRL levels
  – Fewer resources spent redesigning crew systems
  – High usability and integrated testing results
  – Less crew time needed for ground-based training, on-orbit training, procedure execution
Human Health & Performance Summary

- Optimal radiation shielding solution for spacecraft.
- Adequate warning systems & effective operational protection for Solar Particle Events.
- Validated selection criteria for crewmembers that reduces personal risk & mission risk.
- Validated countermeasure system that limits the deleterious effects of space flight to ensure crew health and performance, and provides the means by which observed deficits can be remedied.
- Medical diagnostic capability to monitor all aspects of health, including predicted adaptation, and the means by which observed deficits can be remedied.
- Optimized medical system to diagnose and treat the widest range of potential health problems during all mission phases.
- The best possible prediction of risk (including lifetime) to the crew from radiation exposure.
- A system to support normal psychological adaptation to long duration space flight, and the means by which observed deficits can be remedied.
- Accurate predictors of crew task performance during all mission phases.
- Human Factors Engineering that prevents human error and maximizes successful performance.
Life Support and Habitation

Presenter:
Daniel J. Barta
In addition to the Design Reference Mission and other documents described in introductory slides, many other documents have been considered which have applicability to Life Support and Habitation. This list is for example purposes and is not complete.

• **Advanced Life Support Program Documents**

• **Spacecraft Requirements Documents**
  – Medical Operations and Requirements Documents
  – Manned Systems Integration Standards

• **National Research Council Reports and Guidelines**
  – Spacecraft Maximum Allowable Concentrations for Selected Airborne Contaminants (1994-)
  – Spacecraft Water Exposure Guidelines for Selected Contaminants (2000-)
  – Safe Passage: Astronaut Care for Exploration Missions (2001)
Atmosphere Revitalization

Description

- Air quality control technologies for enabling long duration exploration missions
  - Meet or exceed mission requirements
    - Constraints for mass, volume, power, thermal management, and maintainability, i.e. crew time and logistics
  - Provide sustainable operational robustness
    - Crew and mission safety
    - Mission success
    - Autonomous operation
- Key functional areas for development
  - Atmospheric gas supply, distribution, and partial pressure control
  - Air quality control during normal mission operations
    - Carbon dioxide, trace chemical contaminant, and particulate matter removal
    - Humidity control
  - Waste gas processing
    - Convert to useable forms
    - Enable higher degree of life support system closure
  - Operational robustness to respond and recover from off-nominal situations
  - Process design and integration
    - Interaction with other life support process functions and resources
Atmosphere Revitalization

Benefits

- Control atmospheric quality by maintaining carbon dioxide, humidity, trace chemical components, and particulate matter within specified limits for maintaining crew health and safety
- Robust capability to store and distribute atmospheric gases necessary to control major constituent partial pressure
- Provide operational robustness to respond to and recover from off-nominal cabin atmospheric quality events
- Emphasize maintainability and operational autonomy to achieve minimal crew intervention and logistics resupply
- Minimize equipment mass, volume, power, and thermal loads relative to existing applications
- Advance a functional design approach to achieve life support system oxygen loop closure
- Simplify process design and operations to significantly contribute to advances in system reliability and crew and mission safety
Atmosphere Revitalization
State-of-the-Art

- Atmosphere revitalization technologies in operation on board the International Space Station, Space Shuttle, and Spacelab
  - Carbon Dioxide Partial Pressure Control
    - Shuttle and Spacelab: consumable lithium hydroxide (LiOH) canisters
    - ISS: regenerable 4-bed molecular sieve process that provides for water recovery; regeneration accomplished by combined thermal-vacuum swing
  - Oxygen Generation
    - Shuttle and Spacelab: None
    - ISS: Solid Polymer Electrolyte (SPE) Oxygen Generation Assembly (OGA)
  - Trace Chemical Contaminant and Particulate Matter Control
    - Shuttle: expendable activated charcoal upstream of the LiOH; expendable ambient temperature catalytic oxidation of CO and H₂; 280-micron nominal filters for particulate matter
    - Spacelab: same as Shuttle except added an expendable mixed-media scrubber for trace contaminant and CO control
    - ISS: expendable activated charcoal with a high temperature catalytic oxidation and expendable LiOH for acid gas control; HEPA (0.3-micron nominal) filters for particulate matter
  - Atmospheric Gas Storage
    - Shuttle: High pressure storage; supercritical cryogenic storage for metabolic O₂
    - ISS: High pressure storage; Oxygen recharge capability.
  - Gas Recovery for System Loop Closure
    - Presently not on board Shuttle or ISS; CO₂ reduction risk mitigation in work
Atmosphere Revitalization
Requirements & Assumptions

- Long Duration Missions Drive Requirements
  - Missions to ISS and other LEO operations can use existing SOA with some modification
    - Potential for extended duration Lunar and Mars transit flight demonstration on ISS
  - Extended duration Lunar missions and Mars transit/Mars vicinity drive technological needs and departures from existing SOA

- Additional Assumptions
  - Loop closure and water recovery from CO$_2$ a priority for extended duration missions
  - Mission duration beyond 6 months will result in more challenging air quality standards for carbon dioxide, trace contaminants, and particulate matter
  - Long duration, continuous exposure to suspended particulate matter and the need to protect the crew and equipment from planetary dust will drive particulate filtration
  - Hypogravity environments (Lunar and Mars surface) may alleviate some microgravity issues but may also require Lunar demonstration testing
  - Mission requirements will drive multi-element technology commonality and architectural/functional interfaces with AEVA, ISRU, AEMC, etc
  - Trade studies based on performance testing data support decision points.
  - Consider reduced pressure vehicle and habitat applications. May drive range of developmental testing conditions.
### Atmosphere Revitalization Roadmap

<table>
<thead>
<tr>
<th>Capability</th>
<th>Life Support &amp; Habitation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Gas Supply & Ventilation
- **-CO₂**
- **Humidity**
- **Trace components**
- **Particulate matter**

#### Air Quality Control
- **Open Loop Regenerative**
- **Closed Loop Regenerative**
- **CO₂ Reduction**
- **Trade 1**
- **AEMC Water Waste**
- **AEMC**
- **Surface Version**
- **Transfer Vehicle & Surface Version**
- **AEVA Rover Systems**
- **Mark 1**
- **Mark 2**

#### High Pressure Oxygen Generation
- **AEMC**
- **AEVA**
- **Surface Version**

#### Input from External Entities
- **Trade 1**
- **AEVA**
- **Surface Version**

#### Output to External Entities
- **Trade 2a**
- **Trade 3**
- **AEVA**
- **Surface Version**

#### Atmosphere Revitalization Regenerative Open Loop
- **High Pressure Oxygen Generation**
- **Transfer Vehicle & Surface Version**
- **AEVA**
- **Surface Version**
- **AEVA**

#### Closed Loop with High Pressure Gas Supply
- **Mark 1**
- **Mark 2**

#### Closed Loop w/Mobile Capability
- **Mark 1**
- **Mark 2**

---

**NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005**

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### Atmosphere Revitalization Roadmap

<table>
<thead>
<tr>
<th>Capability</th>
<th>Life Support &amp; Habitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Revitalization</td>
<td>▲ Long Duration Closed Loop ▲ Bioregenerative Integration</td>
</tr>
<tr>
<td>Gas Supply &amp; Ventilation</td>
<td>Mark 2A</td>
</tr>
<tr>
<td>Air Quality Control</td>
<td>▲ Transit &amp; Descent Systems Mark 2A</td>
</tr>
<tr>
<td>- CO₂</td>
<td>▲ AEMC, Water, Crop, Waste, Food, &amp; Biological Systems Interactions</td>
</tr>
<tr>
<td>- Humidity</td>
<td></td>
</tr>
<tr>
<td>- Trace components</td>
<td></td>
</tr>
<tr>
<td>- Particulate matter</td>
<td></td>
</tr>
</tbody>
</table>

**Shuttle & ISS**
- 2018

**Spiral 1: Crew Exploration Vehicle**
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024
- 2025
- 2026
- 2027
- 2028
- 2029
- 2030

**Spiral 2: Extended Duration Moon**
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024
- 2025
- 2026
- 2027
- 2028
- 2029
- 2030

**Spiral 3: Long Duration Moon**
- SDR ▲ PDR ▲ CDR ▲

**Spiral 4: Mars Vicinity**
- SRR ▲ SDR ▲ PDR ▲ CDR ▲

**Spiral 5: Mars Surface**
- 1st Human Mission

**Major Decision**
- Ready to Use

**Input from External Entities**

**Output to External Entities**
<table>
<thead>
<tr>
<th>Mission (Need Date)</th>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Capability Development Needs</th>
<th>Current CRL</th>
</tr>
</thead>
</table>
| Spiral 1 Lunar Capable Low Earth Orbit CEV (2008) | Supply O₂ & N₂  
Control O₂ & N₂ partial pressure  
Regeneratively control CO₂ partial pressure, relative humidity, and remove trace contaminants from cabin atmosphere  
Remove suspended particulate matter  
Provide ventilation & atmospheric mixing |                                                                                             |             |
| Spiral 2 Lunar Surface (2011)       | Spiral 1 plus demonstrate closed loop:  
Provide ambient/high pressure O₂ generation  
Provide CO₂ reduction/demonstrate loop closure  
Provide means to control migration of lunar dust into habitat |                                                                                             |             |
| Spiral 3 Long Duration Lunar Surface (2014) | Spiral 2 plus full loop closure:  
Provide ambient/high pressure O₂ generation  
Open loop systems for EVA support  
Demonstrate CO₂ reduction to carbon  
Mark 1 air quality control equipment |                                                                                             |             |
| Spiral 4 Mars Vicinity (2017)       | Spiral 3 full loop closure plus:  
Provide carbon formation process  
Adapt Spiral 2/3 integrated systems to transfer vehicle application |                                                                                             |             |
| Spiral 5 Initial Mission Mars Surface (2021) | Spiral 3 plus:  
Adapt Spiral 1 systems to descent vehicle  
Adapt Spiral 3 systems to habitat and mobile applications  
Adapt Spiral 2/3 dust isolation methods |                                                                                             |             |
<table>
<thead>
<tr>
<th>Sub-Capability (Level 5/6 CBS)</th>
<th>Leading Technology Candidates</th>
<th>Spiral(s)</th>
<th>Current TRL</th>
</tr>
</thead>
</table>
| Control Carbon Dioxide Partial Pressure | Expendable chemisorbents (LiOH)  
Vacuum swing adsorption  
Combined temperature/vacuum swing adsorption  
Bioregenerative Systems | 1-3  
1-5  
4-5 | 4-9  
4  
3-5 |
| Control Humidity | Vacuum swing adsorption  
Combined temperature/vacuum swing adsorption  
Condenser with phase separation | 1-5  
2-5  
2-5 | 4  
4  
9 |
| Control Trace Atmospheric Components | Expendable adsorbents (activated charcoal)  
Combined temperature/vacuum swing adsorption  
Thermal catalytic oxidation (CH₄ and light VOCs)  
Ambient temperature catalytic oxidation (CO and H₂) | 1-3  
2-5  
2-5  
1-3 | 9  
4  
3-9  
3-9 |
| Remove Suspended Particulate Matter | Macrofiltration (10 microns)  
HEPA filtration (0.3 micron)  
Electrofiltration – (<0.1 micron)  
Regenerative filters | 1-2  
2-5  
2-5  
2-5 | 9  
9  
4+  
3 |
| Store & Distribute Nitrogen | High pressure storage and Cryogenic storage  
Chemical storage | 1-5  
1-5 | 9  
1-2 |
| Generate, Store, & Distribute Oxygen | Cryogenic storage  
Water electrolysis – solid polymer electrolyte  
Water electrolysis – high pressure products  
Oxygen transfer compressor (ORCA)  
Bioregenerative Systems | 1-5  
2-5  
2-5  
1-5  
4-5 | 9  
5  
2  
9  
3-5 |
| Recover Resources | Carbon dioxide reduction (Sabatier, Bosch)  
Carbon formation reactor (Sabatier post-processing) | 2-5  
2-5 | 4+  
2 |
| Provide Ventilation | Fixed and portable axial fans  
Ion discharge air movement systems  
Low power low noise fans | 1-5  
1-5  
1-5 | 9  
4+  
1-4 |
## ATMOSPHERE REVITALIZATION METRICS

<table>
<thead>
<tr>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Figures of Merit</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Control Carbon Dioxide Partial Pressure</strong></td>
<td></td>
<td>Equipment equivalent cube volume</td>
<td>$m^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hourly specific power</td>
<td>Watt-h/kg air</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Equivalent system mass for equipment</td>
<td>kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daily specific crew hours</td>
<td>h/kg air/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daily specific logistics mass</td>
<td>kg/kg air/day</td>
</tr>
<tr>
<td><strong>Control Humidity</strong></td>
<td></td>
<td>Equipment equivalent cube volume</td>
<td>$m^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hourly specific power</td>
<td>Watt-h/kg air</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Equivalent system mass for equipment</td>
<td>kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daily specific crew hours</td>
<td>h/kg air/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daily specific logistics mass</td>
<td>kg/kg air/day</td>
</tr>
<tr>
<td><strong>Control Trace Atmospheric Components</strong></td>
<td></td>
<td>Equipment equivalent cube volume</td>
<td>$m^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hourly specific power</td>
<td>Watt-h/kg air</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Equivalent system mass for equipment</td>
<td>kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daily specific crew hours</td>
<td>h/kg air/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daily specific logistics mass</td>
<td>kg/kg air/day</td>
</tr>
<tr>
<td><strong>Store &amp; Distribute Nitrogen</strong></td>
<td></td>
<td>Equipment equivalent cube volume</td>
<td>$m^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Equivalent system mass for equipment</td>
<td>kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daily logistics mass</td>
<td>kg/day</td>
</tr>
<tr>
<td><strong>Generate, Store, &amp; Distribute Oxygen</strong></td>
<td></td>
<td>Equipment equivalent cube volume</td>
<td>$m^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hourly specific power</td>
<td>Watt-h/kg $O_2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Equivalent system mass for equipment</td>
<td>kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daily specific crew hours</td>
<td>h/kg $O_2$/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daily specific logistics mass</td>
<td>kg/kg $O_2$/day</td>
</tr>
<tr>
<td><strong>Recover Resources</strong></td>
<td></td>
<td>Equipment equivalent cube volume</td>
<td>$m^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hourly specific power</td>
<td>Watt-h/kg $H_2O$ made</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Equivalent system mass for equipment</td>
<td>kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daily specific crew hours</td>
<td>h/kg $H_2O$/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daily specific logistics mass</td>
<td>kg/kg $H_2O$/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hourly specific $CO_2$ and $H_2$ recovery percentage</td>
<td>%-h/kg air</td>
</tr>
<tr>
<td><strong>Provide Ventilation</strong></td>
<td></td>
<td>Equipment equivalent cube volume</td>
<td>$m^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hourly specific power</td>
<td>Watt-h/kg air</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Equivalent system mass for equipment</td>
<td>kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Acoustic noise</td>
<td>db</td>
</tr>
</tbody>
</table>
Water Recovery Systems

- Air Revitalization
- Water Reclamation
- Thermal Control
- Solid Waste Management
- Food Provisioning and Management
- Biomass Production

- Internal Monitoring
- External Monitoring
- Control Systems

- Surface Construction
- Habitat Shell
- Internal Systems & Outfitting
- External Systems and Architecture

Human Health & Support Systems

- Human Health & Performance
- Life Support Systems
  - Environmental Monitoring and Control
  - Contingency Response
  - Exploration Habitats
- Life Support and Habitation
- Extra-Vehicular Activity

Exploration Habitats
Water Recovery Systems

Description

- Water recovery systems transform crew and system wastewater into potable water for crew and system reuse.
- Biological and/or physical/chemical methods employed to remove contaminants
- Biocides added for residual disinfection to inhibit microbial growth in storage tanks.
- Processing strategy
  - Transport and storage of wastewater from human interfaces
  - Primary processing: organic and nitrogenous contaminant reduction
  - Secondary processing: inorganic contaminant reduction
  - Brine dewatering: water removal from highly concentrated brine
  - Post-processing and disinfection: polishing to meet potability standards
  - Storage and transport of potable water prior to consumption
Water Recovery Systems

Benefits

- Potable water ensures crew health
- Recovery of potable water from wastewater reduces mass of consumables required for mission

Effect of water processing on the ESM of a Lunar Outpost, Mars Transit Vehicle, and Mars Habitat with respect to mission duration

Water Recovery Systems
Current State-of-the-Art

- Vapor compression distillation technology
  - Rotating distillation process
  - Used for urine treatment
  - Organic and inorganic removal
  - Produces brine
  - Distillate requires further treatment to reach potable quality

- Multifiltration beds
  - Organic and inorganic removal
  - Requires consumable adsorption / ion exchange beds

- Volatile removal assembly
  - Catalytic oxidation
  - Operates at high temperature conditions
  - Requires adsorption bed for residual organic acid removal

- Microbial check valve
  - Dispenses iodine for disinfection of potable water
  - Iodine must be removed prior to consumption of water by crew
Water Recovery Systems
Requirements /Assumptions

- Driving issue for Water Recovery Systems is the need to reduce the dependency on resupply for long duration missions
- Spirals 3, 4 and 5 drive the need for Water Recovery Systems
- Additional Assumptions:
  - Personal care cleanser will need to be defined early
  - WRS will drive selection of urine pretreat system, with input from waste collection system
  - Prototype urine pretreatment system will be tested in Spiral 1
  - Wastewater sources for Spiral 4 will be pretreated urine and humidity condensate
  - Wastewater sources for Spirals 3 and initial Spiral 5 will be pretreated urine, hygiene wastewater, laundry, and humidity condensate
  - Later Spiral 5 mission will include food processing waste, inputs from ISRU
  - If ISRU water is available, water quality information will be available from prior robotics missions
### Water Recovery Systems Roadmap

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Retire Shuttle</td>
<td>![Symbol]</td>
<td>ISS End of US commitment</td>
<td>![Symbol]</td>
<td></td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

**Capability**

**Life Support & Habitation**

### Water Recovery

**Wastewater collection**

- Urine pretreatment and stabilization
  - Requirements assessment
  - Development
  - Delivery system
  - TRL 5
  - Subsystem development
  - TRL 4
  - Integrate with PPS
  - TRL 4
  - Nitrification subsystem
  - Denitrification subsystem
  - Integrated BWP subsystem
  - Testing
  - TRL 6
  - Integrate with ARS TCCS
  - TRL 6
  - Alternate electron acceptor systems

**Primary WW treatment**

- Distillation technologies
  - Prototype development
  - TRL 5
  - Microgravity refinements
  - TRL 6
  - Develop prototype for Spiral 2 test?
  - TRL 6

**Biological water processor**

- Food processing waste characteristics
  - Integrate with ARS TCCS
  - TRL 3
  - Increase WW to include shower and laundry
  - Spiral 3/5 development
  - TRL 5
  - Prototype development
  - TRL 5
  - Pretreatment systems for mature planetary systems
  - TRL 6

**Regenerative Primary Processors**

- Food processing waste characteristics
  - TRL 6

---

*NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005*
## Water Recovery Systems Roadmap

### Capability
- Life Support & Habitation

### Water Recovery

<table>
<thead>
<tr>
<th>Secondary WW treatment</th>
<th>Brine dewatering</th>
<th>Post-processing and disinfection</th>
<th>Disinfection technologies</th>
<th>Potable water storage</th>
<th>Stored water disinfection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsystem development</td>
<td>Subsystem development</td>
<td>Subsystem development</td>
<td>Residual Requirement?</td>
<td>Technology assessment</td>
<td>N</td>
</tr>
<tr>
<td>TRL 4</td>
<td>TRL 4</td>
<td>TRL 4</td>
<td>Y</td>
<td>TRL 3</td>
<td></td>
</tr>
<tr>
<td>Integrate w/ biological systems</td>
<td>Integrate w/ brine dewatering systems, PPS</td>
<td>Integrate PPS with disinfection system</td>
<td>Selection &amp; Packaging</td>
<td>Tank disinfection system</td>
<td></td>
</tr>
<tr>
<td>Prototype development</td>
<td>Prototype development</td>
<td>Prototype development</td>
<td></td>
<td>TRL 6</td>
<td></td>
</tr>
<tr>
<td>TRL 4</td>
<td>TRL 5</td>
<td>TRL 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluate solid waste processors for brine dewatering</td>
<td>Continued Development</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Water Residual Disinfection

<table>
<thead>
<tr>
<th>Water System Disinfection</th>
<th>Secondary Primary Processors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsystem development</td>
<td>TRL 6</td>
</tr>
<tr>
<td>TRL 4</td>
<td>TRL 6</td>
</tr>
<tr>
<td>Integrate w/ secondary processing systems</td>
<td>TRL 6</td>
</tr>
<tr>
<td>Prototype development</td>
<td>TRL 5</td>
</tr>
<tr>
<td>TRL 4</td>
<td>TRL 5</td>
</tr>
<tr>
<td>Integrate with disinfection system</td>
<td>TRL 6</td>
</tr>
<tr>
<td>TRL 4</td>
<td>TRL 6</td>
</tr>
<tr>
<td>Select &amp; Packaging</td>
<td>TRL 6</td>
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<td>Residual Requirement?</td>
<td>TRL 4</td>
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### Water Recovery Subsystem

- Spiral 1: Crew Exploration Vehicle
- Spiral 2: Extended Duration Moon
- Spiral 3: Lunar Duration Moon
- Spiral 4: Mars Vicinity
- Spiral 5: Mars Surface
### Water Recovery Systems Roadmap

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<th>2018</th>
<th>2019</th>
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### Capability

#### Life Support & Habitation

**Water Recovery**

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**Closed Loop Physicochemical Water Treatment**

**Closed Loop Biological Water Treatment**

**Integration with Biomass Production Systems**
# Water Recovery Systems Roadmap

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## Capability

### Life Support & Habitation

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<td>Brine dewatering</td>
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<td>Potable water storage</td>
<td>Continued development and assessment of storage requirements for increased water availability for mature Spiral 5 missions</td>
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### Water Recovery Systems

**Maturity Level – Capabilities**

<table>
<thead>
<tr>
<th>Mission (Need Date)</th>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Capability Development Needs</th>
<th>Current CRL</th>
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<tbody>
<tr>
<td>Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)</td>
<td>Pretreat urine for stability Provide residual disinfection for stored water Store potable water</td>
<td>Less toxic urine pretreatment Residual disinfectant that does not require removal prior to water consumption None needed</td>
<td>2 1 3</td>
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<tr>
<td>Spiral 2 Lunar Surface (2011)</td>
<td>Same as Spiral 1</td>
<td>Spiral 1 development supports Spiral 2 except Prototype Spiral 3 distillation system available for testing in Spiral 2</td>
<td>2</td>
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<tr>
<td>Spiral 3 Long Duration Lunar Surface (2014)</td>
<td>Wastewater storage Remove organic contaminants from water Remove inorganic contaminants Recover brine solutions Provide polishing and disinfection Store potable water and provide residual disinfection</td>
<td>Same as Spiral 1 Improve energy efficiency and recovery of distillation systems; minimize size of biological systems Increase recovery of secondary processing systems Reduce power requirements, adapt to microgravity Reduce operating temperature and pressure</td>
<td>3 2 2 1 2</td>
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<tr>
<td>Spiral 4 Mars Vicinity (2017)</td>
<td>Same as Spiral 3</td>
<td>Same as Spiral 3 except technologies must operate in a microgravity environment Further reduction in weight and/or expendables</td>
<td>2 1</td>
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<tr>
<td>Spiral 5 Initial Mission Mars Surface (2021)</td>
<td>Same as Spiral 3</td>
<td>Same as Spiral 3 except Wastewater sources include food processing Integration with crop systems and solid waste processing Potential use of in-situ resources Further reduction in weight and/or expendables</td>
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<tr>
<td>Sub-Capability (Level 5 CBS)</td>
<td>Leading Technology Candidates</td>
<td>Development Needed</td>
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<td>Urine Pretreatment</td>
<td>Organic acid</td>
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<td>Increased water flush volume</td>
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<td>Primary Treatment (organic removal)</td>
<td>Rotating distillation process (combines primary and secondary treatment)</td>
<td>System integration Microgravity capability</td>
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<td>Membrane process</td>
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<td>Solid waste processors</td>
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<td>Residual requirement replaced with recirculating tank disinfection and point of use disinfection</td>
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## Water Recovery Systems
### Figures of Merit

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<td>Microbial water quality</td>
<td>CFU/ml</td>
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Active Thermal Control

Description

- Active Thermal Control Systems (ATCS) are required to control cabin and hardware temperatures within a vehicle

  - **Heat Acquisition and Humidity Control** – acquire waste heat from cabin air and vehicle hardware

  - **Heat Transport** – transport heat within the vehicle or habitat

  - **Heat Rejection** – reject energy from the vehicle or habitat, in the form of heat, to the environment
Active Thermal Control

Benefits

• Benefits
  – Maintain a comfortable temperature and humidity environment for crew
  – Maintain hardware temperatures within operating limits

• Benefits of advanced developments in Active Thermal Control System hardware
  – Decreased mass, power, or volume
  – Decreased risk
  – Enable heat rejection in new environments (higher temperatures or different ambient pressures)
  – Increased life
Active Thermal Control
Current State-of-the-Art

• Heat Acquisition and Humidity Control
  – Metal coldplates
  – Liquid-to-liquid compact heat exchangers
  – Air-to-liquid heat exchangers
  – Slurper bars and rotary separators for condensate collection

• Heat Transfer Technologies
  – Pumped liquid loops
  – Internal water loops and external refrigerant loops (Freon 21, ammonia)
  – Metal bellows accumulators

• Heat Rejection
  – Aluminum radiators (Z93 or Silver teflon coatings)
  – Porous plate sublimators
  – Flash Evaporator System (FES) – water spray boiler
  – Ammonia boiler
Active Thermal Control
Requirements /Assumptions

• Driving Mission Requirements and Assumptions
  – General Assumptions
    • Vehicle heat load
    • Heat rejection environment
      ▪ Radiation sink temperature
      ▪ Pressure
      ▪ Micrometeoroid and Orbital Debris
      ▪ Dust – unique to Lunar and Mars surface missions
    • Available vehicle surface area for mounting radiators
    • Mission duration
    • Availability of heat transfer fluid that enables a single loop for inside both the cabin and radiators
  – Mission Specific Requirements and Assumptions
    • Requirement for cabin pressure & depressurization (Spirals 1-5)
    • Requirement for collecting humidity condensate (Spirals 3 – 5)
    • Requirement for assembly and maintenance during the mission (Spirals 3 – 5)
### Active Thermal Control Roadmap

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### Active Thermal Control

- **Heat Acquisition**
  - Humidity Control – Condensate Collection
  - Coldplate Design
  - Fault Tolerant HX
- **Heat Transport**
  - Fluid Selection
  - Technologies Ready
  - Heat Pump
  - Two-phase Fluid Loops
  - Fluid Quick Disconnects
- **Heat Rejection**
  - Radiant Heat Rejection
  - Evaporative Heat Rejection

**Major Decision**

**Major Event / Accomplishment / Milestone**

**Ready to Use**

**Capability**

**Life Support & Habitation**
Active Thermal Control Roadmap

Shuttle & ISS
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024
- 2025
- 2026
- 2027
- 2028
- 2029
- 2030

Spiral 1: Crew Exploration Vehicle
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024
- 2025
- 2026
- 2027
- 2028
- 2029
- 2030

Spiral 2: Extended Duration Moon
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024
- 2025
- 2026
- 2027
- 2028
- 2029
- 2030

Spiral 3: Long Duration Moon
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024
- 2025
- 2026
- 2027
- 2028
- 2029
- 2030

Spiral 4: Mars Vicinity
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024
- 2025
- 2026
- 2027
- 2028
- 2029
- 2030

Spiral 5: Mars Surface
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024
- 2025
- 2026
- 2027
- 2028
- 2029
- 2030

Capability
Life Support & Habitation

Active Thermal Control

Heat Acquisition
- Long Duration Humidity Control – Condensate Collection
- Coldplate Design
- Fault Tolerant HX

Heat Transport
- Fluid Selection
- Heat Pump
- Two-phase Fluid Loops
- Fluid Quick Disconnect

Heat Rejection
- Radiant Heat Rejection

Technologies Ready

Mars Environment Defined

Major Event / Accomplishment / Milestone

Major Decision

Ready to Use
### Active Thermal Control

**Maturity Level – Capabilities**

<table>
<thead>
<tr>
<th>Mission (Need Date)</th>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Capability Development Needs</th>
<th>Current CRL</th>
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</thead>
<tbody>
<tr>
<td>Spiral 1</td>
<td>Provide cooling to avionics and other heat producing hardware</td>
<td>Mass reduction for coldplates</td>
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<tr>
<td>Lunar Capable</td>
<td>Transfer energy from one fluid loop to another</td>
<td>Fault tolerance for interpath leakage</td>
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<tr>
<td>Low Earth Orbit</td>
<td>Provide temperature and humidity control for cabin air</td>
<td>No development needed</td>
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<td>CEV (2008)</td>
<td>Transport energy throughout the vehicle</td>
<td>Fluids that can be used inside the cabin and in radiators</td>
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<tr>
<td></td>
<td>Provide radiant heat rejection</td>
<td>Mass reductions and ability to handle mission transients for radiators</td>
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<tr>
<td></td>
<td>Provide evaporative heat rejection</td>
<td>Extended operating range that included vacuum and post landing; decreased sensitivity to feedwater contamination</td>
<td>2</td>
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<tr>
<td>Spiral 2</td>
<td>Same as Spiral 1 except</td>
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<td></td>
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<tr>
<td>Lunar Surface</td>
<td>Provide heat rejection in hot Lunar environments</td>
<td>Same as Spiral 1 except</td>
<td>2</td>
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<tr>
<td>(2011)</td>
<td></td>
<td>Heat pump systems are needed</td>
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</tr>
<tr>
<td>Spiral 3</td>
<td>Same as Spiral 1 except</td>
<td>Same as Spiral 1 except</td>
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<tr>
<td>Long Duration</td>
<td>Evaporative heat rejection is not required</td>
<td>Long duration systems are needed for humidity control and condensate collection</td>
<td>1</td>
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<td>Lunar Surface</td>
<td>Requirements for assembly and maintenance during the mission</td>
<td>Fluid Quick disconnect</td>
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<tr>
<td>(2014)</td>
<td>Increased heat loads</td>
<td>Two-phase fluid loops</td>
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<tr>
<td>Spiral 4</td>
<td>Same as Spiral 3</td>
<td>Same as Spiral 3</td>
<td></td>
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<tr>
<td>Mars Vicinity</td>
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<tr>
<td>(2017)</td>
<td></td>
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<tr>
<td>Spiral 5</td>
<td>Same as Spiral 3</td>
<td>Same as Spiral 3</td>
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<td>Initial Mission</td>
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<tr>
<td>Mars Surface</td>
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<tr>
<td>(2021)</td>
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<td>Sub-Capability (Level 5 CBS)</td>
<td>Leading Technology Candidates</td>
<td>Development Needed</td>
<td>Current TRL</td>
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<td>----------------------------</td>
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<tr>
<td><strong>Heat Acquisition</strong></td>
<td>Composite Coldplate Shelf</td>
<td>Mass reduction</td>
<td>3</td>
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<tr>
<td></td>
<td>Fault Tolerant Heat Exchanger</td>
<td>Additional barrier for interpath leakage</td>
<td>4</td>
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<tr>
<td></td>
<td>Porous Media Condensing Heat Exchanger; Vortex Dehumidification</td>
<td>Long duration humidity control and condensate collection</td>
<td>3; 4</td>
</tr>
<tr>
<td><strong>Heat Transport</strong></td>
<td>Fluids that enable single loop systems</td>
<td>Performance, safety, compatibility</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Vapor Compression Heat Pump</td>
<td>Gravity independent performance</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Low Power Two-phase ATCS</td>
<td>Decrease mass and power</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>none</td>
<td>Reliable and EVA compatible</td>
<td>-</td>
</tr>
<tr>
<td><strong>Heat Rejection</strong></td>
<td>Lightweight radiator; structural radiator</td>
<td>Mass reduction; ability to handle mission transients</td>
<td>5; 3</td>
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<tr>
<td></td>
<td>Multi-environment evap; ContaminationInsensitive Sublimator</td>
<td>Larger operating envelope; longer life</td>
<td>3; 3</td>
</tr>
</tbody>
</table>

Current TRL: 1-5, 2-5, 3-5

Spiral(s): 1-5, 2-5, 3-5
## Active Thermal Control

### Figures of Merit

<table>
<thead>
<tr>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Figures of Merit</th>
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<tbody>
<tr>
<td><strong>Heat Acquisition</strong></td>
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<tr>
<td>Provide cooling to avionics and other heat producing hardware</td>
<td>Heat transfer per coldplate mass</td>
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<tr>
<td>Transfer energy from one fluid loop to another</td>
<td>Barriers between fluids</td>
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<tr>
<td>Provide temperature and humidity control for cabin air</td>
<td>Operational life</td>
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<tr>
<td><strong>Heat Transport</strong></td>
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<tr>
<td>Transport energy throughout the vehicle</td>
<td>Heat transfer per system mass</td>
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<tr>
<td>Provide heat rejection in hot Lunar environments</td>
<td>Radiator fluid temperature</td>
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<tr>
<td>Increased heat loads</td>
<td>Heat transfer per power input</td>
</tr>
<tr>
<td>Requirements for assembly and maintenance during the mission</td>
<td>Reliability</td>
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<tr>
<td><strong>Heat Rejection</strong></td>
<td></td>
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<tr>
<td>Provide radiant heat rejection</td>
<td>Mass per surface area</td>
</tr>
<tr>
<td>Provide evaporative heat rejection</td>
<td>Operating pressure range</td>
</tr>
<tr>
<td></td>
<td>Operational life</td>
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</tbody>
</table>
Volume Reduction
Storage space for wastes is very limited on space vehicles. Volume reduction or compaction saves valuable space.

Water Removal and Recovery
Many wastes such as concentrated water brines or food scraps contain substantial quantities of water that can be recovered.

Safening – Stabilization
Safening means processing the waste to make it safe for the crew or harmless to planetary surfaces. Once safened, stabilization assures that the waste does not change its state.

Containment and Disposal
Contained waste is isolated from the crew and the rest of the world. Waste is disposed when the final act of handling or accessing is completed. Disposal can be onboard, overboard, in space, and on planetary surfaces.

Resource Recovery
Waste can be processed for reuse for the initial function, or it can be converted to new useful materials. Examples include cleaning clothes for reuse, converting waste to minerals for use as food growth nutrients, and pyrolyzing waste to form activated carbon.
Waste Management
Benefits

The general benefit of waste management capabilities is to reduce mission cost and satisfy mission requirements:

- Crew health and safety
- Crew quality of life
- Planetary protection – forward protection of Mars for instance, and backward protection of Earth

Specific benefits:

- **Compaction** minimizes volume occupied by waste and thereby recovers volume. Used in conjunction with heat, compaction can also recover water and stabilize waste.
- **Mineralization** recovers resources such as water and decreases waste volume. Depending on extent of processing, mineralized products are rendered partially to completely biologically nonhazardous and inert.
- **Water removal and recovery** contributes to closure of the water loop and also results in reduced volume. Microbiological and pathogenic activity is inhibited in dried residue thus protecting crew health.
- **Overboard disposal** eliminates the need to provide stowage volume, eliminates the need to process waste to protect the crew, and reduces propulsion needs.
- **Containment** of waste protects the crew from physical, chemical, and biological waste hazards onboard the spacecraft. It also protects planetary surfaces from contamination with microbes and biomarkers and protects Earth from back-contamination.
- **Resource Recovery** reduces the cost of resupply of items such as clothing and nutrients for plant growth.
Mission Cost (measured by Equivalent System Mass - ESM) Reduction
A Comparison of International Space Station (ISS) Technology with Advanced Life Support (ALS) Technology. For 1000 day Mars mission with 6 crew.

<table>
<thead>
<tr>
<th>Name</th>
<th>ISS ESM</th>
<th>ALS ESM</th>
<th>delta</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste (clothing, feces, food packaging, scraps, etc.) safener - e.g. container vs. mineralizer</td>
<td>3,933</td>
<td>1,000</td>
<td>2,933</td>
<td>assume containers for ISS - processor for ALS</td>
</tr>
<tr>
<td>Waste Disposal on Mars surface</td>
<td>5,899</td>
<td>1,000</td>
<td>4,899</td>
<td>savings on return propulsion</td>
</tr>
<tr>
<td>Water in feces and waste</td>
<td>2,000</td>
<td>500</td>
<td>1,500</td>
<td>water saving vs cost</td>
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<tr>
<td>Clothing</td>
<td>6,780</td>
<td>1,200</td>
<td>5,579</td>
<td>clothing washer</td>
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<tr>
<td>Compaction</td>
<td>3,000</td>
<td>1,000</td>
<td>2,000</td>
<td>assume crewed vol=200 kg/m^3, ISS is 1/2 compact by hand</td>
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</tbody>
</table>
Waste management technologies for space life support systems are currently at low development levels. Manual compaction of waste, collection in plastic bags (general waste) and hard containers (feces), and disposal to earth return vehicles are the primary current waste management practices. Without improvement of capabilities, such practices on future missions will expose the crew to biological and chemical waste hazards, obstruct crew quarters with accumulated waste, forfeit recoverable resources such as water, consume valuable crew time, contaminate planetary surfaces, and risk return to Earth of extraterrestrial life.
Waste Management
Requirements /Assumptions

• Requirements
  – Crew health and safety
    The longer duration of future missions without access to routine resupply and disposal resupply missions means that waste needs improved management to assure crew safety. Detailed requirements in this area are not yet established. Safening is required. It is assumed drying is the minimum level of safening. Mineralization can also dry waste and may provide better protection from hazards at the same cost.
  – Crew quality of life
    Odor, clutter, and other qualities of waste can negatively affect crew outlook and performance. Detailed requirements for waste are not yet established. It is assumed that this requirement supports the need for improved management of waste via deodorization, compaction, drying, and mineralization.
  – Planetary protection – forward protection of Mars, and backward protection of Earth
    International agreements prohibit harm to planetary surfaces such as Mars. Mars biota and the search for life must be protected from Earth biology. Clearly Earth must also be protected from possible Mars biology. Until unknowns are resolved for Mars, early missions may need to manage wastes more carefully than later missions (as was the case for the moon). Bringing all wastes back is prohibitively expensive, hence waste must be managed to allow disposal on Mars. Development of detailed planetary protection requirements is currently being pursued.
Missions and assumptions driving the development plan

For near term missions such as Spirals 1 and 2:
- Odor control and mechanical waste compaction must be ready for these spirals because these capabilities are justified by requirement and/or cost.

As missions progress to longer duration and further distances (Spirals 3 to 5)
- Water recovery, and clothes washing are payout projects and must be ready by spiral 3.
- Capabilities needed for Mars are to be tested on the moon, and hence at least advanced prototypes for capabilities such as mineralization and nutrient recovery must be ready for moon testing.
- Containment will need development specific to missions because requirements differ by mission: the moon (bio contamination not an issue), transit (in-space overboard disposal), and Mars (bio contamination of Mars prohibited).
## Waste Management Roadmap

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<tr>
<td>Retire Shuttle</td>
<td>SRR</td>
<td>SDR</td>
<td>PDR</td>
<td>CDR</td>
<td>Ur-crewed Flight</td>
<td>Crewed Flight</td>
<td>ISS End of US commitment</td>
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<tr>
<td>Spiral 1: Crew Exploration Vehicle</td>
<td>SRR</td>
<td>SDR</td>
<td>PDR</td>
<td>CDR</td>
<td>1st Human Mission</td>
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<tr>
<td>Spiral 2: Extended Duration Moon</td>
<td>SRR</td>
<td>SDR</td>
<td>PDR</td>
<td>CDR</td>
<td>Mars Science Lab</td>
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<tr>
<td>Spiral 3: Long Duration Moon</td>
<td>SRR</td>
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<td>PDR</td>
<td>CDR</td>
<td>Mars Science Lab</td>
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<tr>
<td>Spiral 4: Mars Vicinity</td>
<td>SRR</td>
<td>SDR</td>
<td>PDR</td>
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<tr>
<td>Spiral 5: Mars Surface</td>
<td>SRR</td>
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### Capability

#### Life Support & Habitation

### Waste Management

#### Volume Reduction
- Compactor
- Lab prototype
- Contam control
- Prototype Upgrade
- Integrated Waste Recovery
- Micro-G test
- TRL 6
- Integrated Compaction, Drying

#### Water Removal and Recovery
- Freeze
- Air heat
- Down select Drying method
- WRS Integ Test
- Prototype Upgrade
- Testing
- TRL 6
- Micro-G test
- Integ Test
- Prototype
- TRL 6

#### Safening - Mineralization
- Odor control Req
- Pyrolysis
- Integ - Hydro-Oxid Composting
- Upgrades
- WRS Integ Test
- Prototype Upgrade
- TRL 6
- Micro-G test
- Integ Test
- TRL 6
- Prototype Testing
- Subsys test
- TRL 6

#### Containment
- Investigate alternatives
- Contract for prototypes
- PC bio
- Develop prototypes
- Testing prototypes
- WRS Integ Test
- TRL 5
- Micro g Comp test
- Integ Test
- TRL 6
- Prototype Testing
- TRL 6

#### Resource Recovery
- Plant nutrients
- PC and/or bio
- Develop prototypes
- Testing prototypes
- TRL 5
- Micro g Comp test
- Integ Test
- TRL 6
- Prototype Testing
- TRL 6

### Major Decision

- Ready to Use
- Major Event / Accomplishment / Milestone
- Major Decision
Waste Management Roadmap

Shuttle & ISS
Spiral 1: Crew Exploration Vehicle
Spiral 2: Extended Duration Moon
Spiral 3: Long Duration Moon
Spiral 4: Mars Vicinity
Spiral 5: Mars Surface

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<thead>
<tr>
<th>Year</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
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Volume Reduction
Water Removal and Recovery
Safening - Mineralization
Containment
Resource Recovery

Ready to Use
Major Event / Accomplishment / Milestone
Major Decision

NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005
### Waste Management Maturity Level – Capabilities

<table>
<thead>
<tr>
<th>Mission (Need Date)</th>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Capability Development Needs - Gaps</th>
<th>Current CRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spiral 1&lt;br&gt;Lunar Capable Low Earth Orbit CEV&lt;br&gt;(2008)</td>
<td>Volume reduction and stabilization</td>
<td>Existing waste management can support spiral 1, although some benefits could be obtained from odor control</td>
<td>2</td>
</tr>
<tr>
<td>Spiral 2&lt;br&gt;Lunar Surface (2014)</td>
<td>Volume reduction&lt;br&gt;Stabilization</td>
<td>There is no automated or mechanical volume reduction capability ready for flight&lt;br&gt;Odor control and some vacuum drying stabilization may be needed</td>
<td>2&lt;br&gt;1</td>
</tr>
<tr>
<td>Spiral 3&lt;br&gt;Long Duration Lunar Surface&lt;br&gt;(2017)</td>
<td>Volume reduction&lt;br&gt;Water Recovery&lt;br&gt;Safening- stabilization (mineralization)&lt;br&gt;Containment and Disposal&lt;br&gt;Resource Recovery</td>
<td>Need flight ready mechanical volume reduction&lt;br&gt;Need flight ready capability for water recovery from solid waste&lt;br&gt;Need to test advanced prototypes for safening and stabilization of waste on long duration missions&lt;br&gt;Need flight ready moon containment and test prototype for Mars containment and disposal&lt;br&gt;Need flight ready capability as clothing cleaning and advanced test prototype for nutrient recovery</td>
<td>2&lt;br&gt;2&lt;br&gt;2&lt;br&gt;1&lt;br&gt;1</td>
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<td>Spiral 4&lt;br&gt;Mars Vicinity&lt;br&gt;(2021)</td>
<td>Same as Spiral 3</td>
<td>Much the same as Spiral 3 except technologies must operate in a Micro-gravity environment and must all (except nutrient recovery) be operational rather than test prototypes&lt;br&gt;Overboard disposal is in space</td>
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<td>Spiral 5&lt;br&gt;Initial Mission Mars Surface (2024)</td>
<td>Same as Spiral 3</td>
<td>Same as Spiral 3 except Operation on 1/3 rather than 1/6 g&lt;br&gt;Operational rather than test prototypes</td>
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<td>Sub-Capability (Level 5/6 CBS)</td>
<td>Leading Technology Candidates</td>
<td>Spiral(s)</td>
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<td>Volume reduction Safening - Stabilization</td>
<td>Plastic heat melt compactor</td>
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<td>Water removal and recovery Safening - Stabilization</td>
<td>Lyophiliization</td>
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<td>Volume reduction Water removal and recovery Safening - Stabilization Resource recovery - nutrients</td>
<td>Incineration</td>
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<td>Volume reduction Water removal and recovery Safening - Stabilization Resource recovery - nutrients</td>
<td>Hydrothermal oxidation</td>
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<td>Volume reduction</td>
<td>Composting - aerobic</td>
<td>3,4,5</td>
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<td>Water removal and recovery</td>
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<td>Resource recovery - nutrients</td>
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<td>Safening - Stabilization</td>
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<td>Volume reduction</td>
<td>Composting - anaerobic</td>
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<td>Resource recovery - nutrients</td>
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<td>Resource Recovery - clothes</td>
<td>Clothes washer</td>
<td>3,4,5</td>
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<td>Containment</td>
<td>Containers</td>
<td>3,4,5</td>
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## Waste Management

### Figures of Merit

<table>
<thead>
<tr>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Technology Type</th>
<th>Figures of Merit</th>
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</thead>
<tbody>
<tr>
<td>Volume Reduction</td>
<td>Compactors</td>
<td>Density of compacted material (kg/m^3)</td>
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<tr>
<td></td>
<td>Mineralizers (Bio and PC)</td>
<td></td>
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<tr>
<td></td>
<td>Particle size reducers</td>
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<tr>
<td>Water Removal and Recovery</td>
<td>Dryers</td>
<td>Percent water recovered (%)</td>
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<td>Mineralizers (Bio and PC)</td>
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<tr>
<td>Safening - Stabilization</td>
<td>Deodorizers</td>
<td>Probability of harm</td>
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<tr>
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<td>Dryers</td>
<td>Time that waste is safe and stable (years)</td>
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<td>Mineralizers (Bio and PC)</td>
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<tr>
<td>Containment and Disposal</td>
<td>Containers (on board and surface)</td>
<td>Time that waste is safe and stable or contained (years)</td>
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<td></td>
<td>Containment via use of in situ materials</td>
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<td>Ejectors and container jets (in space disposal)</td>
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<tr>
<td>Resource Recovery</td>
<td>Dryers</td>
<td>Percent recovery (%)</td>
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<td>Mineralizers (Bio and PC)</td>
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<td>Clothes Washers</td>
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</tbody>
</table>
Food Provisioning and Management

Human Health & Support Systems

- Human Health & Performance
- Life Support and Habitation
- Extra-Vehicular Activity

Life Support Systems

- Environmental Monitoring and Control
- Contingency Response
- Exploration Habitats

Food Provisioning and Management

- Air Revitalization
- Water Reclamation
- Thermal Control
- Solid Waste Management
- Biomass Production
- Fire Prevention, Detection, Suppression
- In Situ Fabrication & Repair

Contingency Response

- Internal Monitoring
- External Monitoring
- Control Systems

Food Provisioning and Management

- Surface Construction
- Habitat Shell
- Internal Systems & Outfitting
- External Systems and Architecture

Exploration Habitats

Human Health & Support Systems

- Exploration Habitats
- Contingency Response
- Environmental Monitoring and Control
- Life Support Systems

- Human Health & Performance
- Life Support and Habitation
- Extra-Vehicular Activity

NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005
Advanced Food System is required to maintain health of the crew during the entire mission

- Stored Ready-to-Eat Foods – prepackaged food items will be used during transit and surface missions
  - Food packaging
  - Food preservation
  - Stored food stowage

- Raw Commodity Processing and Stowage – fresh fruits and vegetables can be used throughout mission. The processed food system will be used on lunar or planetary surface.
  - Raw commodity stowage
  - Raw commodity processing
  - Processed ingredient stowage

- Menu Development and Galley Procedures – development of nutritionally complete menu with corresponding galley procedures
  - Food preparation
  - Prepared food stowage
  - Meets nutritional needs of crew
Food Provisioning and Management

Benefits

• The development of an advanced food system will enable support of humans beyond Low Earth Orbit (LEO).

• Food must be safe, nutritious and acceptable to maintain crew health and well being throughout the entire mission.
  – Food has a psychosocial element in addition to nutrition
  – Crew performance and well-being dependant on a high quality food system.
  – Use of resources will be minimized.

• Fresh vegetables provide the crew with bright colors, aromas, and improved nutrition

• Food processing will provide the crew with a variety of fresh and nutritious foods throughout the entire mission
Food Provisioning and Management
Current State-of-the-Art

• Stored Ready-to-Eat Foods
  – Food packaging
    • MRE pouch used for thermostabilized and irradiated foods has a high barrier to moisture and oxygen due to the aluminum layer. However, it is dense and hard to process by solid waste processing team
    • Poly material used for freeze dried foods and natural form foods has poor barrier materials and is overwrapped with a foil pouch for ISS
  – Food preservation
    • Freeze dried and natural form foods have a shelf life of 12 months
    • Thermostabilized and irradiated foods have a shelf life of 3 years

• Raw Commodity Processing and Stowage – there is no available processing equipment

• Menu Development and Galley Procedures
  – Have capability to determine nutritional content of menu
  – Have capability to heat and rehydrate stored food system
  – Have capability of a 10-day menu cycle
Food Provisioning and Management Requirements /Assumptions

- **Spirals 1 and 2**
  - Able to use current ISS food system
  - Depending on vehicle design, may need to develop food warmer and rehydration station

- **Spiral 3**
  - Moon will be used as a test bed for Mars missions
  - Fresh vegetables and fruits will be available for consumption (hypogravity)
  - Some food processing and food preparation will be available during the mission
  - Packaging materials with an aluminum layer will be more difficult for solid waste processing
  - Hypogravity and lower atmospheric pressure will affect food processing and food preparation procedures

- **Spiral 4**
  - Stored ready-to-eat foods will require at least a 3-year shelf life
  - Fresh vegetables and fruits will be available for consumption (microgravity)

- **Spiral 5**
  - Stored ready-to-eat foods, raw commodities, and resupply items will require at least a 5-year shelf life
  - Radiation may affect quality and functionality of ready-to-eat foods
  - Fresh vegetables and fruits will be available for consumption (hypogravity)
  - Radiation may affect quality and functionality of stored raw commodities
  - Hypogravity and lower atmospheric pressure will affect food processing and food preparation procedures
  - All available raw commodities will be processed into edible food ingredients
  - Recipes will be prepared utilizing all available processed food ingredients, resupply items, and freshly harvested vegetables and fruits
  - During a long duration mission, food acceptability and variety will contribute to the crew’s psychosocial well-being
### Food Provisioning and Management Roadmap

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<tr>
<td>Spiral 1: Crew Exploration Vehicle</td>
<td>SRR</td>
<td>SDR</td>
<td>PDR</td>
<td>CDR</td>
<td>Ur-crewed Flight</td>
<td>Crewed Flight</td>
<td>1st Human Mission</td>
<td>SRR</td>
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<td>Spiral 2: Extended Duration Moon</td>
<td>SRR</td>
<td>SDR</td>
<td>PDR</td>
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<td>Spiral 5: Mars Surface</td>
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### Capability Life Support & Habitation

#### Food Provisioning and Management

- **Stored Ready-to-Eat Food**
  - **Food Packaging**
    - Improved barrier w/o foil
    - Low mass
  - **Food Preservation**
    - Thermal
    - Nonthermal
  - **Stored Food Stowage**
    - Radiation protection requirements
    - Environmental conditions requirements

- 10-day menu cycle w/ 5 yr shelf life
- Stowage infrastructure
- Major Decision
- Major Event / Accomplishment / Milestone
- Input from External Entities
- Output to External Entities
- Capability available for mission consideration

- NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005
Food Provisioning and Management Roadmap

Shuttle & ISS

Spiral 1: Crew Exploration Vehicle
SRR ▲  SDR ▲  PDR ▲  CDR ▲  Ur-crewed Flight  ▲  Crewed Flight

Spiral 2: Extended Duration Moon
SRR ▲  SDR ▲  PDR ▲  CDR ▲  1st Human Mission ▲

Spiral 3: Long Duration Moon

Spiral 4: Mars Vicinity

Spiral 5: Mars Surface ▲  Mars Science Lab

Capability
Life Support & Habitation

Food Provisioning and Management

Raw Commodity Processing and Stowage

Raw Commodity Stowage

• Bulk Stored
• Harvested Crops

Raw Commodity Processing

• Bulk
• Harvested Crops

Processed Ingredient Stowage

Food Provisioning and Management

Radiation protection requirements
Environmental conditions requirements

Handling

Vegetable handling

On vehicle

On surface

Prototypes

Test

Stowage requirements

Stowage infrastructure

Spiral 3

Major Decision

Major Event / Accomplishment / Milestone

Input from External Entities

Output to External Entities

Capability available for mission consideration

Low pressure requirements

Low G requirements

Vegetable and fruit stowage

NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005

SRR ▲
Food Provisioning and Management Roadmap

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SRR ▲ SDR ▲ PDR ▲ CDR ▲ Ur-crewed Flight ▲ Crewed Flight

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SRR ▲ SDR ▲ PDR ▲ CDR ▲ 1st Human Mission ▲

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SRR ▲

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Mars Science Lab

Capability
Life Support & Habitation

Food Provisioning and Management

Menu Development and Galley Procedures

Preparation of recipes using equipment

- Low pressure requirements
- Low G requirements
- Variety requirements
- Acceptability requirements
- Nutrition requirements

Meets nutritional needs of crew

Acceptability requirements

Prepared Food Stowage

- Stowage requirements
- Stowage infrastructure

Modified COTS prototype using proc/stowed ingredients

Test

Spiral 3 recipes

Improved and increased quantity
## Food Provisioning and Management Roadmap

<table>
<thead>
<tr>
<th>Capability</th>
<th>Life Support &amp; Habitation</th>
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<tr>
<td>2018</td>
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<td>Shuttle &amp; ISS</td>
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<td>Spiral 2: Extended Duration Moon</td>
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<td>Spiral 3: Long Duration Moon</td>
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<td>Spiral 4: Mars Vicinity</td>
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<tr>
<td>Spiral 5: Mars Surface</td>
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</table>

### Spiral 4, 5
- 10-day menu cycle w/ 5 yr shelf life
- Improved stowage infrastructure
- Improved vegetable stowage
- Baseline crop stowage to maintain 5 yr shelf life
- Improved and increased quantity of prototypes
- Variety reqs
- Acceptability reqs
- Recipes for 15-day menu cycle
- Test

### Spiral 5
- Improved stowage infrastructure
- Improved stowage infrastructure
- Improved stowage infrastructure
- Improved stowage infrastructure
- Improved stowage infrastructure
- Improved stowage infrastructure
- Improved stowage infrastructure
- Improved stowage infrastructure
- Improved stowage infrastructure
### Food Provisioning and Management Maturity Level - Capabilities

<table>
<thead>
<tr>
<th>Mission (Need Date)</th>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Capability Development Needs</th>
<th>Current CRL</th>
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<tbody>
<tr>
<td>Spiral 1&lt;br&gt;Lunar Capable Low Earth Orbit CEV&lt;br&gt;(2008)</td>
<td>Stored Ready-to-Eat Food</td>
<td>Improved barrier packaging with easier solid waste processing capability. Current food preservation and stowage capabilities supports Spiral 1.</td>
<td>1, 7</td>
</tr>
<tr>
<td>Spiral 2&lt;br&gt;Lunar Surface&lt;br&gt;(2011)</td>
<td>Same as Spiral 1</td>
<td>Spiral 1 development supports Spiral 2</td>
<td>1, 7</td>
</tr>
<tr>
<td>Spiral 3&lt;br&gt;Long Duration Lunar Surface&lt;br&gt;(2014)</td>
<td>Stored Ready-to-Eat Food&lt;br&gt;Raw commodity processing and stowage&lt;br&gt;Menu development and galley procedures</td>
<td>Same as Spiral 2 except Improved quality of extended shelf life stored food items Limited food processing capabilities in reduced gravity Limited food preparation capabilities in reduced gravity Handling procedures of fresh food</td>
<td>2, 1, 2</td>
</tr>
<tr>
<td>Spiral 4&lt;br&gt;Mars Vicinity&lt;br&gt;(2017)</td>
<td>Stored Ready-to-Eat Food</td>
<td>Same as Spiral 2 except 5-yr shelf life stored food system with 10-day menu cycle</td>
<td>2</td>
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<tr>
<td>Spiral 5&lt;br&gt;Initial Mission Mars Surface&lt;br&gt;(2021)</td>
<td>Stored Ready-to-Eat Food&lt;br&gt;Raw commodity processing and stowage&lt;br&gt;Menu development and galley procedures</td>
<td>Same as Spiral 4 except 5-yr shelf life stored food system with 15-day menu cycle Food processing of all available ingredients and crops Stowage of bulk ingredients Food preparation using all available ingredients and crops</td>
<td>2, 1, 2, 2</td>
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## Food Provisioning and Management
### Maturity Level - Technologies

<table>
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<tr>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Leading Technology Candidates</th>
<th>Development Needed</th>
<th>Current TRL</th>
<th>Spiral(s)</th>
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</thead>
<tbody>
<tr>
<td>Stored Ready-to-Eat Foods</td>
<td>Preservation technologies which allows safe ambient stowage</td>
<td>Development of emerging technologies to allow ambient temperature storage for up to 5 years</td>
<td>2-9</td>
<td>3-5</td>
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<tr>
<td></td>
<td>High barrier food packaging technologies</td>
<td>Development of emerging technologies of high barrier packaging materials which allows for easier solid waste processing</td>
<td>2-9</td>
<td>1-5</td>
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<td></td>
<td>Develop stored food items with 3 – 5yr shelf life</td>
<td>Integration of preservation and packaging technologies to develop new stored food items with adequate nutrition, variety, and acceptability for duration of mission</td>
<td>2-9</td>
<td>3-5</td>
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<tr>
<td></td>
<td>Stowage compartments – environmental conditions and inventory management</td>
<td>Develop stowage specifications based on the effect of environmental conditions (e.g., radiation, temperature, oxygen, relative humidity) on shelf life</td>
<td>2-5</td>
<td>3-5</td>
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<td>Determine easy-to-use inventory management system</td>
<td>3</td>
<td>2-5</td>
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<tr>
<td>Raw Commodities Processing and Stowage</td>
<td>Raw commodity and resupply item stowage compartments</td>
<td>Develop stowage specifications based on the effect of environmental conditions (e.g., radiation, temperature, oxygen, relative humidity) on shelf life</td>
<td>2</td>
<td>3-5</td>
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<td>Handling procedures of fresh food</td>
<td>Confirm use of hydrogen peroxide or other sanitizer on chamber-grown vegetables</td>
<td>3</td>
<td>3-5</td>
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<td></td>
<td>Miniaturized food processing equipment</td>
<td>Design, fabricate and build processing equipment</td>
<td>2</td>
<td>3, 5</td>
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<td></td>
<td>Processed foods stowage compartments</td>
<td>Determine volume of ambient, refrigerated, and frozen storage needs</td>
<td>4</td>
<td>3, 5</td>
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<tr>
<td>Menu Development and Galley Procedures</td>
<td>Food preparation equipment</td>
<td>Modify appropriate gourmet home appliances for use in hypogravity</td>
<td>3</td>
<td>3, 5</td>
</tr>
<tr>
<td></td>
<td>Recipes utilizing processed ingredients, fresh foods, and resupply items</td>
<td>Design, fabricate and build preparation equipment that is not available as COTS</td>
<td>2</td>
<td>3, 5</td>
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<td></td>
<td>Stowage compartments of prepared menu items</td>
<td>Develop recipes and preparation procedures that will provide a nutritionally complete menu with adequate variety and acceptability for duration of mission</td>
<td>3</td>
<td>3, 5</td>
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<td></td>
<td></td>
<td>Determine volume of ambient, refrigerated, and frozen storage needs</td>
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## Food Provisioning and Management

### Figures of Merit

<table>
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<tr>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Figures of Merit</th>
<th>Units</th>
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<tr>
<td>Stored ready-to-eat foods shelf life</td>
<td>Safety and quality maintenance</td>
<td>Years</td>
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<tr>
<td>Percent of expendable mass within food system</td>
<td>Expendable mass (e.g., food packaging) needs to be disposed of</td>
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<tr>
<td>Stored raw commodity shelf life</td>
<td>Safety and functionality maintenance</td>
<td>Years</td>
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<tr>
<td>Number of food processing pieces of equipment to TRL 6</td>
<td>Processing of raw commodities (stored or harvested)</td>
<td>Quantity</td>
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<tr>
<td>Number of food preparation pieces of equipment to TRL 6</td>
<td>For galley preparation of meals</td>
<td>Quantity</td>
</tr>
<tr>
<td>Number of recipes utilizing crops and bulk commodities</td>
<td>To provide adequate nutrition to the crew</td>
<td>Quantity</td>
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</table>
Biomass Production

Human Health & Support Systems

- Human Health & Performance
  - Life Support Systems
    - Environmental Monitoring and Control
    - Contingency Response
    - Exploration Habitats
  - Internal Monitoring
  - External Monitoring
  - Control Systems
- Life Support and Habitation
  - Air Revitalization
  - Water Reclamation
  - Thermal Control
  - Solid Waste Management
  - Food Provisioning and Management
  - Fire Prevention, Detection, Suppression
  - In Situ Fabrication & Repair
  - Surface Construction
  - Habitat Shell
  - Internal Systems & Outfitting
  - External Systems and Architecture
- Extra-Vehicular Activity
  - Exploration Habitats
  - Contingency Response
  - Life Support Systems
Biomass Production Description

Production of Fresh Food Supplements for Transit

Operate and maintain a transit crop production system to provide:
1) fresh vegetables to supplement the crew diet, and
2) psychological benefits.

Production of Fresh Food Supplements for Planetary Surface

Operate and maintain a surface crop production system (CPS) to provide fresh crop foods for 10% of crew’s diet. The unit would also provide 20% of the crew’s O₂ needs and 20% of the CO₂ removal.

Bioregenerative Life Support

Expanded or multiple CPS units to provide 25% of the diet and 50% of atmospheric regeneration.

Assess alternative biomass production technologies such as algae, aquaculture, etc.
Biomass Production Benefits

- Crops produce a continuous supply of fresh foods that can supplement the crew’s diet.
  - Color, flavor, and variety in the diet
  - Bio-available nutrients and antioxidants

- Living plants provide a positive influence on crew well-being and performance.

- Crops contribute to CO\textsubscript{2} reduction, O\textsubscript{2} production, and water purification, thereby unloading other ECLSS components.

- Bioregenerative systems with crops or other photosynthetic organisms provide the only means for achieving a high level of mission (life support) autonomy.
Biomass Production
Current State-of-the-Art

- **Earth-Based Systems**
  - Terrestrial greenhouses are used for crop production but are not constrained by energy, mass, volume, pressure difference, radiation, and gravity.

- **Space-Based Systems**
  - Short-duration experiments have been carried out on Shuttle and ISS, but we know little about operating sustained crop production systems in space.

  Current small plant chambers* include:
  - SVET (Russian) (lost with Mir)
  - Lada (Russian)
  - PGBA (Plant Generic Bioprocessing Apparatus)
  - Advanced Astroculture
  - PGF (Plant Growth Facility)
  - BPS (Biomass Production System)
  - CPBF (Commercial Plant Biotechnology Facility) (not flown)

  - Component technology challenges include:
    - Energy efficient lighting
    - Reliable water / nutrient delivery systems for μ- and fractional g.
    - Thorough understanding of crop responses to space environments.
    - Appropriate species and cultivars for space.
    - Mechanized and/or automated approaches to reduce crew time.
    - Demonstrated capability to sustain production over mission durations.

* All of these systems provide less than 0.25 m² growing area, and most < 0.1 m².
Assumptions that drove the need for the capability
- Continuous need for fresh foods in the crew’s diet.
- Positive effects of living plants on crew well-being and performance.
- Eventual need to rely on bioregenerative technologies for food, air, and water regeneration for true mission autonomy.
- ISS can be used for component testing of transit technologies.

Crop (biomass) production technologies are appropriate for the following missions:
- Spiral 1 (Robotic Lunar Mission Payload), test regolith, remote operations, and materials for plant growth chambers.
- Spiral 2 (Robotic Mars Mission Payload), test regolith, remote operations, materials, and pre-deploy potential for surface crop production system.
- Spiral 3 (Long-Duration Lunar), validation of planetary surface crop production system.
- Spiral 4 (Mars Vicinity - Transit), operational μ–g crop production system.
- Spiral 5 (Mars Surface), operational planetary surface crop production system. Expansion of bioregenerative life support capability.
# Biomass Production Roadmap

<table>
<thead>
<tr>
<th>Spiral 1: Crew Exploration Vehicle</th>
<th>Spiral 2: Extended Duration Moon</th>
<th>Spiral 3: Long Duration Moon</th>
<th>Spiral 4: Mars Vicinity</th>
<th>Spiral 5: Mars Surface</th>
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<td>2017</td>
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### Capability

**Life Support & Habitation**

- Spiral 1&2 Tech Integrated Testing
- Spiral 3 PC/Bio Water Tech Integrated Testing
- Spiral 3 Mars Tech Demo (Large Scale Biomass Production) Integrated Testing

### Crop (Biomass) Production System

#### Fresh Food Supplements for Transit

- Crop Production System (CPS) Component/Subsystem Development (Nutrient Delivery, Lighting, Crop Selection) w/ Long Duration Ground Testing
- Transit CPS Proof of Concept/Validate Comp in Lab
- Validate CPS Components/Subsystems in µ-g (ISS) w/ Long Duration Testing
- Down-select (Vehicle I/F)
- Down-select (Subsystems)
- Develop CPS Prototype for Transit Vehicle
- Validate Proto in Transit Veh Analog

#### Fresh Food Supplements for Planetary Surface

- Crop Production System (CPS) Component/Subsystem Development (Nutrient Delivery, Lighting, Crop Selection) w/ Long Duration Ground Testing
- Surface CPS Proof of Concept/Validate Comp in Lab
- Validate CPS Component/Subsystem in Partial-g (ISS) w/ Long Duration Testing
- Develop CPS Comp/Subsys for Lunar Robotic Mssn
- Validate CPS Comp/Subsys on Lunar Mssn
- Develop CPS Comp/Subsys for Mars Robotic Mission
- Validate CPS Comp/Subsys on Mars Robotic Mission
- Develop CPS Prototype for Lunar Surf for Ext Duration
- Down-select (Vehicle I/F)
- Down-select (Subsystems)
- Validate CPS Prototype on Lunar Surface
- Develop CPS Prototype for Surf Long Duratn

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**NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005**
## Biomass Production Roadmap

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<td>Spiral 3: Long Duration Moon</td>
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<td>Spiral 4: Mars Vicinity</td>
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<td>Spiral 5: Mars Surface</td>
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</table>

### Capability

#### Life Support & Habitation

#### Crop Prod System

- **Fresh Food Supplements for Transit**
  - CPS Component/Subsystem Development w/ Long Duration Testing
  - Validate Prototype in Transit Vehicle Analog
  - Down-select (Vehicle I/F)
  - Down-select (Subsystems)
  - Mars Transit Vehicle CPS System Operational

- **Fresh Food Supplements for Planetary Surface**
  - CPS Component/Subsystem Development w/ Long Duration Ground Testing
  - Validate CPS Prototype on Lunar Surface Extended Dur
  - Develop CPS Prototype for Surface Long Duration
  - Validate CPS Proto on Lunar Surf Long Dur
  - Down-select (Vehicle I/F)
  - Down-select (Subsystems)
  - Mars Surface CPS System Operational
## Biomass Production
### Maturity Level – Capabilities

<table>
<thead>
<tr>
<th>Mission</th>
<th>Capability (Level 4 CBS)</th>
<th>Leading Capability Candidates</th>
<th>CRL</th>
<th>Date Needed</th>
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<tr>
<td>Spiral 2 Extended Duration Lunar Surface</td>
<td>Robotic Mars Mission Payload (CPS Component Testing)</td>
<td>Integration with Mars Surface Lander Mission</td>
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<tr>
<td>Spiral 3 Long Duration Lunar Surface</td>
<td>Production of Fresh Food for Surface (Prototype CPS)</td>
<td>• CPS Inside the Lander&lt;br&gt;• CPS Attached to Lander&lt;br&gt;• CPS Deployed on Surface</td>
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<td>Spiral 4 Mars Vicinity</td>
<td>Production of Fresh Food for Transit (Operational VPU)</td>
<td>Closed, fixed-volume chamber&lt;br&gt;Open, fixed-volume chamber&lt;br&gt;Open, expandable volume chamber&lt;br&gt;Open, conveyor system</td>
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<td>2019</td>
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<tr>
<td>Spiral 5 Initial Mission Mars Surface</td>
<td>Production of Fresh Food for Surface (Operational CPS)</td>
<td>• CPS Inside the Lander, Electric or Solar Lighting&lt;br&gt;• CPS Attached to Hab Module, Electric or Solar Light&lt;br&gt;• CPS Deployed on Surface, Electric or Solar Lighting&lt;br&gt;• Multiple CPS Modules</td>
<td>1</td>
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### Integration with Mars Surface Lander Mission
- Spiral 1
- Spiral 2
- Spiral 3
- Spiral 4
- Spiral 5

### Integration with Lunar Surface Lander Mission
- Spiral 2
- Spiral 3
- Spiral 4
- Spiral 5
# Biomass Production Maturity Level – Technologies

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<tr>
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<td>Robotic Lunar Mission Payload (CPS Component Testing)</td>
<td>Transparent materials&lt;br&gt;Regolith for crop rooting&lt;br&gt;Remote operations</td>
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<td>Robotic Mars Mission Payload (CPS Component Testing)</td>
<td>Transparent materials&lt;br&gt;Regolith for crop rooting&lt;br&gt;Remote operations&lt;br&gt;Predeployment potential</td>
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<td>Production of Fresh Food for Surface (Prototype CPS)</td>
<td>• LEDs and μ-wave sulfur lamps lighting&lt;br&gt;• Surface solar collectors and light conduits&lt;br&gt;• Recirculating hydroponics&lt;br&gt;• Salad and staple crop cultivars</td>
<td>3&lt;br&gt;2&lt;br&gt;3</td>
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<tr>
<td>Spiral 4 Mars Vicinity</td>
<td>Production of Fresh Food for Transit (Operational Transit CPS)</td>
<td>LEDs for lighting&lt;br&gt;Transit solar collectors and light conduits&lt;br&gt;Porous tube watering with or without media&lt;br&gt;Dwarf salad crop cultivars</td>
<td>4&lt;br&gt;2&lt;br&gt;4&lt;br&gt;2</td>
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<tr>
<td>Spiral 5 Initial Mission Mars Surface</td>
<td>Production of Fresh Food for Surface (Operational Surface CPS)</td>
<td>• LEDs and μ-wave sulfur lamps lighting&lt;br&gt;• Surface solar collectors and light conduits&lt;br&gt;• Recirculating hydroponics&lt;br&gt;• Salad and staple crop cultivars&lt;br&gt;• Mechanized / automated planting and harvesting&lt;br&gt;• Integrated crop / water system&lt;br&gt;• Integrated crop / air system</td>
<td>• 2&lt;br&gt;• 1&lt;br&gt;• 2&lt;br&gt;• 2&lt;br&gt;• 1&lt;br&gt;• 2&lt;br&gt;• 2&lt;br&gt;• 2</td>
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## Biomass Production Figures of Merit

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<td>Edible Productivity</td>
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Environmental Monitoring & Control

Human Health & Support Systems
- Human Health & Performance
- Life Support and Habitation
- Extra-Vehicular Activity

Life Support Systems
- Environmental Monitoring and Control
  - Air Revitalization
  - Water Reclamation
  - Thermal Control
  - Solid Waste Management
  - Food Provisioning and Management
  - Biomass Production

Contingency Response
- In Situ Fabrication & Repair
- Fire Prevention, Detection, Suppression

Exploration Habitats
- Internal Monitoring
  - Control Systems
- External Monitoring
- Surface Construction
  - Habitat Shell
- Internal Systems & Outfitting
  - External Systems and Architecture
Environmental Monitoring & Control Description

• Monitor the Internal environment
  – In a closed environment, trace chemicals can build up
    • Like sick building syndrome, but worse—crew cannot go outside for fresh air
  – Indicators of equipment status
    • For example, a malfunction in air processing may be indicated by a tiny methane leak: not toxic, but the malfunction is hazardous

• Monitor the External environment
  – Look for leaks and other indications of problems
  – Verify that areas such as airlocks are adequately free of lunar or martian dust
  – Monitor for TBD surface environment hazards

• System Integration & Control to reliably and efficiently maintain a safe environment
  – Ground control must play a lesser role since future missions will have long time delays in communications with Earth.
  – Maintaining a large support team 24/7 is expensive, just as it is in manufacturing and other industry
  – Large crew to continuously operate systems is not affordable
Environmental Monitoring & Control Benefits

- Environmental monitoring needed to
  - Detect trace buildup so that countermeasures are implemented before it becomes hazardous
    - Closed loop life support has potential for gradual chemical buildup
  - Detect hazardous events rapidly
    - Events such as spills and leaks can be especially hazardous in the closed environment
    - Many events have proven to be unpredictable, so identification and quantification of unknowns is important
  - Must be done in flight since sample return not feasible

- System Integration & Control benefits:
  - Automation of many processes reduces crew and ground support needs
  - Efficient use of resources: mass, volume, power,…
  - Efficient and safe recovery from environmental perturbations
  - Stable, reliable operation
  - Assistance in predicting, diagnosing, and solving problems
Environmental Monitoring & Control
Current State-of-the-Art

• SOA in flight (Space Station):
  – Volatile Organic Analyzer: Gas Chromatograph/Ion Mobility Spectrometer, has been nonfunctional for several months
  – Major Constituent Analyzer: Magnetic Sector Mass Spectrometer, has been serviced
  – Compound Specific Analyzer/Combustion Products: handheld commercial device
  – Russian monitoring devices of unknown technology
  – Simple thresholding process control

• Ground SOA Monitoring technologies
  – Laboratory benchtop instruments: Highly capable, but
    • Still relatively high in mass & power requirements
    • Require considerable training, regular calibration, consumables
    • Often require gravity to operate
  – Industrial monitors
    • Usually not sensitive enough for NASA purposes
    • Limited to a few targets, so that many devices are needed to cover the dozens of targets required by NASA

• Ground SOA Industrial Control
  – Steady state, vs NASA needs which are dynamic
  – Input/output vs closed loop life support
Environmental Monitoring & Control
Requirements /Assumptions

- All crewed missions require environmental monitoring
  - The shortest missions may need as little as grab sample bottles for later ground analysis
  - The longer the mission, the greater the complexity and number of failure modes, and the greater the monitoring needs
  - Regenerated water quality should be tested before consumption
    - Realtime analysis to avoid need to carry days of stored water while waiting for water test results
  - Regeneration of water and air may have contamination issues which have not yet been seen
    - Chemical buildup, microbial growth

- Process control
  - Offers assistance in diagnosis/prognostics in shorter missions
  - Is crucial for longer missions using closed loop life support
  - Health monitoring with process control helps identify failures earlier, before they become more serious, and can reduce downtime
## Environmental Monitoring & Control Roadmap

<table>
<thead>
<tr>
<th>Capability</th>
<th>Life Support &amp; Habitation</th>
</tr>
</thead>
</table>

### Integrated Monitoring & Autonomous Control with Prognostics and Diagnostics

- Monitoring technologies
- Autonomy
- Prognostics & Diagnostics

### Environmental Monitoring & Control

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<tbody>
<tr>
<td>Spiral 2: Extended Duration Moon</td>
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<tr>
<td>Spiral 3: Long Duration Moon</td>
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<td>Spiral 4: Mars Vicinity</td>
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<td>Spiral 5: Mars Surface</td>
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</tbody>
</table>

- SDR
- PDR
- CDR

### Major Decision
- Ready to Use
- Major Decision partly or fully outside EMC
- Major Event / Accomplishment / Milestone
- Input from External Entities
- Output to External Entities

### SRR

**1st Human Mission**

*Note: The diagram shows a timeline for various spiral missions related to space exploration, with specific years and decision points marked.*
### Environmental Monitoring & Control

**Maturity Level – Capabilities**

<table>
<thead>
<tr>
<th>Mission (Need Date)</th>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Capability Development Needs</th>
<th>Current CRL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spiral 1</strong>&lt;br&gt;Lunar Capable&lt;br&gt;Low Earth Orbit&lt;br&gt;CEV (2008)</td>
<td>Event monitoring&lt;br&gt;Air analysis non-realtime</td>
<td>Detection of Hg and SO(_2), other gases doable&lt;br&gt;Grab sample bottle technology in use</td>
<td>1-5 7</td>
</tr>
<tr>
<td><strong>Spiral 2</strong>&lt;br&gt;Lunar Surface&lt;br&gt;(2011)</td>
<td>Event monitoring&lt;br&gt;Water inorganics monitor&lt;br&gt;Integrated realtime air monitoring&lt;br&gt;Lunar Environment monitor</td>
<td>Same as above&lt;br&gt;Flight hardware addressing micro-G operation&lt;br&gt;Reliability of chemical analyzer&lt;br&gt;Requirements, lunar surface operation</td>
<td>1-5 3 3 1</td>
</tr>
<tr>
<td><strong>Spiral 3</strong>&lt;br&gt;Long Duration&lt;br&gt;Lunar Surface&lt;br&gt;(2014)</td>
<td>Event monitoring&lt;br&gt;Integrated realtime air analysis&lt;br&gt;Water quality suite&lt;br&gt;Lunar Environment Monitor&lt;br&gt;Autonomous Integrated Process Control</td>
<td>Same as above&lt;br&gt;Same as above&lt;br&gt;Organics analysis&lt;br&gt;Above plus tests of simulated Martian conditions if possible&lt;br&gt;Assisted diagnostics and operation</td>
<td>1-5 3 2 1 1</td>
</tr>
<tr>
<td><strong>Spiral 4</strong>&lt;br&gt;Mars Vicinity&lt;br&gt;(2017)</td>
<td>As above, tailored to Mars mission&lt;br&gt;Longer communication lags</td>
<td>As above, tailored to Mars mission&lt;br&gt;More autonomous operation</td>
<td>As above</td>
</tr>
<tr>
<td><strong>Spiral 5</strong>&lt;br&gt;Initial Mission&lt;br&gt;Mars Surface&lt;br&gt;(2021)</td>
<td>• As above, tailored to Mars surface mission&lt;br&gt;–Martian environment</td>
<td>• As above, tailored to Mars surface mission&lt;br&gt;•Chemically reactive dust</td>
<td>As above</td>
</tr>
</tbody>
</table>
## Environmental Monitoring & Control
### Maturity Level – Technologies

<table>
<thead>
<tr>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Leading Technology Candidates</th>
<th>Development Needed</th>
<th>Current TRL</th>
<th>Spiral(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event monitoring</td>
<td>Electronic Nose</td>
<td>Additional target gases</td>
<td>5</td>
<td>1-5</td>
</tr>
<tr>
<td>Integrated realtime air analysis</td>
<td>GCMS FTIR GCIMS TDL, to be used with one of the above</td>
<td>Test in relevant environment Flight testing Reliability MWIR laser development</td>
<td>3 5 6 3</td>
<td>2-5 3-5 2-5 1-5</td>
</tr>
<tr>
<td>Water quality suite</td>
<td>CSPE Microfluidic ion analyzer</td>
<td>Micro-G functionality Lab demo</td>
<td>4 3</td>
<td>3-5 3-5</td>
</tr>
<tr>
<td>Lunar, Martian Environmental Monitoring</td>
<td>TBD</td>
<td>TBD</td>
<td>1</td>
<td>3-5</td>
</tr>
<tr>
<td>Autonomous Integrated Process Control</td>
<td>Integrated system modeling, system design, and process control Diagnostics and Prognostics Autonomous operation</td>
<td>System models and designs coordinated with control needs</td>
<td>1 1</td>
<td>3-5 3-5</td>
</tr>
</tbody>
</table>
# Environmental Monitoring & Control Figures of Merit

<table>
<thead>
<tr>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Figures of Merit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Event monitoring</strong></td>
<td>% priority targets measured</td>
</tr>
<tr>
<td><strong>Integrated realtime air analysis</strong></td>
<td>Number of targets/resource demands</td>
</tr>
<tr>
<td><strong>Water quality suite</strong></td>
<td>Mean Time Between Failure</td>
</tr>
<tr>
<td><strong>Lunar Environment Monitor</strong></td>
<td>Mean Time Between Maintenance</td>
</tr>
<tr>
<td><strong>Autonomous Integrated Process Control</strong></td>
<td>Reduced Number of human interactions</td>
</tr>
<tr>
<td></td>
<td>Reduced resource req’ts</td>
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<td></td>
<td>Reduced downtime</td>
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<tr>
<td></td>
<td>Reduced time to detect fault</td>
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</tbody>
</table>

**Description**

- % priority targets measured
- Number of targets/resource demands
- Mean Time Between Failure
- Mean Time Between Maintenance
- Reduced Number of human interactions
- Reduced resource req’ts
- Reduced downtime
- Reduced time to detect fault

**Units**

- %
- #targets/mass
- months
- #events or hours
- Mass, power
- Time, time
Fire Prevention, Detection, & Suppression (FPDS)

- Human Health & Support Systems
  - Human Health & Performance
  - Life Support and Habitation
  - Extra-Vehicular Activity
  - Life Support Systems
    - Environmental Monitoring and Control
    - Contingency Response
    - Exploration Habitats
  - Contingency Response
  - In Situ Fabrication & Repair
  - Fire Prevention, Detection, Suppression
    - Air Revitalization
    - Water Reclamation
    - Thermal Control
    - Solid Waste Management
    - Food Provisioning and Management
    - Biomass Production
  - Internal Monitoring
  - External Monitoring
  - Control Systems
  - Surface Construction
  - Habitat Shell
  - Internal Systems & Outfitting
  - External Systems and Architecture

Human Health & Support Systems
Life Support Systems
Environmental Monitoring and Control
Contingency Response
Exploration Habitats
Fire Prevention, Detection, Suppression
Air Revitalization
Water Reclamation
Thermal Control
Solid Waste Management
Food Provisioning and Management
Biomass Production
Internal Monitoring
External Monitoring
Control Systems
Surface Construction
Habitat Shell
Internal Systems & Outfitting
External Systems and Architecture

NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005

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Fire in spacecraft is classified as a catastrophic risk. The risk of fires in crew spacecraft and habitats cannot be eliminated. The FPDS element seeks to quantify and minimize the risk (both probability and severity).

**Scope**

- **Materials** must be selected throughout system design and operation stages to minimize the probability of a fire
  - Material flammability acceptance criteria

- Atmosphere selection is a trade-off between material flammability, EVA constraints, and hypoxic limits
  - Ignition, heat release rates, and flammability limits in candidate atmospheres

- **Detection** of a fire event must be accurate, timely and location-specific
  - Network of appropriate sensors and associated fire detection logic
  - Knowledge of fire signatures in low- and partial gravity

- A robust means to **suppress** a fire event must be available and compatible with vehicle design
  - Effectiveness of suppressants and delivery method in low and partial gravity
  - Mitigation of post-fire toxic by-products and collateral damage; minimize impact to crew, system, and mission
Benefits of Fire Prevention, Detection, and Suppression

- Increase the probability of continuing the mission in the event of fire
  - Systematically reduce risk and severity of fire
  - Minimize impact of a fire on the crew, equipment, and mission
- Reduction in vehicle mass through appropriate selection/evaluation of materials
  - Use of COTS hardware typically requires application of fire breaks to pass flammability tests
  - Use reduced mass components where appropriate as determined by quantifiable flammability/risk assessment
- Significantly reduce false positive (nuisance) alarms
  - Susceptibility of ISS smoke detectors to dust requires unnecessary crew action and reduces confidence
- Reduction in suppressant system mass and amount of suppressant dispersed during fire response
  - Reduction of suppressant discharged reduces the impact on the crew and consumables required for clean-up/recovery
- Increased efficiency of fire response through simulation of realistic fire scenarios and crew training
Current State-of-the-Art for FPDS

  - Test 1: Upward Flame Spread Test
- Smoke Detectors
  - STS: ionization
  - ISS RS and FGB: ionization
  - ISS US: photoelectric
- Fire Extinguishers
  - STS: Fixed and portable Halon
    - ISS US: CO$_2$
    - ISS RS: Water-based foam

- All existing technology and requirements are based on 1-g fire behavior
- Effectiveness in low-g is unproven as evidenced by the inconsistent approaches
FPDS capability is driven by the mission requirements of all spirals

- Fire Prevention and Material Flammability
  - Selection of atmosphere for habitable volumes
  - Flammability in partial gravity (Spirals 3, 5: Lunar and Martian habitats) is different than zero-gravity (Spirals 1-5: transit vehicles)

- Fire Detection
  - Driven by experience on ISS
    - Nuisance alarms caused by dust
  - Detectors must be sensitive to appropriate pre-fire and fire signatures
    - Will vary with materials used, atmosphere and gravity level

- Fire Suppression and Response
  - Selection of a suppressant and definition of response strategy will change with gravity level and habitable atmosphere

- Additional Assumptions
  - Habitable atmosphere will be the same for all spirals and different than ISS/STS
    - If not, material assessment/selection and design criteria for fire detection and suppression systems must be re-evaluated for each spiral
### Fire Prevention Detection & Suppression Roadmap

<table>
<thead>
<tr>
<th>Spiral 1: Crew Exploration Vehicle</th>
<th>Spiral 2: Extended Duration Moon</th>
<th>Spiral 3: Long Duration Moon</th>
<th>Spiral 4: Mars Vicinity</th>
<th>Spiral 5: Mars Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRR</td>
<td>SRR</td>
<td>ISS End of US commitment</td>
<td>Retire Shuttle</td>
<td>Mars Science Lab</td>
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<tr>
<td>Un-crewed Flight</td>
<td>Crewed Flight</td>
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</table>

#### FPDS

**Fire Suppression and Response**
- Low-g evaluation of suppressants
- Evaluation of suppressants in ground-based zero-g facilities
- Low-g Suppression Syst Design/ Optimization

**Fire Scenarios and Training**
- Model of gas/particulate transport
- Interactive VR fire/response simulation
- Lunar transit fire scenarios and training
- Experimental evaluation of partial-g simulations
- Lunar surface fire scenarios and training
### FPDS Road Map

<table>
<thead>
<tr>
<th>Project</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
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<th>2027</th>
<th>2028</th>
<th>2029</th>
<th>2030</th>
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<tbody>
<tr>
<td>Shuttle &amp; ISS</td>
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<tr>
<td>Spiral 1: Crew Exploration Vehicle</td>
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<td>Spiral 2: Extended Duration Moon</td>
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<tr>
<td>Spiral 3: Long Duration Moon</td>
<td>SDR ▲</td>
<td>PDR ▲</td>
<td>CDR ▲</td>
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<td>Spiral 4: Mars Vicinity</td>
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<td>Spiral 5: Mars Surface</td>
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<td>1st Human Mission</td>
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### Capability

- **Life Support & Habitation**

### FPDS

#### Fire Signatures and Detection
- Prototype gas/part sensors
- AEMC Candidate Sensors
- Low-g eval of candidate sensors
- Adv Fire Detector Tech-IV
- Prototype gas/part sensors
- AEMC Candidate Sensors
- Low-g eval of candidate sensors
- Adv Fire Detector Tech-V

#### Fire Scenarios and Training
- Lunar habitat fire scenarios and training
- Long-duration transit fire scenarios and training
- Mars surface fire scenarios and training
## Maturity Level – Fire Prevention, Detection, and Suppression

<table>
<thead>
<tr>
<th>Mission (Need Date)</th>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Capability Development Needs</th>
<th>Current CRL</th>
</tr>
</thead>
</table>
| Spiral 1            | • Fire Prevention and Material Flammability  
                      • Fire Signatures and Detection  
                      • Fire Suppression and Response  
                      • Fire Scenarios and Training | Low-gravity material flammability acceptance criteria  
Advanced fire detection system  
Fire signatures in reduced gravity  
Verified models of fire precursor/contaminant transport in low gravity  
Design rules for reduced gravity fire suppression system | 2  
4  
2  
3  
3 |
| Spiral 2            | Same as Spiral 1 | Evaluation of material flammability relevant for partial gravity  
Assessment of material flammability in CEV atmosphere  
• Advanced fire detection system (assessment and implementation of future sensor technology)  
Evaluation of fire suppression in partial gravity | 1  
3  
2  
2 |
<p>| Spiral 3            | Same as Spiral 1 | • Advanced fire detection system (assessment and implementation of future sensor technology) | 1 |
| Spiral 4            | Same as Spiral 1 | Same as Spiral 3 | 1 |
| Spiral 5            | Same as Spiral 1 | Same as Spiral 3 | 1 |</p>
<table>
<thead>
<tr>
<th>Capability (Level 5 CBS)</th>
<th>Leading Technology Candidates</th>
<th>TRL</th>
<th>Products (Spirals Needed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Prevention and Material Flammability</td>
<td>Low-stretch scaling of ignition delay, mass loss rate, heat release, production of toxic products</td>
<td>2</td>
<td>Low gravity material flammability acceptance criteria (Spirals 2-5)</td>
</tr>
<tr>
<td></td>
<td>Flight hardware to validate scaling of ignition delay, flame spread, heat release, and release of toxic products (FEANICS/Combustion Integrated Rack (CIR))</td>
<td>6</td>
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</tr>
<tr>
<td></td>
<td>Normal gravity analog for reduced gravity flammability</td>
<td>2</td>
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</tr>
<tr>
<td>Fire Signatures and Detection</td>
<td>MEMS chemical sensors for species measurements</td>
<td>4</td>
<td>Fire signatures in reduced gravity (Spirals 2-5)</td>
</tr>
<tr>
<td></td>
<td>Electronic nose technology for detection of pre-fire signatures</td>
<td>4</td>
<td>Advanced fire detector and detection logic</td>
</tr>
<tr>
<td></td>
<td>Particulate sensors and size classifiers</td>
<td>3</td>
<td>Verified models of fire precursor transport in low gravity (Spirals 1-5)</td>
</tr>
<tr>
<td></td>
<td>Database of reduced gravity fire signatures</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flight hardware to quantify reduced gravity signatures of pre-fire particulate (Smoke Aerosol Measurement Experiment)</td>
<td>6</td>
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</tr>
<tr>
<td>Fire Suppression and Response</td>
<td>Low-gravity evaluation of candidate fire suppressants</td>
<td>3</td>
<td>Design rules for reduced gravity fire suppression system (Spirals 1-5)</td>
</tr>
<tr>
<td></td>
<td>Flight hardware for initial screening of effectiveness of fire suppressants (Flame Extinguishment Experiment/CIR)</td>
<td>6</td>
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</tr>
<tr>
<td>Fire Scenarios and Training</td>
<td>Simulation of relevant fire scenarios in a low-g habitable volume</td>
<td>4</td>
<td>• Simulation and evaluation of relevant fire scenarios</td>
</tr>
<tr>
<td></td>
<td>Realistic visualization of fire/smoke transport</td>
<td>2</td>
<td>• Realistic crew training modules (Spirals 2-5)</td>
</tr>
<tr>
<td></td>
<td>Development of fire response training module</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Sub-Capability (Level 5 CBS)</td>
<td>Figures of Merit</td>
<td>Units</td>
<td></td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td>------------------------------------------------------</td>
<td>-------------------</td>
<td></td>
</tr>
<tr>
<td>Fire Prevention and Material Flammability</td>
<td>Reduce mass</td>
<td>kg</td>
<td></td>
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<tr>
<td></td>
<td>Decrease risk of fire</td>
<td>%</td>
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<tr>
<td>Fire Signatures and Detection</td>
<td>Reduce mass</td>
<td>kg</td>
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<tr>
<td></td>
<td>Reduce power</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduce detection time</td>
<td>sec</td>
<td></td>
</tr>
<tr>
<td>Fire Suppression</td>
<td>Reduce system mass</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduce suppressant mass released</td>
<td>kg (or ppm)</td>
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<tr>
<td></td>
<td>Reduce response time</td>
<td>sec</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduce consumables for clean-up/recovery</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>Fire Scenarios and Training</td>
<td>Decrease risk of fire</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Decrease response time</td>
<td>sec</td>
<td></td>
</tr>
</tbody>
</table>

**Units**: kg, %, W, sec, kg (or ppm), kg
In Situ Fabrication and Repair Capabilities

- **Multi-Material Fabrication (MMF) Capability**
  - Will utilize shop level equipment to provide a means of fabricating new or replacing existing parts, tools, components, etc.
  - Fabricated products will include various material types such as metals, plastics, ceramics and composites to fulfill requirements for all functioning elements used in the in situ equipment and habitat
  - Products include newly defined parts or tools within an element of the transport vehicle, other vehicle equipment, habitat equipment, and necessary medical products (such as syringes, needles, surgical instruments, inflatable casts, IV bags, etc.)

- **Electrical/Electronics Fabrication (EF) Capability**
  - Will utilize printed electronics techniques to provide a means of fabricating new or replace existing electronic boards and components

- **Multi-Material Repair (MMR) Capability**
  - Multi-material patching, bonding, and filling techniques will be developed to provide repair capabilities for most or all materials subject to in-situ failures
  - MMR will utilize in-situ, imported, and recycled materials as provided by a logistics support function
  - Repairs will target the inclusion of all system and element material types utilized during transport and while on extraterrestrial bodies

- **Electrical/Electronics Repair (ER) Capability**
  - Self-healing materials and metal joining techniques will be developed to provide repair capabilities for electrical/electronics materials subject to in-situ failures
  - ER capabilities will utilize in-situ, imported, and recycled materials as provided by a logistics support function
In Situ Fabrication & Repair Benefits

- In Situ Fabrication capabilities will reduce/eliminate the need for spares through the utilization of in-situ, imported, and recycled materials in the restoration of system and element functionality, thereby decreasing risk to crew and system functionality and enhancing mission safety.
- Fabrication capabilities minimize mission risk due to equipment design flaws, by providing the capability to fabricate new parts, in situ, with updated design specifications (spares would be worthless in this case).
- Providing just-in-time fabrication of parts and tools to meet maintenance requirements of system failures via closed loop quality controlled solid freeform fabrication technologies, thereby reducing spare parts inventory.
- In Situ Repair capabilities will reduce/eliminate the need for spares through the utilization of in-situ, imported, and recycled materials in the restoration of system and component functionality.
- Repairs will minimize risk due to functional backup for critical systems and greater flexibility in recovering from failures – enabling self-sufficiency.
- Repairs will utilize shop, portable, handheld, and robotic equipment to perform functions, providing portability and ease-of-use.
- Autonomous robotic systems will reduce/eliminate man-in-the-loop requirements.
  - Will use available feedstocks which include materials delivered from Earth or materials produced in situ on moon/mars.
Current SOA for Multi-Material Fabrication

- Multiple technologies with various ranges of materials processing capabilities
- Evolving additive techniques for solid freeform fabrication (SFF) improving yearly, with focus on multi-material & direct manufacturing

Current SOA for Electrical/Electronics Fabrication

- PCB manufacturing is multi-step process, steps include artwork preparation, developing, etching, cleaning, drilling, and finishing using subtractive techniques
- Electronics/Electrical manufacturing require use of chemicals, metals, plastics, and resins
- Discrete components are fabricated separately from PCB and attached in assembly build-up
- Emerging technologies use additive printing techniques
- Emerging material include flexible electronics - Flextronics
- Emerging technologies are developing Thin Film Transistor Circuits (TFTC) using additive techniques

Current SOA Multi-Material Repair

- Extensive commercial, aerospace, and defense applications and adhesive materials available and in place
- Low to extremely high temperature bonding methods possible
- Diverse material compatibility
- Few actual space-based toolkit single or multi-component adhesive systems applied

Current SOA for Electrical/Electronics Repair

- Current soldering methods include Standard Hot resistive Tip, Hot Air Station, Laser Soldering Station, COLDHEAT Soldering iron
- Laser soldering repair stations are in current commercial use
- Self-healing wire insulation proof of concept testing completed for embedded healing agent wire insulation repair
- Concept development for wire repair using Shape Memory Alloys (SMA)
- Concept development for wire insulation repair using viscous polyisobutane
- All experimental runs of In-Space Soldering Investigation (ISSI) on ISS have been completed, to provide valuable data with return of experimental coupons on Shuttle RTF mission
Requirements / Assumptions for In Situ Fabrication & Repair

Design Framework/Reference Missions
- Infrastructure Characteristics
  - Operational Gravity: Hypo-g (Lunar 1/6-g & Martian 1/3-g) for Spiral 2
  - Operational Gravity: Hypo-g and Micro-g for Spirals 3-5
  - Operational Environment: Cabin IVA; T=10-35C, P=10-15psia
  - Operating Mode:
    - Crew tended for Fabrication capability (exchange feedstock, transfer parts, perform parts cleaning, etc.)
    - Crew or robotic operation for Repair capability
  - System Reliability: ≥ 95% Uptime
  - Power available up to 48 hours continuously to perform complete build cycle for fabrication capability
  - Power Requirement: TBD

Additional Assumptions that drove the need for the capability
- Electrical Failures comprise a high percentage of failures, based on prior mission data
- Unpredicted Failures will always occur, introducing mission risk. Methods for correcting failures will always be a major factor for reducing mission risk
- Crew Time will always be a premium commodity. Any autonomous repair capability will be value-added
## In Situ Fabrication & Repair Road Map

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<td>SDR▲</td>
<td>PDR▲</td>
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<td>SDR▲</td>
<td>PDR▲</td>
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<td>Spiral 5: Mars Surface</td>
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<td>▲ Mars Science Lab</td>
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</tbody>
</table>

### Capability

#### Life Support & Habitation

**In Situ Fabrication & Repair**

- **Multi-Material Fabrication**
  - Trade Studies
  - Failure Analysis Studies
  - Parts Comparisons

- **Electronics Fabrication**
  - Printed Circuit Boards
  - Discrete Components
  - Other Components

- **Multi-Material Repair**
  - Repair Toolkit with existing adhesives

- **Electronics Repair**
  - Develop manually activated self-healing wire insulation prototype

**Part Comparison**

- Refined Regolith Feedstocks
- Mars Mission Material Rqts.

**Multi-Material**

- TRL4 Adhesives Repair Toolkit
- TRL6 Fabricated PCB with planar discrete components
- TRL6 Repair Toolkit
- TRL6 Additional Material hypo-g Moon unit
- TRL6 TFC with Simple Logic Circuits
- TRL6 Handheld Soldering Capability

**Electronics Fabrication**

- TRL4 Single Material Lunar Unit
- Low precision discrete components (resistors, capacitors, simple sensors)
- Single layer PCB (1e-5) features
- High precision discrete components
- Antennas, inductors, thermoelectric components
- Battery, fuel cells, solar cells, photo voltaic cells
- Medium complexity logic circuits (MUXs, Decoders, Flip-Flops, Counters, Registers)
- Built-in-testing for basic functionality

**Multi-Material Repair**

- TRL4 Self-Healing Wire Insulation – Manual Activated
- TRL4 Repair Toolkit with new bonding

**Electronics Repair**

- TRL4 Self-Healing Wire
- Prototype for self-activating self-healing wire in relevant environment
- Prototype for self-activating self-healing wire in relevant environment
- TRL4 Self-Healing Wire

**Regolith Feedstocks**

- TRL4 Multi Material µ-g Mars unit
- TRL6 Multi Material µ-g Mars unit

**Lunar Mission Material Rqts.**

- Mars Mission Material Rqts.

**Electronics Tester Facility**

- ETF 1.0
- ETF 1.1
- ETF 1.2
- ETF 1.3

**Efficiency**

- EFF 1.0
- EFF 1.1
- EFF 1.2
- EFF 1.3
### In Situ Fabrication & Repair Road Map

<table>
<thead>
<tr>
<th>Capability</th>
<th>Life Support &amp; Habitation</th>
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<tr>
<td><strong>In Situ Fabrication &amp; Repair</strong></td>
<td><strong>Multi-Material Fabrication</strong></td>
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<td></td>
<td><strong>Electronics Fabrication</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Multi-Material Repair</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Electronics Repair</strong></td>
</tr>
</tbody>
</table>

#### Shuttle & ISS
- **Spiral 1:** Crew Exploration Vehicle
- **Spiral 2:** Extended Duration Moon
- **Spiral 3:** Long Duration Moon
- **Spiral 4:** Mars Vicinity
- **Spiral 5:** Mars Surface

#### Key Dates:
- **2018:**
  - **SRR**
  - **SDR**
- **2019:**
  - **PDR**
  - **CDR**
- **2020:**
  - **1st Human Mission**
- **2021:**
  - **1st Human Mission**
- **2022:**
  - **1st Human Mission**
- **2023:**
  - **1st Human Mission**
- **2024:**
  - **1st Human Mission**
- **2025:**
  - **1st Human Mission**
- **2026:**
  - **1st Human Mission**
- **2027:**
  - **1st Human Mission**
- **2028:**
  - **1st Human Mission**
- **2029:**
  - **1st Human Mission**
- **2030:**
  - **1st Human Mission**

---

**Electronics Fabrication**
- TRL6 TFTC with MSI (1e-6) features
- TRL6 TFTC with SSI (1e-7) features
- TRL6 TFTC with NSI (1e-8) features

**Multi-Material Repair**
- Tech. Enhancements due to feedback from ECLSS
- Complement Mars flight-unique H/W

**Electronics Repair**
- TRL6 Self-Healing Wire Capability

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**In Situ Fabrication & Repair**
- TRL6 Complex logic circuits
- TRL6 CEV & Robotic hypo-g Unit
- TRL6 TFTC SSI Components
- TRL6 Final Integrated Mars Repair Kit
- TRL6 Full scale Mars surface unit
- TRL6 TFTC NSI Components
<table>
<thead>
<tr>
<th>Mission (Need Date)</th>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Capability Development Needs</th>
<th>Current CRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spiral 2 Lunar Surface (2011)</td>
<td>Multi-Material Patching, Filling, Joining</td>
<td>Develop Adhesives Repair Toolkit Demo with existing adhesives for demo on ISS and/or lunar surface</td>
<td>4</td>
</tr>
<tr>
<td>Spiral 3 Long Duration Lunar Surface (2014)</td>
<td>Multi-Material Fabrication - Fabricator</td>
<td>Multi-material fabricator with closed loop control in hypo-g moon capability. Full scale lunar hypo-g flight unit with closed loop control and post-build finishing for pressurized cargo module launch to moon</td>
<td>1</td>
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<tr>
<td></td>
<td>Multi-Material Fabrication - Fabricator</td>
<td>Full scale system stand alone cargo element testbed for lunar surface for independent deployment ahead of manned expedition</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Multi-Material Fabrication - Fabricator</td>
<td>Identify, develop &amp; apply new in-situ bonding components press &amp; unpress areas.</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>• Multi-Material Patching, Filling, Joining</td>
<td>Apply learned soldering methods &amp; technology to development of prototype portable soldering equipment for ISS</td>
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<tr>
<td></td>
<td>Multi-Material Patching, Filling, Joining</td>
<td>Develop manually activated self-healing wire insulation prototype</td>
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<tr>
<td>Spiral 4 Mars Vicinity (2017)</td>
<td>Multi-Material Fabrication - Fabricator</td>
<td>Breadboard of Mars transit µ-g for CEV cabin</td>
<td>2</td>
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<tr>
<td></td>
<td>Multi-Material Fabrication - Fabricator</td>
<td>Full scale µ-g Mars transit TRL6 unit for controlled CEV cabin w/ closed loop control &amp; post finishing; µ-g Mars transit flight unit with restricted part size up to 12x12x12</td>
<td>2</td>
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<tr>
<td></td>
<td>Multi-Material Fabrication - Fabricator</td>
<td>Full scale system stand alone cargo element testbed for lunar surface for independent deployment ahead of manned expedition</td>
<td>2</td>
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<tr>
<td></td>
<td>Electronics Fabrication</td>
<td>Single layer printed circuit boards (PCB) with 10 micron (1e-5) features and low precision planar discrete components (resistors, capacitors, and simple sensors)</td>
<td>2</td>
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<tr>
<td></td>
<td>Electronics Fabrication</td>
<td>Single layer PCBs with 1 micron (1e-6) features and high precision planar discrete components (resistors, capacitors, and simple sensors)</td>
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<td></td>
<td>Electronics Fabrication</td>
<td>Addition of antenna and inductor components, thermoelectric components</td>
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<tr>
<td></td>
<td>Electronics Fabrication</td>
<td>Multilayer PCBs with large scale implementation (LSI) of simple logic Thin Film Transistor Circuit (TFTC) components with 10 micron (1e-5) features (AND, OR, NAND, NOR, Invertors)</td>
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<tr>
<td></td>
<td>Electronics Fabrication</td>
<td>Addition of energy components (batteries, fuel cells, and solar cells)</td>
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<tr>
<td></td>
<td>Electronics Fabrication</td>
<td>Addition of LSI of medium complexity logic TFTC components with 10 micron (1e-5) features (MUX, Decoders, Flip-flops, Counters, and Registers)</td>
<td>1</td>
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<tr>
<td></td>
<td>Electronics Fabrication</td>
<td>Addition of LSI of complex logic TFTC components with 10 micron (1e-5) features (PLA, ROM, and FPGA)</td>
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<tr>
<td></td>
<td>Electronics Fabrication</td>
<td>Semi-autonomous test/verification and validation tester with probes for testing continuity/isolation of PCB boards; probes for basic continuity/isolation testing, voltages, and currents of PCB boards; probes for testing continuity/isolation, voltages, and currents of PCB boards</td>
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<tr>
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<td>Electronics Fabrication</td>
<td>Autonomous Built-in-Test (BIT) test/verification and validation tester with probes for electrical testing and basic functionality of PCB boards</td>
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<tr>
<td></td>
<td>Electronics Fabrication</td>
<td>Autonomous test/verification and validation tester with probes for electrical testing and complex functionality testing of PCB boards</td>
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</table>
### Capability Development Needs

<table>
<thead>
<tr>
<th>Mission (Need Date)</th>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Capability Development Needs</th>
<th>Current CRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spiral 5 Initial Mission Mars Surface (2021)</td>
<td>Multi-Material Fabrication - Fabricator</td>
<td>• Optimize functions &amp; mass of μ-g design for Mars transit; build &amp; test ground unit modified for transition from lunar to Mars surface gravity. Full scale Mars version w/ optimized functionality for independent deployment ahead of manned Mars expedition.</td>
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<tr>
<td></td>
<td>Multi-Material Fabrication - Fabricator</td>
<td>• Refine TFTC components to medium scale implementation with 1 micron (1e-6) features, to small scale implementation with 100 nanometers (1e-7) features and to nano scale implementation with 10 nanometers (1e-8) features.</td>
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<tr>
<td></td>
<td>Electronics Fabrication</td>
<td>• Final integrated Mars adhesive kit contents. Flight H/W and environment compatibility.</td>
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<tr>
<td></td>
<td>Multi-Material Patching, Filling, Joining</td>
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<td>Sub-Capability (Level 5 CBS)</td>
<td>Leading Technology Candidates</td>
<td>Current TRL</td>
<td>Spiral(s)</td>
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<td>Multi-Material Fabrication</td>
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<td>Electronics Fabrication</td>
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<td>Self-Healing Wire Self-Healing Wire Insulation</td>
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### Figures of Merit

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<td>Multi-Material Fabrication</td>
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<td>Product Surface Finish</td>
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<td>Product Tolerances</td>
<td>in/in</td>
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<td>Electronics Fabrication</td>
<td>Trace Width</td>
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<td>Fabrication Tolerance</td>
<td>µm</td>
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<tr>
<td>Multi-Material Repair</td>
<td>Strength</td>
<td>%</td>
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<td>Temperature Tolerance</td>
<td>Degrees</td>
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<tr>
<td>Electronics Repair</td>
<td>Strength</td>
<td>%</td>
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<tr>
<td></td>
<td>Environmental Compatibility of repair</td>
<td>%</td>
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Exploration Habitats

Human Health & Support Systems
- Human Health & Performance
- Life Support and Habitation
- Extra-Vehicular Activity

Life Support Systems
- Environmental Monitoring and Control
- Contingency Response
- Exploration Habitats

Air Revitalization
- Water Reclamation
- Thermal Control
- Solid Waste Management
- Food Provisioning and Management
- Biomass Production

Internal Monitoring
- External Monitoring
- Control Systems

Contingency Response
- Fire Prevention, Detection, Suppression
- In Situ Fabrication & Repair

In Situ Fabrication & Repair
- Surface Construction
- Habitat Shell
- Internal Systems & Outfitting
- External Systems and Architecture
Habitats for crew and crew systems will be required to provide shelter and facilities both in transport vehicles and on the surface of the moon and Mars.

These Habitats and their systems will provide crew interfaces to all major systems as well as safe haven, recreation, relaxation, sleep, cooking, and work areas.

Habitat subsystems include Habitat Structure (vehicle, shell, structural, & in-situ components), all Internal Systems (Life support, Habitation elements, Maintenance, Safety, Racks, Systems Integration Tools & Environmental Systems), and all External Systems (Airlock, Micrometeoroid protection, Storage systems, rover accommodations).
• Habitat design and development process is equivalent to that of vehicle design
  – An individual Habitat’s structure and functionality will be driven by its specific mission’s operational requirements
    • Various habitat structure and styles will be required to support the exploration program
    • Habitat, Mission scope, and Vehicle design will trade requirements to meet available resources
  – Habitats consists of an Integrated system of systems and subsystems
    • Each subsystem will be chosen, per spiral, from available capabilities and traded within design resource constraints
    • Overall integration of designs is key to successful implementation
    • Each subsystem has it’s own defined roadmap and development process (see CBS on next page for details)
Surface Construction – to be covered in ISRU Road map (Unique to Surface Habitats)

- Habitat Shell
  - Alloy Module (integrated)
  - Inflatable
  - Composites
  - In-Situ

Internal Systems & Outfitting

Environmental control Systems
- ALS (Capability Roadmaps under ALS section)
- Radiation Protection (Capability Roadmap under HHP)

Dust control/seals
- Trash processing (Capability Roadmaps under ALS section)

Lighting

Habitat Facilities
- Sleep station (including Entertainment system, sleep systems, privacy areas)
- Galley (Capability Roadmaps under ALS section)
- Exercise (Capability Roadmap under HHP)
- Science & Work Stations (including mechanical and electrical repair shop, fabrication shop, computer hardware/software maintenance station, comm, & Robotics station)
- WCS (Capability Roadmaps under ALS section)
- Laundry (Capability Roadmaps under ALS section)
- Medical facility (Capability Roadmap under HHP)

Utility centers (Included in other Capability Roadmaps)
- (power, water, comm, data)

External Systems and Architecture
- Airlock (Capability Roadmap under EVA)
- Micrometeoroid protection
- Rover Accommodations (Included in other Capability Roadmaps)
- Greenhouse (Capability Roadmaps under ALS section)
Benefits

- Well designed habitats will provide for maximum crew safety
- Integrated Habitats will support overall mission success in all phases of the Manned Exploration Program
- Reconfigurable Habitat systems architectures will enable multiple configurations
- State of the art living, communication, and work centers will facilitate crew work efforts and crew-ground interaction
- Advanced life support and environmental systems (lighting, dust control, etc) will increase crew comfort, decrease the amount of required consumables, increase autonomous operations, self sufficiency, and reliability of habitats to provide for more efficient mission and crew operations
- Utilization of common hardware with other vehicles will decrease mission mass through common sparing (e.g., power, communication, instrumentation, life support, thermal control)
Exploration Habitats
Current State-of-the-Art

- Shuttle provides crew living and working environments for short duration LEO flights
- ISS provides orbital habitation facilities for 3 crew members with resupply.
- Apollo era moon lander is only existing design for a tested moon surface habitat
- Many terrestrial facilities incorporate well designed facilities necessary in a crew transport or surface habitat, but these are not micro-g or low-g designs
<table>
<thead>
<tr>
<th>Exploration Habitats Roadmap</th>
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<tbody>
<tr>
<td>Spiral 1: Crew Exploration Vehicle</td>
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<tr>
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<td>Spiral 3: Long Duration Moon</td>
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<tr>
<td>Spiral 4: Mars Vicinity</td>
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<tr>
<td>Spiral 5: Mars Surface</td>
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</table>

**Sub-Capability**

**Exploration Habitats**

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<th><strong>Exploration Habitats</strong></th>
<th><strong>Subsystems</strong></th>
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<td>Mission scenario defined</td>
<td>Architectural Trades</td>
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<td>Integrate Module concept</td>
<td>Systems R&amp;D</td>
</tr>
<tr>
<td>Integrate, build, and verify</td>
<td>Mission scenario defined</td>
</tr>
<tr>
<td>Launch</td>
<td>Lunar Environment Characterization</td>
</tr>
<tr>
<td>System &amp; Subsystem Integration Verification</td>
<td>Build &amp; Test</td>
</tr>
<tr>
<td>Habitat Design Baseline</td>
<td>Moon Habitat Concept</td>
</tr>
<tr>
<td>First USE</td>
<td>Habitat Design Baseline</td>
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<tr>
<td>Systems at TRL 6</td>
<td>System &amp; Subsystem Integration Verification</td>
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<td>Systems at TRL 6</td>
<td>Build &amp; Test</td>
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<td>Systems at TRL 6</td>
<td>Moon Habitat Concept</td>
</tr>
<tr>
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<td>Habitat Design Baseline</td>
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<tr>
<td>Long Duration Moon Concept/Requirements</td>
<td>Subsystem Trades</td>
</tr>
<tr>
<td>Mission scenario defined</td>
<td>Subsystem Trades</td>
</tr>
</tbody>
</table>

**Materials (alloy, composite, flexible), Structures, Subsystem, & System Research & Design**
Exploration Habitats Roadmap

<table>
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<tr>
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<td>PDR</td>
<td>CDR</td>
<td>1st</td>
<td>Human Mission</td>
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<td>Spiral 5: Mars Surface</td>
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</table>

Sub-Capability Exploration Habitats

- Moon habit first use
- Mars Habitat Concept
- Initial Mars Habitat design
- USE

Exploration Habitats

- Build & Test
- Habitat Design Baseline
- System & Subsystem Integration Verification
- Integrations, Build & Test
- Habitat Design Baseline
- System & Subsystem Integration Verification
- Integrations, Build & Test
- USE

- Systems R&D
- Mission scenario defined
- Systems at TRL 6
- Mars Habitat Concept
- System & Subsystem Integration Verification
- Mission scenario defined
- Mars Surface Habitat Concept

Materials (alloy, composite, flexible), Structures, Subsystem, & System Research & Design

NOTE: Milestone colors correspond to spiral color bars above.
**Exploration Habitats**

**Maturity Level - Capabilities**

**Integration Approach**

- Preliminary Mission Requirements
  - Define Preliminary Architecture

- Primary System
  - Concept Trade Studies Performed

- Ancillary System
  - Concept Trades Performed (ISRU, Rover Accom, Science Ops)

- Concept Down Selects Performed

- Concept Evaluated in Simulators, Earth Analog Test Beds, &/or Moon Test Bed

- Concepts refined

- Final Requirement/Specs

- Final Design

- Build, Test & Verification of Integrated Habitat systems

**Capability Readiness Level**

1. Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

   The Capability is defined in written form. The uses and/or applications of the Capability are described and an initial Proof-of-Concept analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)
## Exploration Habitats
### Maturity Level - Capabilities

<table>
<thead>
<tr>
<th>Mission (Need Date)</th>
<th>Sub-Capability (Level 5 CBS)</th>
<th>Capability Development Needs</th>
<th>Current CRL</th>
</tr>
</thead>
</table>
| Spiral 1            | Integrated Vehicle habitat  
Lunar Capable  
Low Earth Orbit  
CEV (2008)  
Vehicle life support systems  
Crew habitation facilities | ISS and Shuttle type system upgrades  
Reduce weight, crew maintenance time and ground processing through use of new materials and current state of the art capabilities  
Improve overall human environmental conditions | 3           |
| Spiral 2            | Initial Lunar Surface Habitat with airlock  
Lunar Surface (2011)  
Environmental Control Systems  
Habitat Facilities  
External systems and interfaces | Lighter weight structural materials (composites and/or inflatable material)  
Reduced use of consumables resources/increased recycling processes  
Seals & Mechanisms for Dust control systems  
Shielding (radiation and micrometeoroid) | 1           |
| Spiral 3            | Expanded Lunar Surface Habitat utilizing ISRU capabilities  
Long Duration (2014)  
Environmental Control Systems  
Habitat Facilities  
External systems and interfaces  
Crew habitation facilities | Construction materials and processes  
Reduced use of consumables resources/increased recycling processes  
Closed loop environmental systems/ISRU systems  
Module mating technologies  
Improved Shielding (radiation and micrometeoroid)  
“greenhouse” technologies | 1           |
| Spiral 4            | Long term Vehicle habitat  
Mars Vicinity (2017)  
Closed loop life support systems  
Crew habitation facilities | Above plus:  
Lighter weight structural materials | 1           |
| Spiral 5            | Initial Mars Surface Habitat  
Initial Mission (2021)  
Mars Surface | Above plus:  
Automated setup/construction  
Logistical supply Surface launch support system  
Seal technology | 1           |
## Exploration Habitats - Habitat Shell Maturity Level - Technologies

<table>
<thead>
<tr>
<th>Gaps (not identified on other roadmaps)</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflatable Structures</td>
<td>Environmental and Pressure tested materials and concepts</td>
<td>5/2014</td>
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<tr>
<td>Composite Structures</td>
<td>Environmental and Pressure tested materials and concepts</td>
<td>7/2011</td>
</tr>
<tr>
<td>Alloy Structures</td>
<td>Environmental and Pressure tested materials and concepts</td>
<td>9/2011</td>
</tr>
<tr>
<td>Integrated Module concepts</td>
<td>Vehicle and Surface requirements/concepts</td>
<td>na/2011</td>
</tr>
<tr>
<td>In situ structures</td>
<td>Verifiable Surface build concepts and processes</td>
<td>1/2025</td>
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</tbody>
</table>

Assumes need date as date of mission to first use capability
### Habitats – Internal Systems & Outfitting

#### Maturity Level - Technologies

<table>
<thead>
<tr>
<th>Gaps (not identified on other roadmaps)</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
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</thead>
<tbody>
<tr>
<td>Dust control Systems</td>
<td>Requirements for robotic precursor mission</td>
<td>2/2014</td>
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<tr>
<td></td>
<td>Analysis of Lunar/Martian environment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seals &amp; Filtration technology</td>
<td></td>
</tr>
<tr>
<td>Habitat Facilities</td>
<td>Detailed specification of mandatory crew and habitat facilities</td>
<td>2-6/2014</td>
</tr>
<tr>
<td></td>
<td>Technology and concepts for each facility (galley, sleep stations, work stations,...)</td>
<td></td>
</tr>
<tr>
<td>Lighting systems</td>
<td>Standards and guidelines for lighting</td>
<td>5-6/2014</td>
</tr>
<tr>
<td></td>
<td>Technology and concepts for lighting across habitats</td>
<td></td>
</tr>
<tr>
<td>Overall integration of Habitat systems and interface dependencies</td>
<td>System Trade Studies Habitats</td>
<td>na/2014</td>
</tr>
</tbody>
</table>

Note: Assumes mission worst case scenario (Mars)
### Habitats – External Systems and Architecture Maturity Level - Technologies

<table>
<thead>
<tr>
<th>Gaps (not identified on other roadmaps)</th>
<th>Deliverables</th>
<th>Current TRL/Need Date</th>
</tr>
</thead>
</table>
| **Micrometeoroid Protection System** (vehicle and surface) | Requirements for robotic precursor mission  
Analysis of Lunar/Martian/Transport environment  
Micrometeoroid and exhaust plume protection technologies | 2-4/2014                |
| **Module Interfaces/Connects** (airlocks, transportation systems, greenhouse) | Environmental and Pressure tested materials and concepts | 4/2014                |
| **External storage systems** (rover accommodation...) | Requirements and integrated concepts | 2/2014                |

Note: Assumes all ISRU external systems and gaps identified in ISRU Roadmap
Exploration Habitats Figures of Merit

• **Ultimate:**
  – Increase autonomy of habitat operations/Decrease in mission time required for habitat maintenance
  – Increased operational redundancy, usability, and reliability
  – Decreased transport mass, consumable usage, and resupply requirements
  – Decrease in likelihood of errors, effects of errors

• **Annual:**
  – Increasing percentage of human support requirements incorporated into design concepts
  – Increasing usability ratings
  – Reduction in rework required as a result of integrated testing
  – Less crew time needed for ground-based training, on-orbit training, and system procedure execution
  – Increasing reliability/maintainability (MTBF=Mean Time Between Failures, maintenance time) measures of systems
  – Progression of TRL/CRL levels of technology components
Life Support and Habitation
Key Challenges

• Uncertainty of requirements that impact LSH systems: location, duration, spacecraft resource allocation, planetary protection.
• Acquiring manifests on future space vehicles/platforms for flight testing
  • Many LSH capabilities will require validation in relevant environment of space.
  • There will be competition for limited resources on Shuttle, ISS
  • There is a lack of defined microgravity resources between ISS and Spiral 4
• Infusing lessons learned from Spiral 3 Lunar planetary surface demonstrations into capabilities under development for Spiral 4
  • Spirals 3 & 4 are closely spaced on proposed strategic timelines
  • May be resolved during upcoming interchange between Roadmap Teams
• Obtaining adequate & timely information from precursor missions that characterize local environments and in situ resources to infuse into capability development
• Reducing complexity of regenerative and closed loop systems, reducing equivalent system mass and improving reliability
• Adequately addressing reliability to reduce mission risk
• Development of monitoring and control capabilities in parallel with development of capabilities that will be monitored and controlled.
Life Support and Habitation Systems, including Advanced Life Support, Environmental Monitoring and Control, Contingency Response and Exploration Habitats, represents a suite of enabling capabilities necessary to support human exploration missions as outlined in the U.S. Vision for Exploration.

Advanced regenerative life support systems, with integrated components, including air revitalization, water reclamation, thermal control, solid waste management, food provisioning and biomass production, are key capabilities needed to dramatically decrease the mass of future spacecraft for human exploration and to decrease dependency on resupply.

Key aspects will include “closing the loop” to recover usable mass, utilize *in situ* resources, decrease requirements for expendables, energy, volume, heat rejection and crew time, while providing a high degree of reliability.

Remote missions far from Earth will require Contingency Response capabilities for prevention and recovery from anomalies that may threaten mission success and crew safety, including fire and hardware failure.

Vehicle and surface habitats will need additional capabilities to accommodate new environments, longer periods of service, unique mission operations and configurations, and includes focus on the habitat shell, internal systems and outfitting, and external systems and architecture.
The draft content within this progress report includes content from many different individuals within the NASA community.

**Human Health and Support Systems Capability Roadmap Team**
- Daniel J. Barta/JSC
- Robyn Carrasquillo/MSFC
- Al Boehm/Hamilton Sundstrand (retired)

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- Water Reclamation: Karen D. Pickering/JSC
- Thermal Control: David Westheimer/JSC
- Solid Waste Management: John Fisher/ARC
- Food Provisioning & Management: Michele Perchonok/NSBRI
- Biomass Production: Raymond Wheeler/KSC
- Environmental Monitoring & Control: Darrell Jan/JPL
- Fire Prevention, Detection, Suppression: Gary A. Ruff/GRC
- In Situ Fabrication & Repair: Julie Bassler/MSFC
- Exploration Habitats: Michelle Kamman/JSC

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- John W. Hines/ARC
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- Guy J. Etheridge/KSC
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- Melanie. P. Bodiford/MSFC
- Monica. S. Hammond/MSFC
- Ronald J. King/MSFC
- John A. Hogan/Rutgers University/NSGF
- Julie A. Ray/Teledyne Brown Engineering
- Aaron L. Mills/University of Virginia

**Public Workshop**
White Papers from numerous individuals from private industry, academia, other government institutions and the general public.

**NASA Principal Investigators**
Content from ongoing research and technology projects was considered.
Advanced EVA Systems

Presenter:
Kerri Knotts
Between this capability road-mapping effort and the previous CRAI road-mapping effort, the following individuals provided either endless technical knowledge, philosophical insight or content review:

**AEVA Systems Project:**
- JSC/Mike Rouen (AEVA LSS)
- JSC/Gretchen Thomas (AEVA LSS)
- JSC/Luis Trevino (Thermal, Airlocks)
- JSC/Joe Kosmo (Suit Pressure Garment/Mobility)
- JSC/Sandra Wagner (EP, GSS)
- JSC/Amy Ross (Suit Pressure Garment/Mobility)
- JSC/Robert Trevino (AEVA)
- JSC/Heather Paul (AEVA)
- GRC/Dave Foltz (Comm, Avionics, Informatics)
- ARC/James Hieronymus (Informatics)
- GRC/Michelle Manzo (Power)
- JSC/Lara Kearney (AEVA Program Element)
- JSC/Jeff Patrick (AEVA Program Element)
- GRC/Diane Malarik (AEVA Program Element)
- JSC/Keith Todd (Mission Operations)
- JSC/ S. Rajulu (Human Factors)
- JSC/M. Whitmore (Human Factors)

**HHSS CRM EVA Review Team:**
- JSC/Glenn Lutz
- HS/Bob Poisson
- University of Maryland/Dave Akin
- JSC/CB/Mike Gernhardt
Advanced EVA Systems

- The Advanced Extravehicular Activity (AEVA) system includes the hardware and software necessary to allow a crewperson to perform tasks outside of the primary vehicle.
- As a fundamental capability within the Exploration Super-System, the AEVA system will require System-of-Systems integration, with contributions and dependencies from across many areas such as life support, power, communications, avionics, robotics, materials, pressure systems and thermal systems.
- The complete EVA system includes the highly-integrated human-centric EVA suit, and also consists of ancillary EVA tools and equipment, EVA translation and mobility aids, rover vehicles interfaces, human-robotic interactions, vehicle sub-system interfaces, airlocks and ground support systems.
Advanced EVA Systems

Human Health & Support Systems

- Human Health & Performance
- Life Support & Habitation
- Advanced EVA Systems
  - Suits
    - Suit Integration
    - Pressure Garment
    - Life Support System
  - EVA Tools and Mobility Aids
    - In-Space EVA Tools
    - EVA Surface Tools
    - Human-Robotic Workaids
  - Airlocks/Pressurized Volumes
    - Airlocks
    - Pressurized Rovers
    - Field Servicing System
  - Ground Support Systems
    - Test Facilities
    - Simulators
    - Ground Processing Facilities
Requirements /Assumptions for Advanced EVA Systems

• Various Design Reference Missions and studies were referenced during the development of this roadmap, not limited to the following:
  – RTF0004/ RTF0016 (Lunar Scenarios)
  – Initial Capability Roadmap Framework
  – Interviews with the Apollo Lunar Surface Astronauts in Support of Planning for EVA System Design, NASA Tech Memo 108846
  – Many EVA LSS related studies

• Based on the current Exploration Concept of Operations (Con Ops) and Crew Exploration Vehicle (CEV) Level I Requirements, the following capabilities are needed:
  – Contingency EVA capability for CEV
  – Crew survivability capability and protection from vehicle depress
  – Surface exploration capability

• Therefore, pressurized suits are needed to support the three distinct sub-capabilities: crew protection during launch and landing, in-space contingency EVA and planetary surface exploration
  – The technical challenges for these three capabilities are very different and depending on the mission, 2 or 3 suit designs may be necessary, imposing a logistical penalty
Advanced EVA Systems

- Suits
  - Suit Integration
    - Pressure Garment
    - Life Support System
  - EVA Tools and Mobility Aids
    - In-Space EVA Tools
    - EVA Surface Tools
    - Human-Robotic Workaids
  - Airlocks/Pressurized Volumes
    - Airlocks
    - Pressurized Rovers
    - Field Servicing System
  - Ground Support Systems
    - Test Facilities
    - Simulators
    - Ground Processing Facilities
The EVA suits will support launch and entry capability, in-space contingency EVA capability and surface exploration. These highly-integrated suits will allow autonomous human operation outside the pressurized environment and contain the following critical sub-capabilities:

- Livable Pressure Containment (Pressure Garment)
- Breathable Atmosphere (Ventilation System)
  - The ventilation system capabilities include the primary and emergency oxygen systems; CO2, trace gas and humidity removal; pressure regulation; ventilation flow, as well as, monitoring, sensing, command and control and caution and warning functions
- Thermal Control: heat acquisition, heat transfer and heat rejection
- Power: power generation, power storage and power transfer
- Communications and Informatics
- Environmental Protection
- Cross-cutting System Adaptability (Vehicle Interface: CEV, LSAM, Habitats, Airlocks, Rovers)
- Self Rescue
Benefits of the Suits

- An in-space suit (s) will support launch and entry crew survivability and CEV-based on-orbit operations
- A surface EVA suit will be based on a flexible, open architecture which will support multi-destination operation with minimal system reconfiguration
- Benefits of maximizing commonality between suit designs
  - Maintainable life support system architecture that is easily reconfigurable to enable multiple destinations
  - Lightweight, highly mobile suits and dexterous gloves to increase crew productivity, enable long-duration missions and high EVA use rates, mitigate crewmember injury and fit the full range of EVA crewmember sizes
  - Integrated human-robotic work capability to increase safety, efficiency, & productivity
  - State of the art communications and computing capability for multi-media crew-ground interaction (e.g., integrated communications, high tech information systems, and heads-up displays)
  - Operating pressure regimes which decrease EVA overhead by drastically reducing or even eliminating pre-breathe protocols
  - Advanced thermal control to increase crew comfort, decrease consumables, and enable multiple destinations (e.g., aerogel insulation, active cooling and heating
  - Common hardware with other vehicle systems to increase vehicle safety & decrease mission mass through common sparing (e.g., power, communication, instrumentation, life support, thermal control)
Current State-of-the-Art for Suits

- The current state-of-the-art for this capability is the Shuttle/ISS Extravehicular Mobility Unit (EMU) and the Russian Orlan
  - The EMU is over 25 years old and is facing significant obsolescence issues. In addition, it is not compatible with the planetary environments of either the Moon or Mars and does not support the logistical requirements of long term missions.
  - Similarly, the Orlan is not compatible with the planetary environments of either the Moon or Mars
- EVA overhead penalties are high in terms of mass, volume and time.
- Suit consumables are expended and require frequent replenishment or considerable time/power to recharge. No in-situ resource utilization is possible.
- Lack of suit maintenance capability beyond limited resizing, ORU replacement and consumables replacement.
- Suit mass, mobility, visibility and comfort are not compatible with partial gravity planetary environments. Inertial control and useful work/reach area in zero gravity is hampered.
- Suit protection from dust intrusion is inadequate.
- Available thermal insulation materials either only work in vacuum conditions or are thick and impede suit mobility and glove dexterity. Even with active heating, touch temperatures are limited to short durations and narrow ranges (-120 to +150F).
- Radiation definition, monitoring and protection are inadequate beyond earth’s ionosphere.
- Sensitive environments and science devices are contaminated from suit by-products
- Lack of integrated voice, high quality video, smart suit sensor technology, and informatics software to provide mission autonomy.
## Suits Roadmap

### Shuttle & ISS
- **SRR**: SRR
- **SDR**: SRR
- **PDR**: PDR
- **CDR**: CDR
- **UR**: Ur-crewed Flight
- **Crewed Flight**: Crewed Flight

### Spiral 1: Crew Exploration Vehicle
- **SRR**: SRR
- **SDR**: SRR
- **PDR**: PDR
- **CDR**: CDR

### Spiral 2: Extended Duration Moon
- **SRR**: SRR
- **SDR**: SDR
- **PDR**: PDR
- **CDR**: CDR

### Spiral 3: Long Duration Moon
- **SRR**: SRR

### Spiral 4: Mars Vicinity

### Spiral 5: Mars Surface
- **Mars Science Lab**: Mars Science Lab

### Sub-Capability
#### AEVA Suits
- EVA Project
- AEVA System Requirements
- AEVA System Requirements

### Suit Integration
- Architectural Trades
- Master Architecture for Suit
- Umbilical Trades
- AEVA System Con Ops
- Suit PDR
- Suitable CDR
- Human Vacuum Chamber Test TRL 6
- Certification Unit Fabrication
- Test
- Flight Unit Fabrication

### Pressure Garment System
- Component Development (TRL 1-4)
- Prototype Evaluation
- Complete R&T for Spiral 1 Human Rating Qualification
- Component Development (TRL 1-4)

### Life Support System
- Proof-of-Concept Development (TRL 1-2)
- Component Development (TRL 1-2)
- Complete R&T for LSS Architecture
- Proof-of-Concept Component Development (TRL 1-2)
## Suits Roadmap

### Spiral 1: Crew Exploration Vehicle
- **2018**: SDR
- **2019**: PDR
- **2020**: CDR
- **2021**: Human Rating Qualification
- **2022**: Human Rating Qualification
- **2023**: Prototype Component Development (TRL 3-4)
- **2024**: Complete R&T for Spiral 3
- **2025**: Certification Unit Fabrication
- **2026**: Test
- **2027**: Flight Unit Fabrication

### Spiral 2: Extended Duration Moon
- **2018**: SDR
- **2019**: PDR
- **2020**: CDR
- **2021**: Human Rating Qualification
- **2022**: Human Rating Qualification
- **2023**: Prototype Component Development (TRL 3-4)
- **2024**: Complete R&T for Spiral 3
- **2025**: Certification Unit Fabrication
- **2026**: Test
- **2027**: Flight Unit Fabrication

### Spiral 3: Long Duration Moon
- **2018**: SDR
- **2019**: PDR
- **2020**: CDR
- **2021**: Human Rating Qualification
- **2022**: Human Rating Qualification
- **2023**: Prototype Component Development (TRL 3-4)
- **2024**: Complete R&T for Spiral 3
- **2025**: Certification Unit Fabrication
- **2026**: Test
- **2027**: Flight Unit Fabrication

### Spiral 4: Mars Vicinity
- **2018**: SDR
- **2019**: PDR
- **2020**: CDR
- **2021**: Human Rating Qualification
- **2022**: Human Rating Qualification
- **2023**: Prototype Component Development (TRL 3-4)
- **2024**: Complete R&T for Spiral 3
- **2025**: Certification Unit Fabrication
- **2026**: Test
- **2027**: Flight Unit Fabrication

### Spiral 5: Mars Surface
- **2018**: SDR
- **2019**: PDR
- **2020**: CDR
- **2021**: Human Rating Qualification
- **2022**: Human Rating Qualification
- **2023**: Prototype Component Development (TRL 3-4)
- **2024**: Complete R&T for Spiral 3
- **2025**: Certification Unit Fabrication
- **2026**: Test
- **2027**: Flight Unit Fabrication

### Sub-Capability AEVA Suits
- **2018**: AEVA System Requirements
- **2019**: AEVA System Requirements
- **2020**: AEVA System Requirements
- **2021**: AEVA System Requirements
- **2022**: AEVA System Requirements
- **2023**: AEVA System Requirements
- **2024**: AEVA System Requirements
- **2025**: AEVA System Requirements
- **2026**: AEVA System Requirements
- **2027**: AEVA System Requirements
- **2028**: AEVA System Requirements
- **2029**: AEVA System Requirements
- **2030**: AEVA System Requirements

### Integration of Suit
- **2018**: Architectural Trades
- **2019**: Suit PDR
- **2020**: Suit CDR
- **2021**: Human Vacuum Chamber Test
- **2022**: Certification Unit Fabrication
- **2023**: Test
- **2024**: Flight Unit Fabrication

### Pressure Garment System
- **2018**: Pressure Garment Trades (mobility)
- **2019**: Pressure Garment Baseline
- **2020**: Complete R&T for Spiral 3
- **2021**: Human Rating Qualification
- **2022**: Component Development (TRL 5-6)
- **2023**: Proof-of-Concept Component Development (TRL 1-2)

### Life Support System
- **2018**: Component Specifications
- **2019**: Full-Scale Component Prototype Development (TRL 5-6)
- **2020**: Human Rating Qualification
- **2021**: Complete R&T for Spiral 3
- **2022**: Proof-of-Concept Component Development (TRL 1-2)
**Maturity Level - Capabilities**

**Advanced EVA Systems Capabilities (CRL 1:5)**

<table>
<thead>
<tr>
<th>Suits (CRL 1:5)</th>
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<tbody>
<tr>
<td>Pressure Garments (TRL 2 → 6)</td>
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<tr>
<td>Ventilation System (TRL 1 → 9)</td>
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<td>Thermal System (TRL 1 → 9)</td>
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<tr>
<td>Power System (TRL 3 → 4)</td>
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<tr>
<td>Communication and Informatics (TRL 2 → 5)</td>
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<tr>
<td>Environmental Protection (TRL 1 → 8)</td>
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<tr>
<td>Vehicle Interfaces (TRL 2 → 5)</td>
</tr>
<tr>
<td>Self rescue (TRL 4 → 9)</td>
</tr>
</tbody>
</table>

EVA Tools and Mobility Aids (CRL 1:5)

- In-space EVA Tools (TRL 3 → 7)
- EVA Surface Tools (TRL 1 → 9)
- Human-Robotic Work-aids (TRL 2 → 5)

Airlocks/Pressurized Volumes (CRL 1:5)

- Airlocks (TRL 2 → 5)
- Pressurized Rovers (TRL 2 → 3)
- Field Servicing System (TRL 2 → 4)

Ground Support Systems (GSS) (CRL 1:5)

- Test Facilities (TRL 3 → 9)
- Trainers and Simulators (TRL 3 → 9)
- Ground Processing Facilities (TRL 3 → 9)

*CRL shown is in terms of the starting/ending level (to TRL 6). TRL shown is the range covered in that technology area.
# Technology Maturity Level – Suits

<table>
<thead>
<tr>
<th>Sub-Capability</th>
<th>Current Capabilities</th>
<th>Capability Required</th>
<th>Sub-Capability Development Needs</th>
<th>Technology Area Candidates</th>
<th>TRL</th>
<th>Time to TRL 6 (yrs)</th>
</tr>
</thead>
</table>
| **Pressure Garments**| • Shuttle Launch and Entry Suit (LES)  
• Sokol  
• Extravehicular Mobility Unit (EMU)  
• Orlan  
• Apollo Suit | • Launch, entry and abort pressure protection  
• In-space and surface pressure protection  
• IVA comfort and mobility  
• In-space EVA mobility  
• Surface EVA mobility | • Vehicle Requirements Definition  
• Lighter weight  
• Increased Mobility  
• In-space EVA requirements  
• Increased Mobility  
• Increased Mobility  
• Increased Mobility  
• Increased Mobility | • Modified LES/ACES  
• Modified Sokol  
• Modified LES/ACES for contingency EVA  
• Mark III, I-suit, D-suit  
• Modified LES/ACES for contingency EVA  
• Mark III, I-suit, D-suit  
• Mark III, I-suit, D-suit | 6  
2  
6  
2  
5  
5 | 0  
4-6  
0  
0  
1  
1 |
## Technology Maturity Level – Suits

<table>
<thead>
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<th>Sub-Capability</th>
<th>Current Capabilities</th>
<th>Capability Required</th>
<th>Sub-Capability Development Needs</th>
<th>Technology Area Candidates</th>
<th>TRL</th>
<th>Time to TRL 6 (yrs)</th>
</tr>
</thead>
</table>
| Ventilation    | • Expendable LiOH canisters  
• Regenerable Metox  
• Low pressure primary O2 (900 psia)  
• High pressure secondary O2 (6000 psia)  
• Condensing Heat Exchanger  
• Regenerable Activated charcoal  
• Fan  
• Mechanical regulator | • CO2/trace gas removal  
• Humidity control  
• Ventilation flow  
• Primary/Secondary oxygen supply  
• Pressure regulation | • Lightweight  
• Regenerable  
• Low Venting and Low Resupply Penalties  
• Increased Recharge Safety (i.e., lower pressure recharge)  
• Increased component and system reliability  
• Increased cycle life  
• CO2 rejection into Mars’ CO2 atmosphere | Absorption/Regeneration  
Rapid Cycle Amine  
Pellets  
Geodes  
Rapid Cycle Molecular Sieve  
Zirconia Cell  
Photo-ionization LiOH  
Pellets  
Plastic  
Metal Oxides (Metox)  
Perm-Selective Venting Membrane  
Cryogenic Freeze Out  
Desiccant  
Condensing Heat Exchanger | 3-4  
1  
3-4  
2  
2  
9  
2  
2  
3  
8  
9 | 1  
3  
1  
3-4  
3-4  
2  
3-5  
2 |
## Technology Maturity Level – Suits

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<thead>
<tr>
<th>Sub-Capability</th>
<th>Current Capabilities</th>
<th>Capability Required</th>
<th>Sub-Capability Development Needs</th>
<th>Technology Area Candidates</th>
<th>TRL</th>
<th>Time to TRL 6 (yrs)</th>
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<tr>
<td><strong>Ventilation</strong></td>
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<td>Containment vessels</td>
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<td>Emergency Oxygen Low Pressure</td>
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<td>Recirculation with Venting</td>
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<td>Other Ventilation</td>
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<td>Traditional Fan</td>
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<td>Ejector/Transvector Regulators</td>
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<td>Solenoid Valve</td>
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<td>MEMS</td>
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<td>Capability Required</td>
<td>Sub-Capability Development Needs</td>
<td>Technology Area Candidates</td>
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<td>R</td>
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</tbody>
</table>
| Thermal        | • Multi-layer Insulation  
• Sublimator  
• Liquid Cooling Garment  
• Manual temperature control | • Heat Acquisition  
• Heat Transfer  
• Heat Rejection | • Lightweight  
• Regenerable  
• Low Venting and Low Resupply Penalties  
• Increased component and system reliability  
• Increased cycle life  
• Utilization of Mars’ convection environment to increase heat rejection  
• High insulation and heat rejection performance in a non-vacuum environment | Aerogel Thermal Insulating Materials  
Heat Management and Rejection  
Sublimator  
Water Boiler  
Thermal Storage  
Ice pack  
Wax  
Chemical Heat Pumps  
Lithium Chloride  
Lithium Bromide  
Miniature Mechanical Heat Pumps  
Vapor Compression  
Thermoelectric  
Cryogenic Cooler  
Venting Hydride  
Highly Conductive LCG  
Tubeless LCG | 2 | 2-3 | 9 | 3-4 | 2-3 |
|                |                      |                     |                                 |                           | 1 | 1 |
|                |                      |                     |                                 |                           | 4-5 | 1 |
|                |                      |                     |                                 |                           | 4-5 | 1 |
|                |                      |                     |                                 |                           | 3 | 2-3 |
|                |                      |                     |                                 |                           | 3 | 2-3 |
|                |                      |                     |                                 |                           | 3-4 | 1 |
|                |                      |                     |                                 |                           | 4 | 1 |
|                |                      |                     |                                 |                           | 4 | 1 |
|                |                      |                     |                                 |                           | 2 | 1 |
|                |                      |                     |                                 |                           | 1 | 5 |
### Technology Maturity Level – Suits

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<tr>
<th>Sub-Capability</th>
<th>Current Capabilities</th>
<th>Capability Required</th>
<th>Sub-Capability Development Needs</th>
<th>Technology Area Candidates</th>
<th>Time to TRL 6 (yrs)</th>
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<td><strong>Thermal</strong></td>
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<td>Radiator</td>
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<td>Sublimator</td>
<td>Heat Transfer</td>
<td>Regenerable</td>
<td>Convection</td>
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<td>Liquid Cooling Garment</td>
<td>Heat Rejection</td>
<td>Low Venting and Low Resupply Penalties</td>
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<td>Increased component and system reliability</td>
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<td>Increased cycle life</td>
<td>Heat Pipe</td>
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<td>Utilization of Mars’ convection environment to increase heat rejection</td>
<td>Control Valves</td>
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<td>High insulation and heat rejection performance in a non-vacuum environment</td>
<td>Structure</td>
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<td>Coatings</td>
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<td>Auto cooling control</td>
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<tr>
<td><strong>Power</strong></td>
<td>Batteries</td>
<td>Heat Acquisition</td>
<td>Batteries (increasing performance over current SOTA batts)</td>
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<td>Silver Zinc</td>
<td>Heat Transfer</td>
<td>Silver Zinc</td>
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<td>Lithium Ion</td>
<td>Heat Rejection</td>
<td>Lithium Ion</td>
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<td>Nickel Metal Hydride</td>
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<td>Nickel Metal Hydride</td>
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<td></td>
<td>Super Capacitors</td>
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<td></td>
<td>Lightweight, high power</td>
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<td>Fuel cells</td>
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<td>Standardized units</td>
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<td>PEM</td>
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<td>Methane</td>
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<td>CO-O2</td>
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<thead>
<tr>
<th>Sub-Capability</th>
<th>Current Capabilities</th>
<th>Capability Required</th>
<th>Sub-Capability Development Needs</th>
<th>Technology Area Candidates</th>
<th>TRL</th>
<th>Time to TRL 6 yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comm and informatics</td>
<td>• Paper cuff checklist&lt;br&gt;• Single band Radio&lt;br&gt;• IR CO2 sensor&lt;br&gt;• Limited sensor data for suit performance monitoring</td>
<td>Wireless comm&lt;br&gt;Integrated comm&lt;br&gt;Maintenance and diagnostic trending</td>
<td>• Increased crew communication and data transfer&lt;br&gt;• Lightweight informatics system&lt;br&gt;• Higher crew efficiency for real-time data acquisition&lt;br&gt;• Increased data insight for maintainability&lt;br&gt;• High reliability sensors</td>
<td>• Wireless sensors and electronics&lt;br&gt;• Heads up display&lt;br&gt;• Ultra Wideband Communication&lt;br&gt;• Solid state CO2 sensors&lt;br&gt;• IR CO2 sensors&lt;br&gt;• Voice Control&lt;br&gt;• Maintainability systems&lt;br&gt;• Diagnostics</td>
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<td>2-4</td>
<td>1-3</td>
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<tr>
<td>Environmental Protection</td>
<td>• EMU MLI&lt;br&gt;• EMU Ortho fabric&lt;br&gt;• Orlan</td>
<td>• In-space contingency EVA protection&lt;br&gt;• Surface exploration protection</td>
<td>• Dust protection/resistant materials and bearings&lt;br&gt;• Radiation protective materials&lt;br&gt;• Lightweight&lt;br&gt;• Flexible</td>
<td>• Micrometeoroid Protection&lt;br&gt;• Dust mitigating material&lt;br&gt;• Puncture resistant material&lt;br&gt;• Radiation protective material&lt;br&gt;• Biochemical protective material</td>
<td>8</td>
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<td>2-4</td>
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</tbody>
</table>
Quantitative measures will be established in the future from the results of early trade studies and requirements development. However, the following will be the high-level goals of this sub-capability:

- Decrease consumable use
- Minimize crew on-back weight
- Decrease weight and volume minimizing vehicle logistical penalty
- Increased modularity and maintainability
- Increased useful EVA work duration
  - High Work Efficiency Index (WEI)
- Maximize commonality across all Constellation vehicles
- Maximize crew comfort
Ancillary EVA tools and equipment include items that attach to a space suit, such as lighting and cameras, sensors, task-specific devices and safety gear. EVA tools, such as power and hand tools, provide the capability for a space suited human to conduct exploration and on-orbit operations. In a micro-gravity environment, EVA translation aids will be required to enable an EVA crewmember to translate, react forces and loads, and restrain themselves in order to do useful work.

Surface exploration will require a new complement of tools for sample acquisition, archiving, and handling. Surface infrastructure (habitats, rovers, robotic assistants) will require maintenance and servicing, which will in turn necessitate handling of substantial objects in a gravitational field. This new cadre of tools will be determined as surface exploration requirements are further defined.

Mobility aids provide the capability for controlled mobility with reduced metabolic workloads, and allow self-rescue from contingency or emergency situations.

Technological challenges in this area are typically related to adapting existing design devices to space requirements and do not represent a huge risk to constellation planning. However, surface exploration requirements will determine the specific tool development needs.
Benefits of the EVA Tools and Mobility Aids

- Increased EVA efficiency, greater work (task) efficiency index
- Lower metabolic expenditures from physical tasks
- Increased productivity with assistance from human-interactive robotic assistants
- Task reallocation, optimizing human involvement to high payoff/high dexterity/highly complex task sets
- Greater assurance of mission success, as robotic and EVA capabilities overlap to provide multiple options for achieving mission goals
- Safer work sites, due to robotic replacement or support of EVA in hazardous or demanding tasks
Current State-of-the-Art for EVA Tools and Mobility Aids

- Current tools are limited to manual force/torque reaction and zero-gravity transport/restraint.
- There is limited environmental and mechanical analysis.
- Delicate materials are not easily handled.
- There is very limited ability to interact with spacecraft systems other than at the preplanned ORU level.
- Robotic EVA aids currently in use are primarily large positioning arms with limited mobility and dexterity. Current robotic aids are too reliant upon low-latency remote human control, and unique visual alignment targets and handling interfaces.
- Human capable rovers and dexterous robots for EVA support are conceptual and will require development by other agency experts. Interfaces to the suited crew will be defined by advanced EVA systems expertise.
## EVA Tools/Mobility Aids Roadmap

### Shuttle & ISS
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024
- 2025
- 2026
- 2027
- 2028
- 2029
- 2030

### Spiral 1: Crew Exploration Vehicle

### Spiral 2: Extended Duration Moon

### Spiral 3: Long Duration Moon
- SDR
- PDR
- CDR
- 1st Human Mission

### Spiral 4: Mars Vicinity
- SRR
- SDR
- PDR
- CDR
- 1st Human Mission

### Spiral 5: Mars Surface

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### Sub-Capability

**EVA Tools/Mobility Aids**

<table>
<thead>
<tr>
<th>Sub-Capability</th>
<th>AEVA System Requirements</th>
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</thead>
</table>

---

### In-space EVA Tools

### Surface EVA Tools

- Thermal Vacuum Chamber Test TRL 6
- Certification Unit Fabrication
- Test
- Flight Unit Fabrication

### Human-Robotic Work-aids

- Surface AEVA/Robotic Interface Reqmts
- Certification Unit Fabrication
- Test
- Flight Unit Fabrication

---

**NOTE:** Milestone colors correspond to spiral color bars above.
Advanced EVA Systems Capabilities  (CRL 1:5)

Suits  (CRL 1:5)
Pressure Garments (TRL 2 → 6)
Ventilation System (TRL 1 → 9)
Thermal System (TRL 1 → 9)
Power System (TRL 3 → 4)
Communication and Informatics (TRL 2 → 5)
Environmental Protection (TRL 1 → 8)
Vehicle Interfaces (TRL 2 → 5)
Self rescue (TRL 4 → 9)

EVA Tools and Mobility Aids (CRL 1:5)
In-space EVA Tools (TRL 3 → 7)
EVA Surface Tools (TRL 1 → 9)
Human-Robotic Work-aids (TRL 2 → 5)

Airlocks/Pressurized Volumes (CRL 1:5)
Airlocks (TRL 2 → 5)
Pressurized Rovers (TRL 2 → 3)
Field Servicing System (TRL 2 → 4)

Ground Support Systems (GSS) (CRL 1:5)
Test Facilities (TRL 3 → 9)
Trainers and Simulators (TRL 3 → 9)
Ground Processing Facilities (TRL 3 → 9)

*CRL shown is in terms of the starting/ending level (to TRL 6).  TRL shown is the range covered in that technology area.*
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<tr>
<th>Roadmap Sub-Capability</th>
<th>Current Capabilities</th>
<th>Capability Required</th>
<th>Sub-Capability Development Needs</th>
<th>Technology Area/Candidates</th>
<th>TRL</th>
<th>Time to TRL = 6</th>
</tr>
</thead>
</table>
| **In-Space EVA Tools** | • Shuttle & Space Station Tool Set (~1900 pieces) | • Common EVA/Robotic Tool Set  
• Simple Operation  
• Low Maintainability | • EVA compatible Common with other systems  
• Decrease EVA overhead time/effort | • Common Constellation Tool Set  
• Training  
• Robotic  
• Human | 7 | - |
| **Surface Tools and Mobility Aids** | • Apollo Era Tool Set | • Common EVA/Robotic Tool Set  
• Dust Tolerant  
• Low Maintainability  
• Simple Operation  
• Science Objectives | • EVA compatible tools  
• Common with other systems  
• Decrease EVA overhead time/effort  
• Deep surface penetration (Science) | • Common Constellation Tool Set  
• Training  
• Robotic  
• Human  
• Dust Tolerance  
• Shallow Surface  
• Deep Surface  
• Field Analyzers  
• Incapacitated Crew Rescue | 5 | 2 |
| **Human/Robotic Work-Aids** | • NA | • Assistants  
• Common Tool Set | • Decrease EVA overhead time/effort  
• Increase crew task efficiency  
• Increase safety | • Communications  
• Human/robotic interfaces | 2 | 6-8 |

*TLR stands for Technology Readiness Level.*
Quantitative measures will be established in the future from the results of early trade studies and requirements development. However, the following will be the high-level goals of this sub-capability:

- Major reduction in tool complement supporting EVA
- Decrease weight and volume minimizing vehicle logistical penalty
- Increased commonality among Constellation vehicles
- Increased maintainability
- Lower metabolic expenditures from physical tasks
- Increased EVA efficiency (EVA work duration)
  - High Work Efficiency Index
- Increased productivity with assistance from human-interactive robotic assistants
- Maximize commonality across all Constellation vehicles
Airlocks/Pressurized Volumes

- An airlock is the system that permits an EVA crewmember to go from a pressurized space craft environment to a uninhabitable external environment
  - Hard vacuum, low pressure, toxic atmospheres
  - Microgravity, reduced gravity
- Microgravity assembly and servicing systems (non-anthropomorphic work volumes) are potential extensions of more traditional EVA, allowing use of both suit-type arms and integral robotics while maintaining the operator in a comfortable shirtsleeve environment.
- Pressurized rovers will provide a shirtsleeve habitat on a mobility platform to allow multi-day exploration sorties for the moon and Mars. The rover will also support repeated EVA operations during each sortie.
- Mobile habitats, although the design responsibility of other agency experts, enable the development of advanced infrastructure while visiting multiple science exploration sites. Habitat elements will autonomously navigate across the planetary surface between human missions, allowing reuse of surface systems at multiple locations. Interface definition will be provided by Advanced EVA discipline.
Benefits of the Airlocks/Pressurized Volumes

- Airlocks provide external access without additional operational demands on pressurized cabins to tolerate routine depressurization cycles.
- Airlocks provide separable constrained volumes to deal with dust mitigation and other contamination issues from planetary surfaces.
- Shirtsleeve microgravity assembly and servicing systems may enable extended operations in environments beyond low earth orbit, mitigating radiation and micrometeorite issues with deep space operations.
- Pressurized rovers and mobile habitats will enable extended human exploration on planetary surfaces, taking advantage of extended stay times to expand range of exploration activities.
Current State-of-the-Art for Airlocks/Pressurized Volumes

- Current airlock designs waste atmosphere and are not compatible with dust/biologic isolation.
- Dust contamination will be a significant issue on the surface of both the Moon and Mars. Dust mitigation and control must be considered in the design of planetary vehicles and EVA suit systems so that dust particles are not brought into the breathing volume. Along with dust-repelling suit technology advancements, habitat and vehicle design play a key role in preventing dust from entering the habitable volume.
- Other pressurized systems (atmospheric assembly and maintenance systems, pressurized rovers, mobile habitats) are at early TRL levels and need focused development support.
## Pressurized Volumes/Airlocks Roadmap

<table>
<thead>
<tr>
<th>Sub-Capability</th>
<th>Pressurized Volumes/Airlocks</th>
<th>Lunar Surface Suit Requirements</th>
<th>Lunar Lander Airlock</th>
<th>Field Servicing Systems</th>
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<tbody>
<tr>
<td>Airlocks</td>
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<tr>
<td>Pressurized Rovers (EVA Interfaces)</td>
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<td>Field Servicing Systems</td>
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<tr>
<td>Spiral 1: Crew Exploration Vehicle</td>
<td>SRR ▲</td>
<td>SDR ▲</td>
<td>PDR ▲</td>
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<td>Spiral 5: Mars Surface</td>
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<td>Mars Science Lab</td>
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</tbody>
</table>

### Milestone Colors
- **▲** indicate milestones.
- **CDR** stands for Critical Design Review.
- **PDR** stands for Preliminary Design Review.
- **SRR** stands for System Requirements Review.
- **SDR** stands for System Design Review.

### Where Airlocks Required?
- CEV, Landers, Hab, Rovers, Safe Havens

### Alternate A/L Studies
- Lunar Surface Suit Requirements
- Airlock Architecture Strategy Development (Constellation)

### Airlock Requirements
- Lunar Lander Airlock
- System Integration with Lander

### Rover Architecture Strategy
- Rover Commonality Study (Constellation)
- Field Servicing System Interface Established

### Unpressurized Rover Requirements Established?
- Tool Stowage Requirements

### First Lunar Lander Flight
- CEV Airlock Delivery (TBR)

### NOTE:
- Milestone colors correspond to spiral color bars above.
## Pressurized Volumes/Airlocks Roadmap

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</tbody>
</table>

### Airlocks

- Habitat Airlock
  - System Integration with Habitat PDR CDR
  - Airlock Delivery
- Mars Habitat Airlock
  - System Integration with Lander PDR CDR
  - Airlock Delivery
- Lunar Habitat Launch?

### Pressurized Rovers

- Rover Airlock
  - System Integration with Rover PDR CDR
  - Airlock Delivery
- Mars Rover Airlock
  - System Integration with Lander PDR CDR
  - Airlock Delivery
- EVA Task Requirements

### Field Servicing Systems

- EVA way station (extend EVA walk-back) SRR PDR CDR
  - Delivery
- Mars Servicing System (extend EVA walk-back) SRR PDR CDR
  - Delivery
- Unpressurized Rover Requirements

**NOTE:** Milestone colors correspond to spiral color bars above.
Advanced EVA Systems Capabilities (CRL 1:5)

Suits (CRL 1:5)
- Pressure Garments (TRL 2 to 6)
- Ventilation System (TRL 1 to 9)
- Thermal System (TRL 1 to 9)
- Power System (TRL 3 to 4)
- Communication and Informatics (TRL 2 to 5)
- Environmental Protection (TRL 1 to 8)
- Vehicle Interfaces (TRL 2 to 5)
- Self rescue (TRL 4 to 9)

EVA Tools and Mobility Aids (CRL 1:5)
- In-space EVA Tools (TRL 3 to 7)
- EVA Surface Tools (TRL 1 to 9)
- Human-Robotic Work-aids (TRL 2 to 5)

Airlocks/Pressurized Volumes (CRL 1:5)
- Airlocks (TRL 2 to 5)
- Pressurized Rovers (TRL 2 to 3)
- Field Servicing System (TRL 2 to 4)

Ground Support Systems (GSS) (CRL 1:5)
- Test Facilities (TRL 3 to 9)
- Trainers and Simulators (TRL 3 to 9)
- Ground Processing Facilities (TRL 3 to 9)

*CRL shown is in terms of the starting/ending level (to TRL 6). TRL shown is the range covered in that technology area.*
## Technology Maturity Level – Airlocks/Pressurized Volumes

### Roadmap Sub-Capability

<table>
<thead>
<tr>
<th>Roadmap Sub-Capability</th>
<th>Current Capabilities</th>
<th>Capability Required</th>
<th>Sub-Capability Development Needs</th>
<th>Technology Area/Candidates</th>
<th>TRL</th>
<th>Time to TRL = 6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Airlock</strong></td>
<td>• Shuttle Airlock</td>
<td>• Ingress/Egress</td>
<td>• Minimum consumable use (air and power)</td>
<td>• Lightweight Structure</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>• Space Station</td>
<td></td>
<td>• Time efficiency</td>
<td>• Inflatable</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Joint Airlock</td>
<td>• Suit Supportability</td>
<td>• Dust Tolerance</td>
<td>• Minimum Volume (Clamshell, suit ports)</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>• Russian Space</td>
<td></td>
<td>• Rapid Consumable Re-supply</td>
<td>• Environmental Protection (e.g. Dust Mitigation)</td>
<td>2</td>
<td>8</td>
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<tr>
<td></td>
<td>Station Airlock (DC-1)</td>
<td></td>
<td>• Low Mass</td>
<td>• Hatch Mechanisms</td>
<td>5</td>
<td>2</td>
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<tr>
<td></td>
<td>• Skylab Airlock</td>
<td></td>
<td></td>
<td>• Rapid Suit Checkout &amp; Recharge</td>
<td>3</td>
<td>6</td>
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<table>
<thead>
<tr>
<th><strong>Pressurized Rovers (EVA Interface)</strong></th>
<th>Capability Required</th>
<th>Sub-Capability Development Needs</th>
<th>Technology Area/Candidates</th>
<th>TRL</th>
<th>Time to TRL = 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Lunar Rover</td>
<td>• Airlock</td>
<td>• See airlocks</td>
<td>• See airlocks</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>• Suit Supportability</td>
<td></td>
<td>• EVA Suit/rover consumable commonality</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>• Tool Stowage</td>
<td></td>
<td>• Simple external maintenance</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>• Commonality</td>
<td></td>
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<tr>
<td></td>
<td>• EVA Maintainable</td>
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</tbody>
</table>

| **EVA Field Service Stations**         | • NA                | • Service Stations              | • Rapid Recharge            | • Life Support Commonality | 2   | 8               |
|                                        |                     | • Safe havens                   | (lightweight)               | • Communications           | 4   | 4               |
|                                        |                     |                                 |                               | • Suit Checkout and Recharge | 2   | 8               |
|                                        |                     |                                 |                               | • Environmental protection |     |                 |
Quantitative measures will be established in the future from the results of early trade studies and requirements development. However, the following will be the high-level goals of this sub-capability:

- Decrease consumable use
- Decrease consumable recharge time
- Maximize dust/contamination control
- Decrease weight and volume minimizing vehicle logistical penalty
- Increased maintainability
- Maximize commonality across all Constellation vehicles
The EVA Ground Support System includes the necessary facilities and associated infrastructure to support EVA-related testing, technology development and flight program simulations and EVA system ground processing.

Ground Support Systems include:

- Component and integrated system test facilities
- Ground facilities for processing training and flight hardware
- Analogs and trainers for planetary environments for testing suit components, subsystem and integrated systems in relevant environments, proving operational concepts and conducting training.
  - Dust
  - Radiation
  - Micrometeorite
  - Biochemical
  - Pressure
  - Terrain
  - Vacuum
  - Low-gravity
  - Virtual reality
Benefits of the EVA Ground Support System

- EVA Ground Support Systems decrease technical and safety risk of human exploration by testing candidate technologies in applicable environments to validate system safety and reliability.

- EVA Ground Support Systems decrease cost risk by supporting testing of competing technologies for cost-benefit evaluation.

- EVA Ground Support Systems decrease schedule risk by providing testing of high value/high risk technologies while allowing testing of lower risk off-ramp technologies.
Because EVA testing, training, execution and ground-processing functions for previous EVA programs have been primarily run out of the Johnson Space Center, the following chart lists JSC facilities that could support Advanced EVA Systems if an upgrade plan is implemented.

- A detailed survey of laboratory capability across NASA centers, industry, and academia should be performed to create a baseline of all capability in existence at presence.
- Testing requirements for components, subsystems and integrated system testing should be performed.
- A gap analysis should be performed to identify gaps between existing capability and test requirements.
- Facility upgrades should be developed to fill capability gaps.
Current State-of-the-Art for EVA Ground Support System

• JSC facilities that could support the Advanced EVA subsystem testing if an upgrade plan is implemented:

Advanced Extravehicular Development Laboratory
  • The Advanced EVA Development Lab is a “hands on” lab for development, fabrication, and test of proof of concept and new technology space suit components and mobility systems. The lab supports ground based (sea level) manned dedicated testing as well as unmanned life cycle, mobility, and torque range testing of suit components.

Advanced Portable Life Support System (PLSS) Lab
  • The Advanced PLSS lab consists of the Ventilation Benchtop laboratory and the Thermal Loop benchtop laboratory that support the Advanced Technology Spacesuit activities. The Ventilation Benchtop is a laboratory setup to help define, try out, and design the ventilation module of the Advanced Technology Spacesuit. The Thermal Loop benchtop is a laboratory setup to test and verify the thermal loop systems for the Advanced Technology Spacesuit project.

Sonny Carter Training Facility (SCTF)/Neutral Buoyancy Laboratory (NBL)
  • The Sonny Carter Training Facility provides controlled neutral buoyancy operations to simulate zero-g or weightless condition that is experienced by spacecraft and crew during space flight. It is an essential tool for the design, testing and development of the International Space Station and future NASA space programs.

Planetary Surface Simulated Field Test Site
  • A JSC facility that provides a realistic 1-acre test site representative of a Mars-like strewn rock field and cap-rock hill structure to conduct a series of engineering evaluations and functionality testing of advanced space suit system mobility test activities, prototype rover vehicle driving dynamic and human-interface ergonomic studies, human/robot interactive task development activities, and advanced communications voice, video and data transmission to JSC mission control “remote science team” members. This facility enables the integrated testing of various advanced technology hardware systems that are being developed for future planetary exploration in a realistic (out-of-the-lab) terrestrial analog setting and representative of extraterrestrial surface conditions.

Reduced Gravity Aircraft
  • In order to investigate human and hardware reactions to operating in a weightless/reduced gravity environment, a reduced gravity environment is obtained with a specially modified C-9 aircraft, which flies parabolic arcs to produce weightless periods of 20 to 25 seconds. The C-9 can also provide short periods of lunar (1/6) and Martian (1/3) gravity. Approximately 80,000 parabolas have been flown in support of the Mercury, Gemini, Apollo, Skylab, Space Shuttle, and Space Station programs.

Partial-Gravity Counterbalance System (PGCS) Laboratory
  • A CTSD facility located at JSC (Bldg 29) that provides for the simulation of a Lunar or Mars gravity environment for conducting a wide variety of both shirtsleeve and spacesuit isolated joint mobility, system walking dynamics studies as well as engineering assessment evaluations of advanced space suit and portable life support system elements. The facility contains a treadmill that is used to conduct engineering evaluation and assessment of various planetary surface flexible boot designs while under a variety of simulated walking conditions and reduced gravity conditions. Simulants representative of Lunar and Mars surface materials are also available for introducing more realistic surface conditions for space suit and boot material abrasion resistance and dust abatement studies.

Human-Rated Thermal Vacuum Chambers
  • The six Altitude Chambers, two Thermal-Vacuum Chambers and necessary Test Support systems are utilized primarily for development, certification and parametric testing of life support systems for man in the hostile environments of space. Each of the Altitude Chambers is configured for a particular type of testing. However, within the chamber’s capabilities, each chamber complex may be used to perform other types of tests.

  Chamber V Thermal-Vacuum
    • Chamber V is a high vacuum system consisting of a mechanical pump and oil diffusion pump. The test section is accessible through a removable bell jar. The system is configured with a guarded hot plate thermal conductance measuring system for determining the thermal performance of insulations and other materials of relatively low thermal conductance.

Building 32 Chambers
  • The facility provides full scale testing of large systems and human testing/training in a high fidelity simulated space environment. In addition to the chambers, a high bay area supports test article buildup and preparation for installation into the chambers.
<table>
<thead>
<tr>
<th>Sub-Capability Ground Support System</th>
<th>AEVA Project Plan</th>
<th>AEVA Systems In-space Requirements</th>
<th>AEVA Systems Lunar Requirements</th>
<th>AEVA Systems Lunar Requirements</th>
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<tbody>
<tr>
<td>Test Facilities</td>
<td>Facility Survey</td>
<td>Facility Upgrades</td>
<td>Facility Survey</td>
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<tr>
<td>Trainers/Simulators</td>
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<td>Ground Processing Facilities</td>
<td>Facility Survey</td>
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**Mars Science Lab**
Ground Support System Roadmap

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Sub-Capability

Ground Support System

Pressurized Rover Launch?

AEVA Systems Mars Requirements

Mars Habitat Launch?

Mars Lander Launch?

Test Facilities

Facility Survey

Test Requirements

Gap Analysis

Facility Upgrades

Trainers/Simulators

Facility Survey

Test Requirements

Gap Analysis

Facility Upgrades

Ground Processing Facilities

Facility Survey

Test Requirements

Gap Analysis

Facility Upgrades

NOTE: Milestone colors correspond to spiral color bars above
Advanced EVA Systems Capabilities (CRL 1:5)

Suits (CRL 1:5)
- Pressure Garments (TRL 2 → 6)
- Ventilation System (TRL 1 → 9)
- Thermal System (TRL 1 → 9)
- Power System (TRL 3 → 4)
- Communication and Informatics (TRL 2 → 5)
- Environmental Protection (TRL 1 → 8)
- Vehicle Interfaces (TRL 2 → 5)
- Self rescue (TRL 4 → 9)

EVA Tools and Mobility Aids (CRL 1:5)
- In-space EVA Tools (TRL 3 → 7)
- EVA Surface Tools (TRL 1 → 9)
- Human-Robotic Work-aids (TRL 2 → 5)

Airlocks/Pressurized Volumes (CRL 1:5)
- Airlocks (TRL 2 → 5)
- Pressurized Rovers (TRL 2 → 3)
- Field Servicing System (TRL 2 → 4)

Ground Support Systems (GSS) (CRL 1:5)
- Test Facilities (TRL 3 → 9)
- Trainers and Simulators (TRL 3 → 9)
- Ground Processing Facilities (TRL 3 → 9)

*CRL shown is in terms of the starting/ending level (to TRL 6). TRL shown is the range covered in that technology area.
### Technology Maturity Level – EVA Ground Support System

#### Test Facilities
- **Shuttle & Space Station Test Facilities**
  - NBL
  - Systems Integration Lab
  - Simulated Surface Sites
  - 0G Environment
  - Partial Gravity Environment
  - Micrometeorite testing
  - Radiation testing
  - Dust effects testing

<table>
<thead>
<tr>
<th>Roadmap Sub-Capability</th>
<th>Current Capabilities</th>
<th>Capability Required</th>
<th>Sub-Capability Development Needs</th>
<th>Technology Area Candidates</th>
<th>TRL</th>
<th>Time to TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Facilities</td>
<td>• Shuttle &amp; Space Station Test Facilities</td>
<td>• Human Rated Vacuum Chambers</td>
<td>Updates/consolidation required</td>
<td>• Lunar and Martian Simulants</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td></td>
<td></td>
<td>• Systems Integration Lab</td>
<td>Simulated integrated gravity, pressure, dust, radiation, atmosphere, micrometeoroid Martian Environment</td>
<td>• Integrated Lunar and Martian environmental conditions</td>
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<td>NA</td>
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<td>• Simulated Surface Sites</td>
<td>Simulated integrated gravity, dust, radiation, micrometeoroid Lunar Environment</td>
<td>• Software for Simulation Based Acquisition</td>
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<td>• 0G Environment</td>
<td>Emission and leak testing</td>
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<td></td>
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<td>• Partial Gravity Environment</td>
<td>Boot and Glove Sizing</td>
<td>• Boot and Glove Sizing</td>
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<tr>
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<td>• Micrometeorite testing</td>
<td>Advanced Processing for suit components</td>
<td>• Advanced Processing for suit components</td>
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<td>• Radiation testing</td>
<td>Advanced AEVA Life Support lab upgrades</td>
<td>• Advanced AEVA Life Support lab upgrades</td>
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<tr>
<td></td>
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<td>• Dust effects testing</td>
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</tbody>
</table>

#### Training Facilities
- **Shuttle & Space Station Training Facilities**
  - Shuttle & Space Station Training Facilities
  - NBL
  - Systems Integration Lab
  - Simulated Surface Sites
  - 0G Environment
  - Partial Gravity Environment

<table>
<thead>
<tr>
<th>Roadmap Sub-Capability</th>
<th>Current Capabilities</th>
<th>Capability Required</th>
<th>Sub-Capability Development Needs</th>
<th>Technology Area Candidates</th>
<th>TRL</th>
<th>Time to TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training Facilities</td>
<td>• Shuttle &amp; Space Station Training Facilities</td>
<td>• NBL</td>
<td>Updates/consolidation required</td>
<td>• Lunar and Martian Simulants</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Systems Integration Lab</td>
<td>Simulated integrated gravity, pressure, dust, radiation, atmosphere, micrometeoroid Martian Environment</td>
<td>• Integrated Lunar and Martian environmental conditions</td>
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<td>NA</td>
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<tr>
<td></td>
<td></td>
<td>• Simulated Surface Sites</td>
<td>Simulated integrated gravity, dust, radiation, micrometeoroid Lunar Environment</td>
<td>• Software for Simulation Based Acquisition</td>
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<td>NA</td>
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<tr>
<td></td>
<td></td>
<td>• 0G Environment</td>
<td>Emission and leak testing</td>
<td>• Emission and leak testing</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td></td>
<td></td>
<td>• Partial Gravity Environment</td>
<td>Boot and Glove Sizing</td>
<td>• Boot and Glove Sizing</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Micrometeorite testing</td>
<td>Advanced Processing for suit components</td>
<td>• Advanced Processing for suit components</td>
<td>NA</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>• Radiation testing</td>
<td>Advanced AEVA Life Support lab upgrades</td>
<td>• Advanced AEVA Life Support lab upgrades</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Dust effects testing</td>
<td></td>
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</tr>
</tbody>
</table>

#### Ground Processing Facilities
- **Shuttle & Space Station Ground Processing Facilities**
  - Shuttle & Space Station Ground Processing Facilities
  - EVA Systems:
    - • Prep
    - • Storage
    - • Maintain
    - • Test
    - • Troubleshoot

<table>
<thead>
<tr>
<th>Roadmap Sub-Capability</th>
<th>Current Capabilities</th>
<th>Capability Required</th>
<th>Sub-Capability Development Needs</th>
<th>Technology Area Candidates</th>
<th>TRL</th>
<th>Time to TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Processing Facilities</td>
<td>• Shuttle &amp; Space Station Ground Processing Facilities</td>
<td>• EVA Systems:</td>
<td>Updates/consolidation required</td>
<td>• Crew escape and EVA Integrated processing facility</td>
<td>3</td>
<td>NA</td>
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<tr>
<td></td>
<td></td>
<td>• Prep</td>
<td>• Needs Analysis</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>• Storage</td>
<td>• Gap Analysis</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>• Maintain</td>
<td>• Facility Upgrades</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>• Test</td>
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</tbody>
</table>
Quantitative measures will be established in the future from the results of early requirements development. However, the following will be the high-level goals of this sub-capability area:

- Maximize reliability
- Maximize maintainability
- Maximize safety
- Maximize operational life time
- Maximize evolvability
Key technical challenges:

- Major challenges in meeting required technologies/capabilities
  - Exploration Concept of Operations and Architecture
    - Number of crew
    - Vehicle configurations
    - EVA operational requirements
  - Vehicle pressure versus suit pressure
    - Suit operating pressure
    - EVA prebreathe time
  - Anthropometric size range
  - Integration with other Constellation systems

- Alternatives or off ramps
  - Number of suits to support spirals is a major decision point that drives the rest of the roadmap
EVA Critical Capabilities for Exploration

- Highly-integrated human-centric EVA suits for in-space operations and planetary surface operations
- Task efficient EVA tools and equipment
- Safe and effective EVA translation and mobility aids
- Human-interactive robotic assistants and human-centric rover vehicles interfaces
- Standard EVA sub-system interfaces
- Functionally efficient airlocks
- Ground support systems that effectively produce, test, train and maintain EVA systems
Back Up
The Bioastronautics Roadmap guides the prioritized research and technology development that, coupled with operational space medicine, will inform:

- the development of medical standards and policies;
- the specification of requirements for the human system;
- the implementation of medical operations.

The Roadmap provides information that helps:

- establish tolerances (i.e. operating bands or exposure limits) for humans exposed to the effects of space travel and develop countermeasures to maintain crew health and function within those limits; and
- develop technologies that make human space flight safe and productive.
<table>
<thead>
<tr>
<th>High Energy Power &amp; Propulsion</th>
<th>Human Health &amp; Support Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-Topic or Subsidiary Capability</td>
<td>Capability Flow &amp; Criticality</td>
</tr>
<tr>
<td>Nuclear Propulsion</td>
<td>Human Health Performance</td>
</tr>
<tr>
<td></td>
<td>Reqmts for vehicle/ nuclear power separation is also beneficial for artificial gravity</td>
</tr>
<tr>
<td>Nuclear Propulsion</td>
<td>Human Health Countermeasures/ Radiation Protection</td>
</tr>
<tr>
<td>Nuclear Propulsion</td>
<td>EVA</td>
</tr>
<tr>
<td>Power</td>
<td>Human Support Systems</td>
</tr>
</tbody>
</table>

**Red** - Critical

**Blue** - Moderate
<table>
<thead>
<tr>
<th>In-Space transportation</th>
<th>Human Health &amp; Support Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-Topic or Sub-sub-topic</td>
<td>Sub-Topic or Sub-sub-topic</td>
</tr>
<tr>
<td>All of In-space transportation</td>
<td>Life Support/ Human Health &amp; Performance/ EVA</td>
</tr>
</tbody>
</table>

*Red - Critical
Blue - Moderate*
<table>
<thead>
<tr>
<th>Sub-Topic or Subsidiary Capability</th>
<th>Sub-Topic or Subsidiary Capability</th>
<th>Sub-Topic or Subsidiary Capability</th>
<th>Nature of Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>EVA</td>
<td>Mission timing- Humans required to deploy? - concept of ops/ design compatibility contamination structural loads</td>
<td></td>
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<tr>
<td>All</td>
<td>Advanced Life Support</td>
<td>contamination</td>
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Red - Critical
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<tbody>
<tr>
<td>Sub-Topic or Subsidiary Capability</td>
<td>Sub-Topic or Subsidiary Capability</td>
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<tr>
<td>All</td>
<td>Human Health/Radiation</td>
<td>Direct access to space weather systems for Mars</td>
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<tr>
<td>All</td>
<td>Human Health/Artificial Gravity</td>
<td>Antennae design &amp; location</td>
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<tr>
<td>All</td>
<td>Human Health</td>
<td>Secure comm/ private conference/ psych consults Embedded human performance measures Bandwidth</td>
<td></td>
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<tr>
<td>EVA</td>
<td></td>
<td>Surface navigation/ information display Communication within &amp; between EVA/ vehicle/ rover/ base</td>
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Red - Critical
Blue - Moderate
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<tbody>
<tr>
<td>Sub-Topic or Subsidiary Capability</td>
<td>Sub-Topic or Subsidiary Capability</td>
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<tr>
<td>Entry, Descent, and Landing/Observations</td>
<td></td>
<td>Human Health/Radiation</td>
<td>Rqmts for radiation definition on moon &amp; Mars</td>
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<tr>
<td>Entry, Descent, and Landing/Observations</td>
<td>Human Support</td>
<td>Human Support</td>
<td>Rqmts for site characterization</td>
</tr>
<tr>
<td>Entry, Descent, and Landing/Observations</td>
<td>Human Health/Life Support/EVA</td>
<td>Human Health/Life Support/EVA</td>
<td>environment characterization (dust, toxicity, radiation, etc.)</td>
</tr>
</tbody>
</table>

Red - Critical
Blue - Moderate
<table>
<thead>
<tr>
<th>Human planetary landing systems</th>
<th>Capability Flow and Criticality</th>
<th>Human Health &amp; Support Systems</th>
<th>Nature of Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-Topic or Subsidiary Capability</td>
<td>Sub-Topic or Subsidiary Capability</td>
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</tr>
<tr>
<td>All</td>
<td>Habitation</td>
<td>Architecture - integrated habitat? / Precision landing/pressure</td>
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<tr>
<td>All</td>
<td>Human Health</td>
<td>Human performance - g-load</td>
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<tr>
<td></td>
<td>EVA</td>
<td>Routine access to planetary surface</td>
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</table>

Red - Critical
Blue - Moderate
## Human Exploration Systems & Mobility

<table>
<thead>
<tr>
<th>Sub-Topic or Subsidiary Capability</th>
<th>Capability Flow and Criticality</th>
<th>Human Health &amp; Support Systems</th>
<th>Nature of Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rovers, in-space systems</td>
<td>Human Health/Space Human Factors/EVA</td>
<td>Habitat</td>
<td>Rover interface</td>
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<tr>
<td>Rovers</td>
<td></td>
<td>Human Health/Radiation Reqmts</td>
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Red - Critical
Blue - Moderate
<table>
<thead>
<tr>
<th>Sub-Topic or Subsidiary Capability</th>
<th>Sub-Topic or Subsidiary Capability</th>
<th>Nature of Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human-Machine Interaction</td>
<td>Human Health/EVA</td>
<td>Robotic interface</td>
</tr>
<tr>
<td></td>
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<td>Application versus</td>
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<tr>
<td></td>
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<td>task functional</td>
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<td></td>
<td></td>
<td>allocation</td>
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<tr>
<td></td>
<td></td>
<td>Robotic assistance for</td>
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<tr>
<td></td>
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<td>medical care?</td>
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</tbody>
</table>

Red - Critical
Blue - Moderate
<table>
<thead>
<tr>
<th>Scientific instruments and sensors</th>
<th>Capability Flow and Criticality</th>
<th>Human Health &amp; Support Systems</th>
<th>Nature of Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-Topic or Subsidiary Capability</td>
<td>Sub-Topic or Subsidiary Capability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Sample Acquisition &amp; Analysis</td>
<td>Human Support</td>
<td>Site selection reqmts</td>
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</table>

Red - Critical
Blue - Moderate
<table>
<thead>
<tr>
<th>In situ resource utilization</th>
<th>Capability Flow and Criticality</th>
<th>Human Health &amp; Support Systems</th>
<th>Nature of Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-Topic or Subsidiary Capability</td>
<td>Sub-Topic or Subsidiary Capability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>Human Support</td>
<td>reqmts for composition, quality, quantity</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>EVA</td>
<td>tools and functional reqmts</td>
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<tr>
<td>All</td>
<td>Radiation</td>
<td>potential shielding</td>
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</tr>
<tr>
<td>All</td>
<td>Life Support</td>
<td>Water, oxygen production</td>
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</table>

Red - Critical
Blue - Moderate
<table>
<thead>
<tr>
<th>Advanced modeling, simulation, analysis</th>
<th>Capability Flow and Criticality</th>
<th>Human Health &amp; Support Systems</th>
<th>Nature of Relationship</th>
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</thead>
<tbody>
<tr>
<td>Systems engineering cost/risk analysis</td>
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<td></td>
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</tr>
<tr>
<td>Nanotechnology/advanced technology concepts</td>
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<tr>
<td>Transformation Spaceport/Range</td>
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<td>Sub-Topic or Subsidiary Capability</td>
<td>Sub-Topic or Subsidiary Capability</td>
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</tr>
<tr>
<td>All</td>
<td>Unknown</td>
<td>All</td>
<td>Unknown</td>
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</tbody>
</table>

Red - Critical  
Blue - Moderate
The Capability is defined in written form. The uses and/or applications of the Capability are described and an initial Proof-of-Concept analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.
2 Sub-Capabilities* Demonstrated in a Laboratory Environment

Proof-of-Concept analyses of the Sub-capabilities are performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.
Sub-Capabilities* Demonstrated in a Relevant Environment

Sub-capabilities are demonstrated with realistic supporting elements to simulate an operationally relevant environment to the Capability.
- of appropriate scale
- functionally equivalent flight articles
- major system interactions and interfaces identified
Integrated Capability Demonstrated in a Laboratory Environment

A representative model or prototype of the integrated Capability is tested in an ambient laboratory environment. Performance of the constituent Sub-capabilities is observed in addition to the Capability as an integrated system. Analytical modeling of the integrated Capability is performed.
An integrated prototype of the Capability is demonstrated with realistic supporting elements to simulate an operationally relevant environment to the Capability.

- of appropriate scale
- functionally equivalent flight articles
- all system interactions and interfaces identified
Capability Readiness Level 6

6 Integrated Capability Demonstrated in an Operational Environment

The Capability is near or at the completed system stage. The integrated Capability is demonstrated in an operational environment with the intended user organization(s).
- full scale flight articles
- demonstrated in the intended operational ‘envelope’
The Capability has been proven to work in its final form under expected operational condition. This level represents the application of the Capability in its operational configuration and under “mission” conditions.
-heritage? (multiple missions…?)