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

Government	Industry	Academia
J. Charles, JSC	B. Harris	J. Becker, NSBRI
R. Carrasquillo, MSFC	R. Poisson, Ham.Sunstrand	D. Akins, Univ. Maryland
G. Jahns, ARC		R. Schlegel, Univ. Oklahoma
G. Lutz, JSC		

NASA Technical Leads

D. Barta, JSC
K. Knotts, JSC

Other/Independent

G. Miller, Lockheed Martin

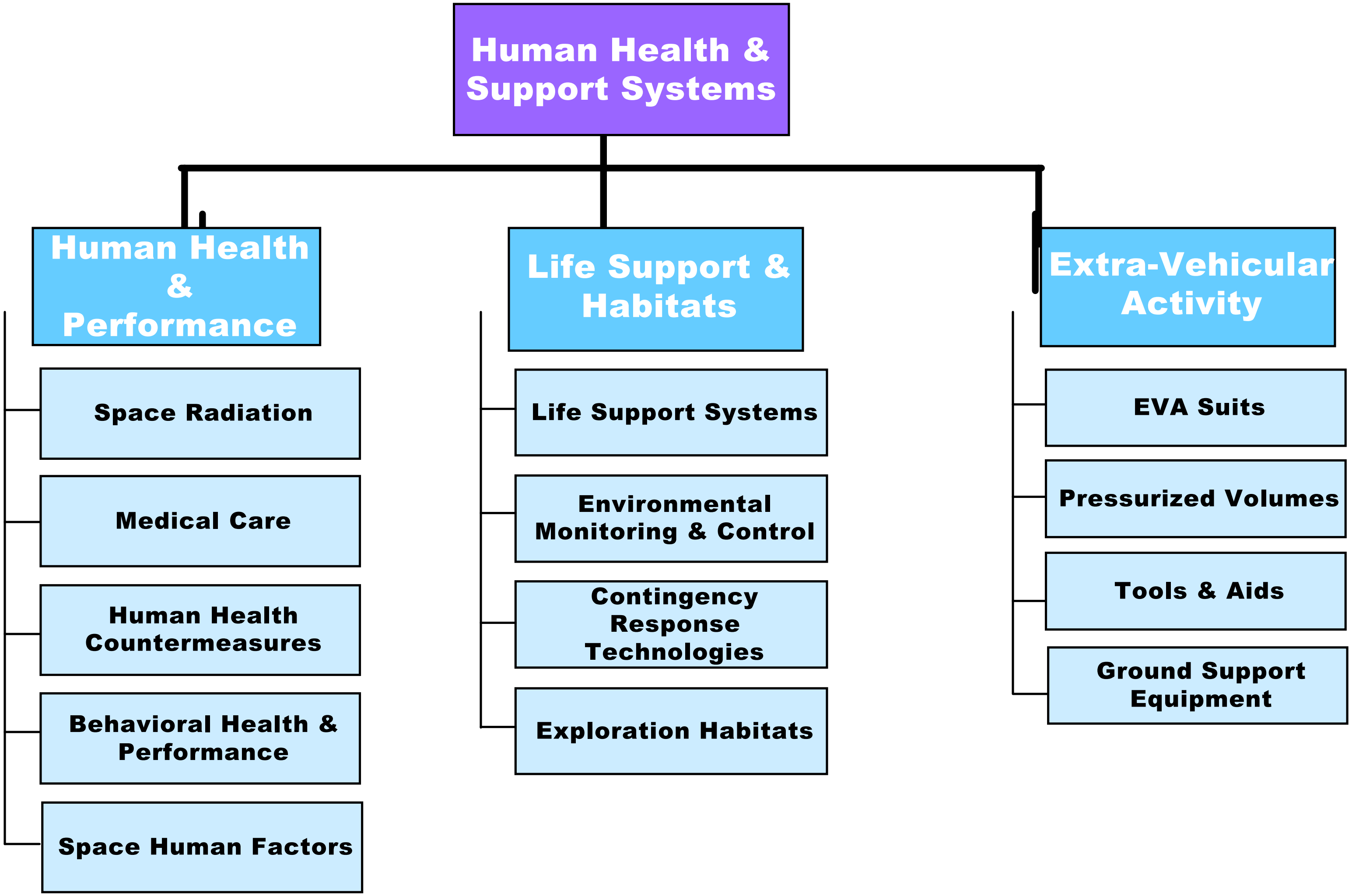
Coordinators

Directorate: E. Trinh, HQ ESMD; D. Craig, HQ ESMD
APIO: J. Aikins, JPL

Capability Description

- **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**

Capability Breakdown Structure



Benefits of the Human Health & Support Systems CRM

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- 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

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- 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

Capability Readiness Levels

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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.

7. Capability Operational Readiness
6. Integrated Capability Demonstrated in an Operational Environment
5. Integrated Capability Demonstrated in a Relevant Environment
4. Integrated Capability Demonstrated in a Laboratory Environment
3. Sub-Capabilities* Demonstrated in a Relevant Environment
2. Sub-Capabilities* Demonstrated in a Laboratory Environment
1. Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

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

Technology Readiness Levels/ Countermeasure Readiness Levels

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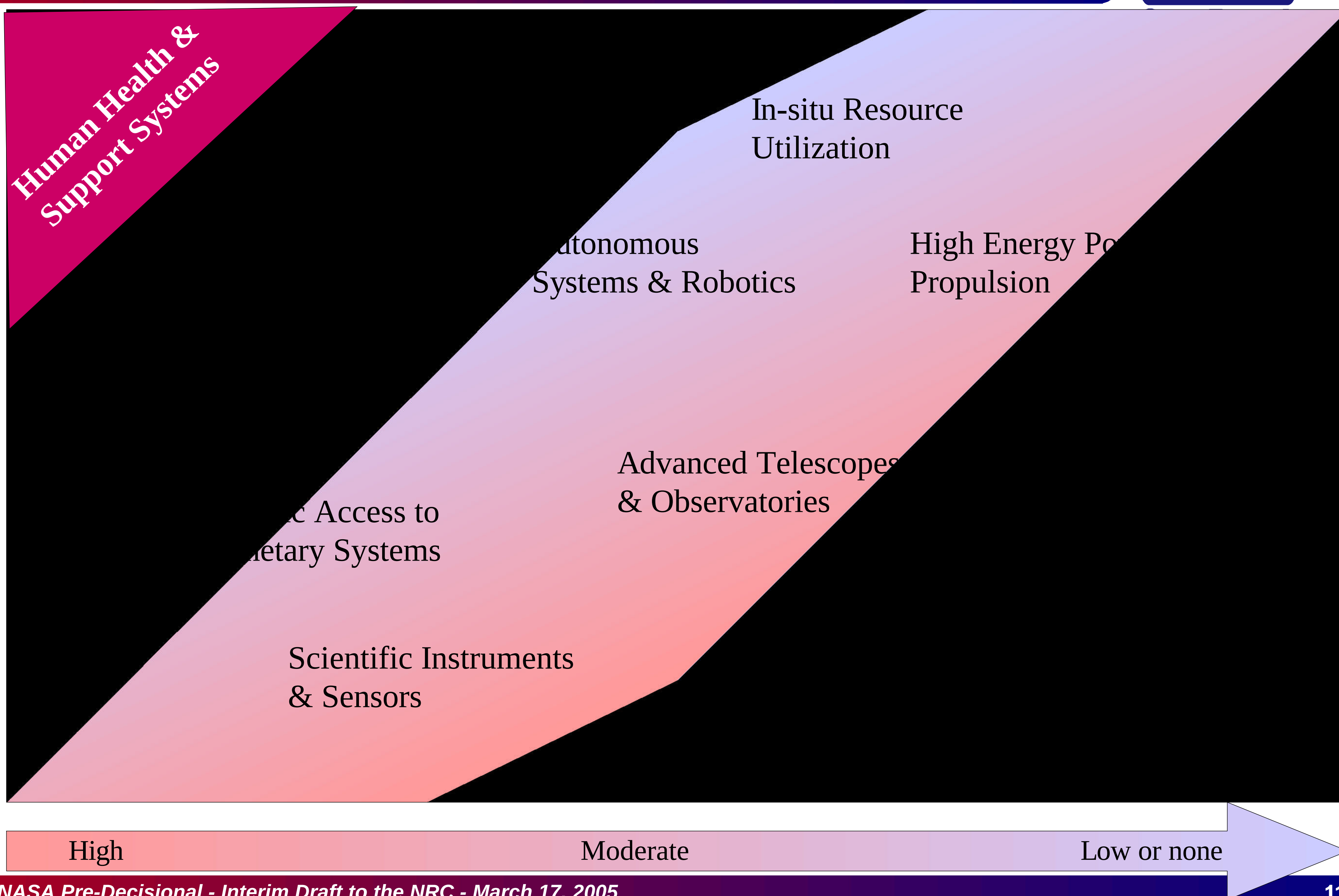
<table>
<tr><th>TRL Definition</th><th>TRL/CMRL Score</th><th>CMRL Definition</th><th colspan="2">CMRL category</th></tr>
<tr><td>Basic principles observed</td><td>1</td><td>Phenomenon observed and reported. Problem defined.</td><td rowspan="3">Basic research</td><td rowspan="2"></td></tr>
<tr><td>Technology concept and/or application formulated</td><td>2</td><td>Hypothesis formed; preliminary studies to define parameters. Demonstrate feasibility.</td></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 rowspan="3">Research to prove feasibility</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 rowspan="4">Countermeasure development</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></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 rowspan="2">Countermeasure demonstration</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 colspan="2">Countermeasure operations</td></tr>
</table>

Roadmap Connections/Dependencies



Mars Missions Decisions Related to Human Health & Support Systems

	Mission Factors	Human Health	Life Support	Habitats	EVA
Mission Design	Transit time	Critical	Critical		
	*Planetary stay	Critical	Critical	Critical	Moderate
	Precursor Robotic Missions	Critical	Critical	Critical	Critical
Objectives	*Location - single outpost/base/ alternate outposts?	Moderate	Critical	Critical	Critical
	*Surface Mobility/Range	Moderate	Moderate	Moderate	Critical
	*ISRU	Moderate	Critical	Critical	Critical
Key Program Decisions	*Crew Size	Critical	Critical	Critical	
	Artificial Gravity	Critical	Critical	Critical	
	Aerocapture	Moderate			
	*Robotic Assistants				Critical
	Lunar Missions as a testbed	Critical	Critical	Critical	Critical
	*ISS as a testbed	Critical	Moderate		

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[Critical symbol] = Critical   [Moderate symbol] = Moderate

Human Health & Performance

Presenter:

Dennis Grounds

Human Health & Performance

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- 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

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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 Physio-logical 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

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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

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- **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.**

2005	2014	2017	2025	2030
	1st Crewed CEV	1st Human Lunar (extended)	1st Human Lunar (long)	1st Human Mars

Space Radiation

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Human Health & Performance

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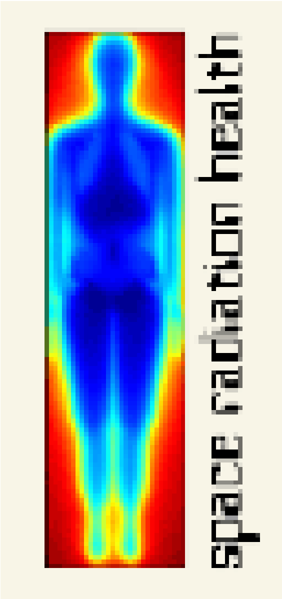
Space Radiation

Definition

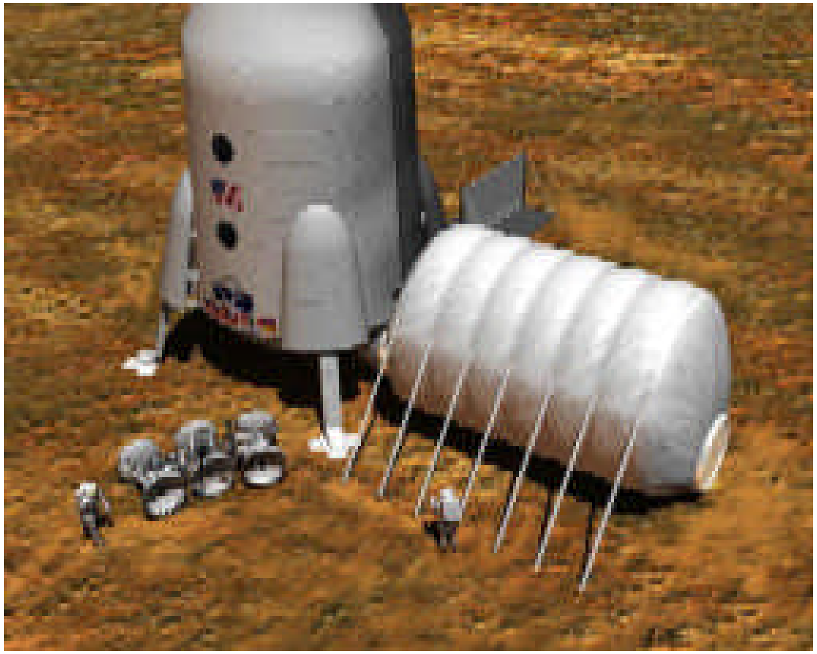
- Space Radiation addresses the risks to human exploration from exposure to space radiation, including ionizing radiation, solar particle events (SPE) and galactic cosmic rays.
  - Possible health risks include cancer, damage to the central nervous system, degenerative tissue disease (cataracts, heart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



Space Radiation

Benefits

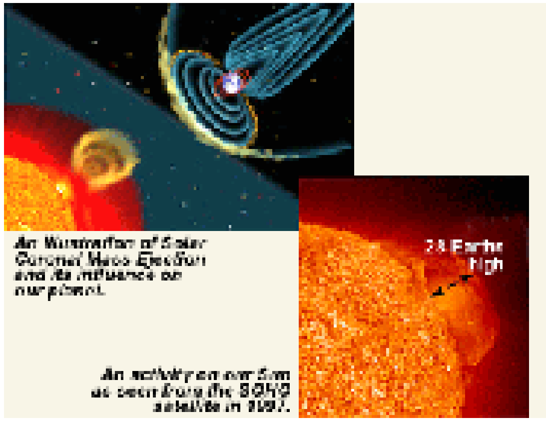
- Assure that we can safely live and work in the space radiation environment, anywhere, any time.
- Assure astronauts return to Earth safely, and continue to maintain an acceptable quality of life.



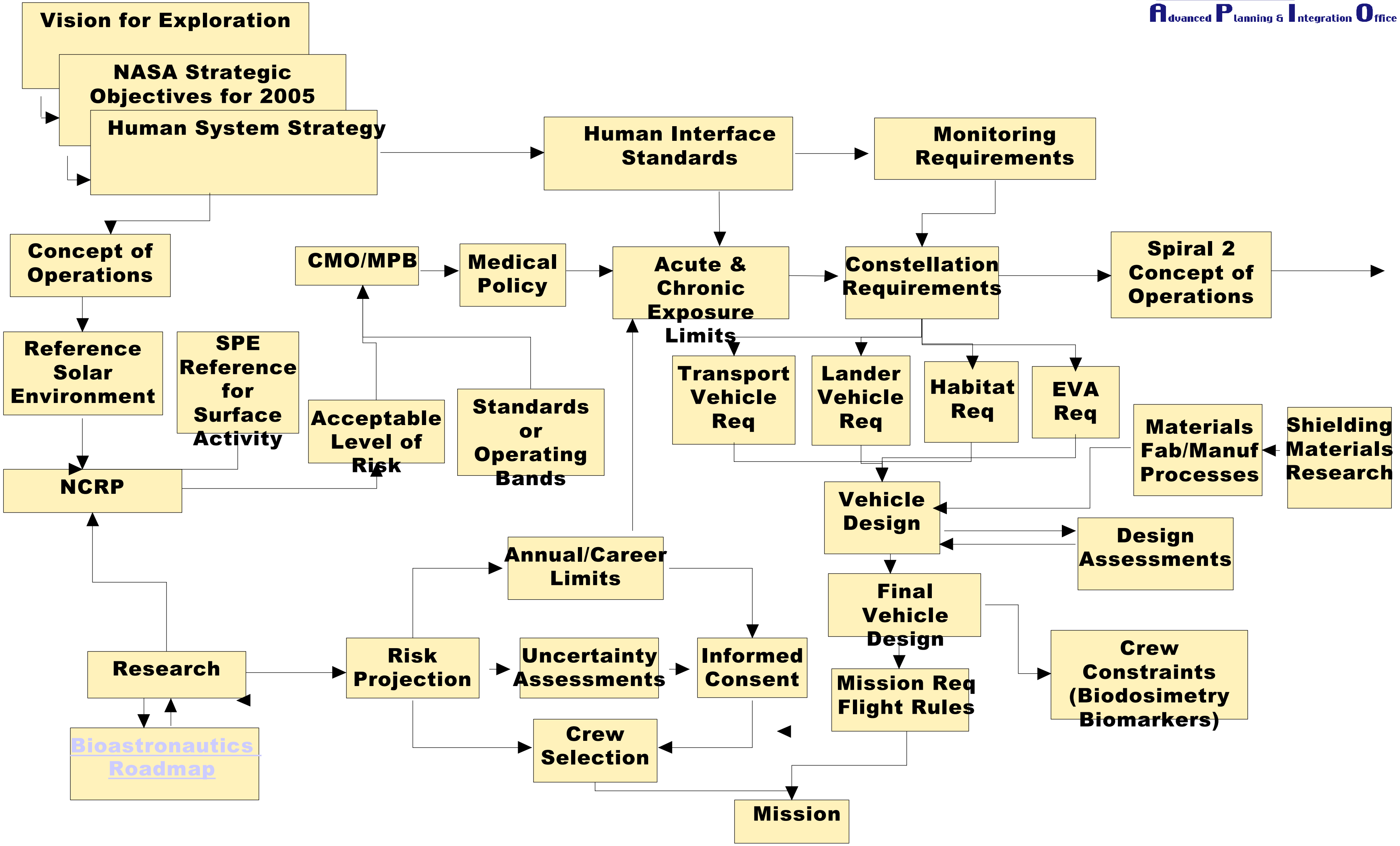
Current State-of-the-Art for Space Radiation

State of the Art

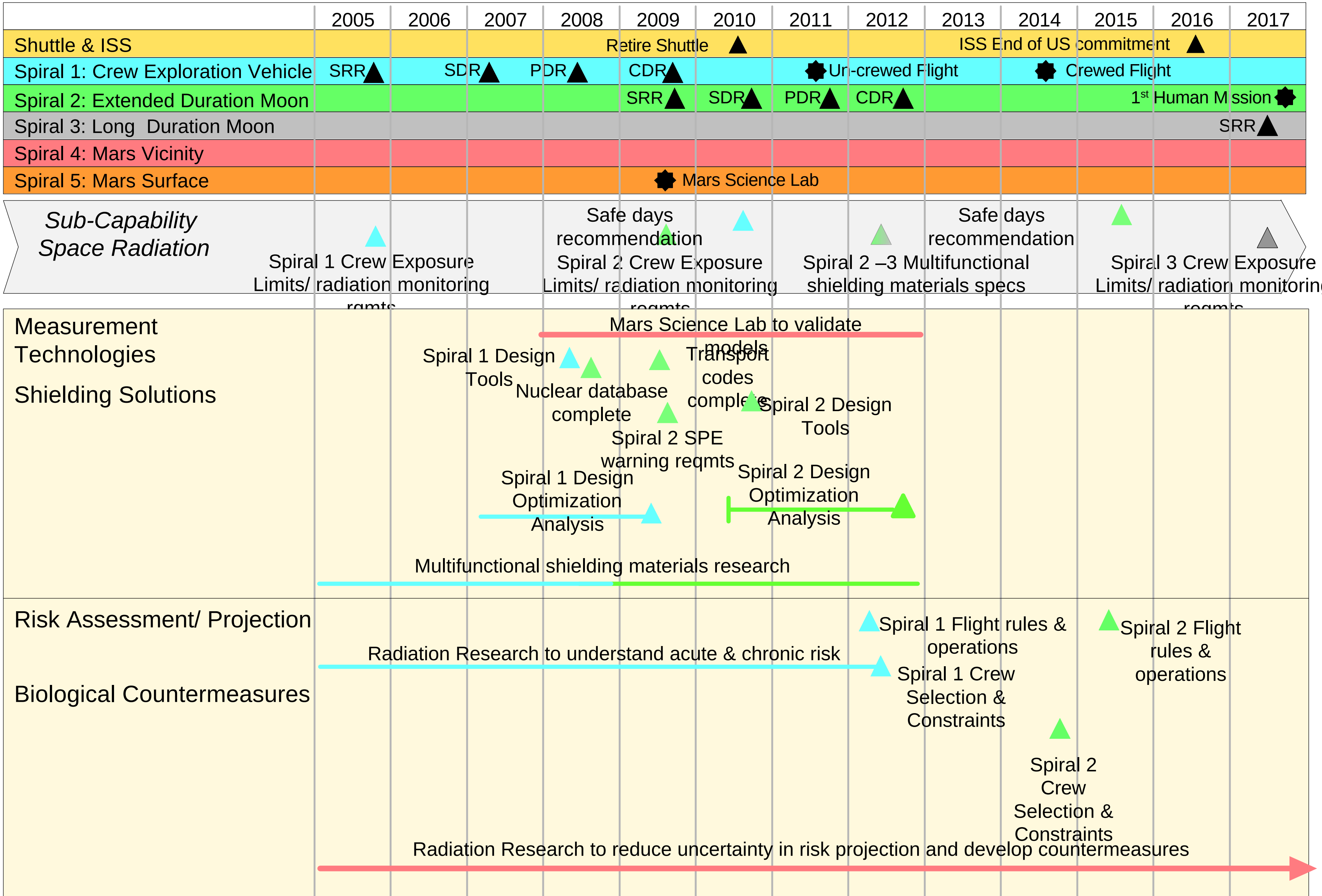
- **Shuttle and ISS shielding**
  - Not inherently part of the vehicle design; some components added late in development
- **Shuttle and ISS monitoring**
  - Equipment no longer reliable
  - Lack system integration
  - Require extensive ground analysis
  - SPE early warning uses NOAA space weather satellites 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**



Requirements /Assumptions for Space Radiation

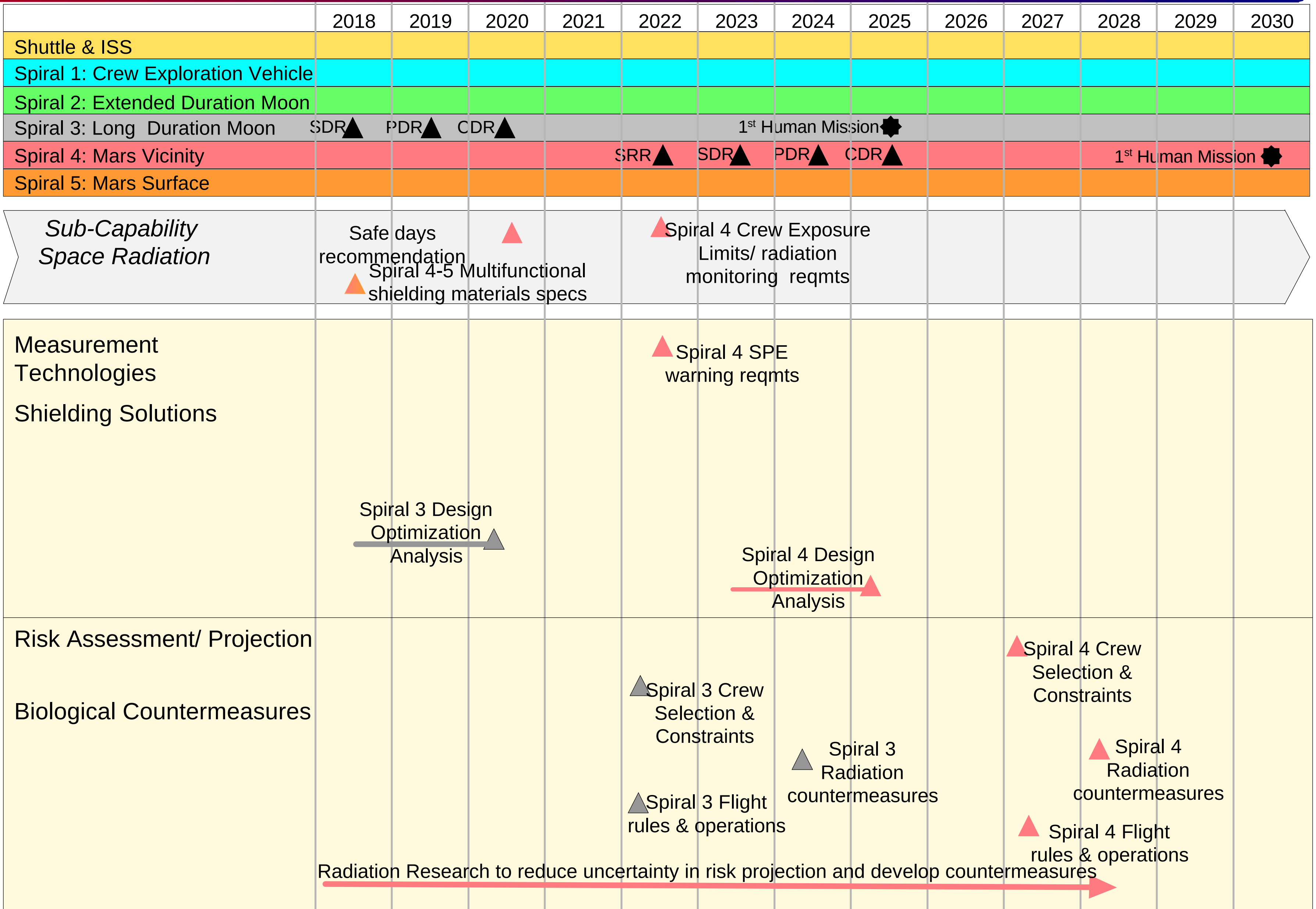


Space Radiation Roadmap



NOTE: Milestone colors correspond to spiral color bars above

Space Radiation Roadmap



Maturity Level – Capabilities Space Radiation

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Integration Approach

Risk

- 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 tech-nologies 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

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

Maturity Level – Technologies for Measurement Technologies

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

*Utilizes ISS as testbed

**Utilizes Moon as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Shielding Solutions

Gaps	Deliverables	Current TRL/ Need Date
Optimized shielding solutions	Requirements for vehicle design/ materials to optimize radiation shielding	3/2012 (moon) 3/2020 (Mars)
Multifunctional Materials	Vehicle Design recommendations (ALARA); Manufacturable materials w/high Radiation protection characteristics for use in vehicle structures	2/2008

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Risk Assessment/Projection

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Gaps	Deliverables	Current TRL/ Need Date
Risk prediction tools with $\leq$ 2 - fold uncertainty in prediction	Risk Assessment and Projection tools with 95% Confidence Level	1/2024

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Biological Countermeasures

Gaps	Deliverables	Current TRL/ Need Date
Biological countermeasures	Validated Biological countermeasures for space radiation risks	1/2028

Note: Unless otherwise indicated, assumes Mars mission scenario

Metrics for Space Radiation

- **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)

Medical Care

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Human Health & Performance

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Medical Care

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

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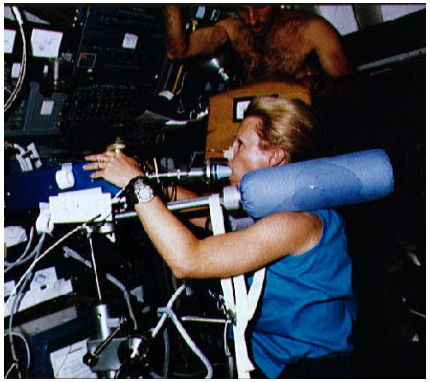
Benefits

- **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

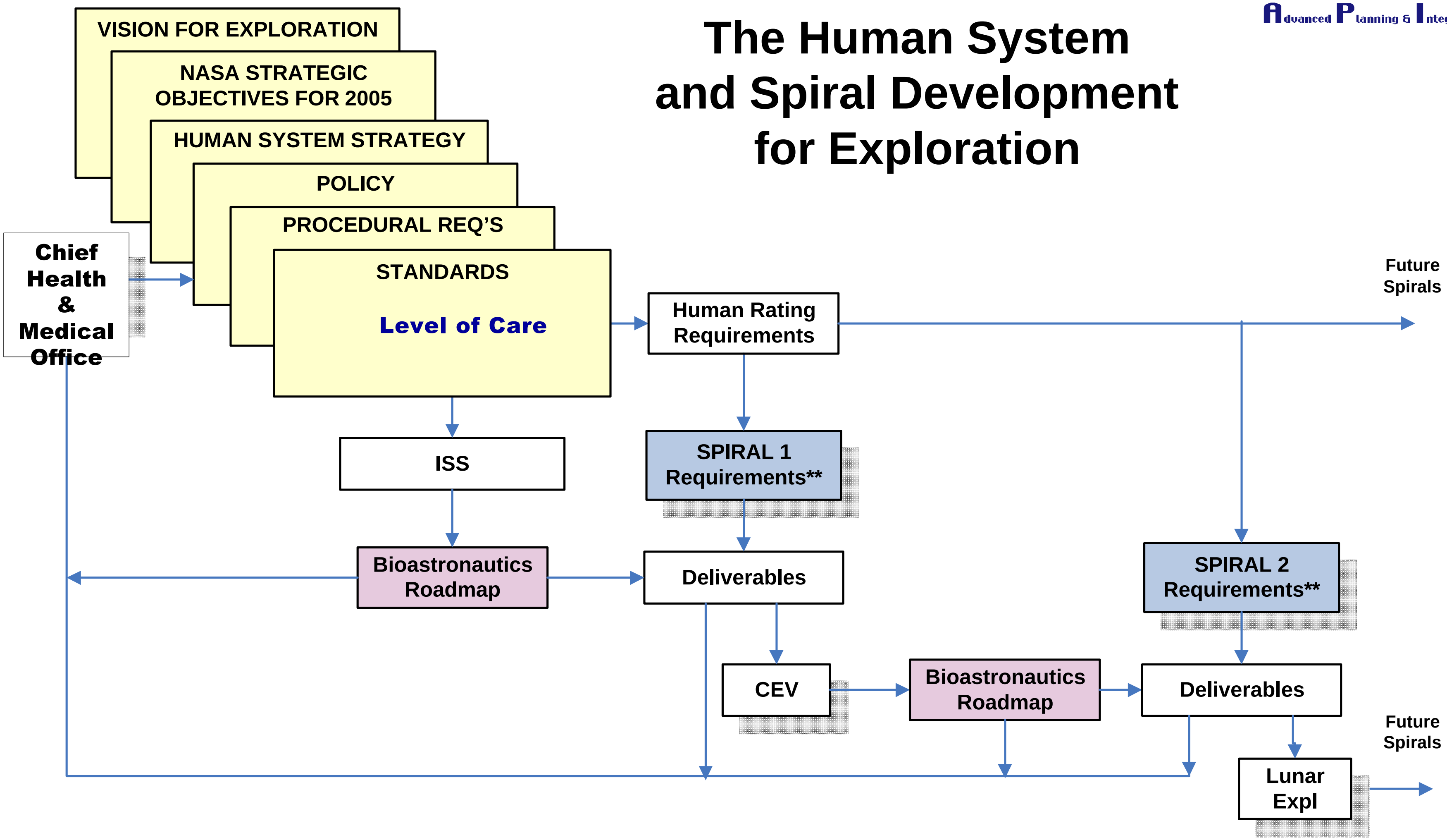
Current State-of-the-Art Medical Care

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



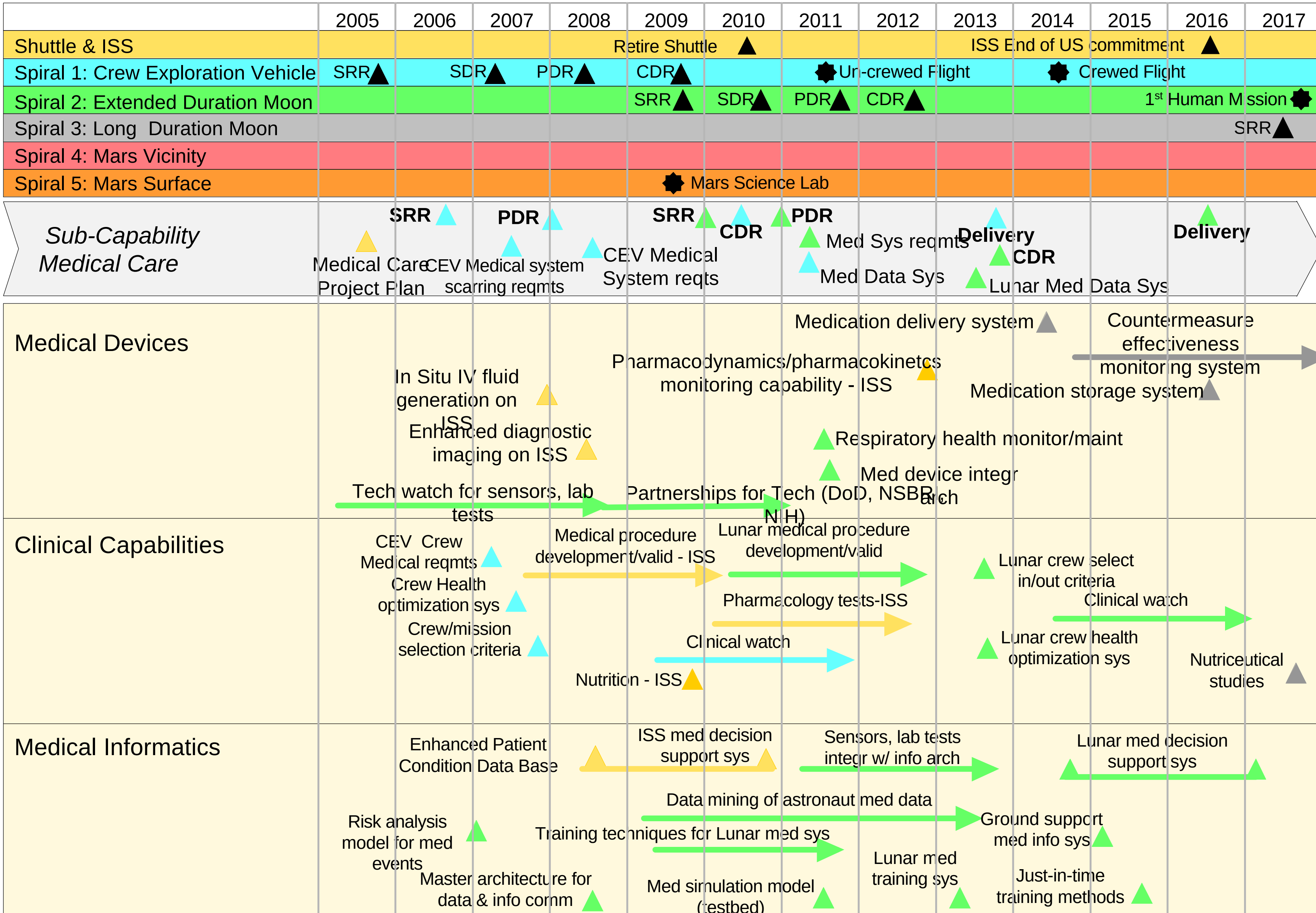
The Human System and Spiral Development for Exploration



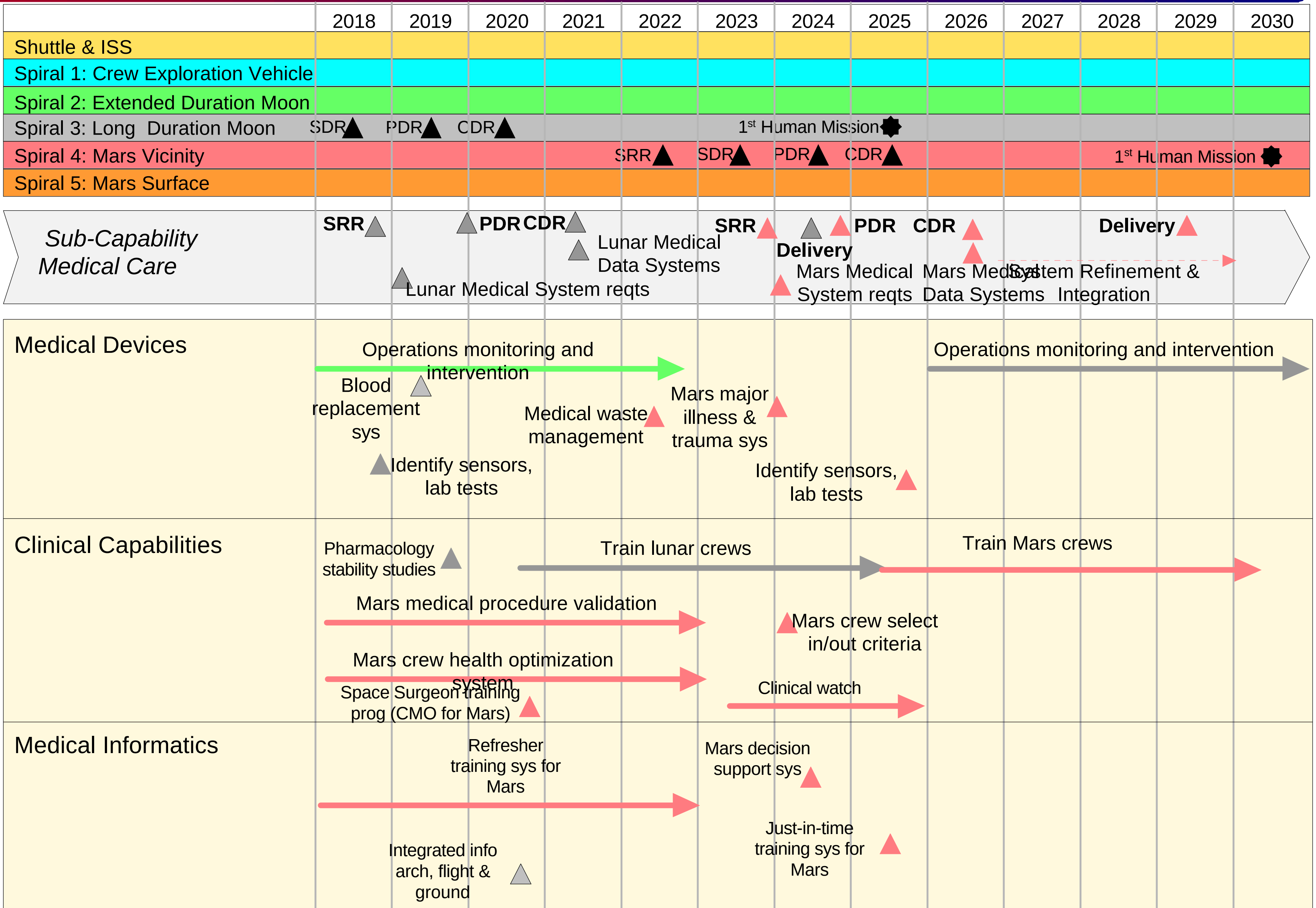
** Includes all program requirements

03/10/05

Medical Care Roadmap



Medical Care Roadmap



Maturity Level – Capabilities Medical Care

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Integration A

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

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Maturity Level – Technologies for Medical Devices

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

*Utilizes ISS as testbed

**Utilizes Moon as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Clinical Capabilities

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

*Utilizes ISS as testbed

**Utilizes Moon as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Medical Informatics

Advanced Planning & Integration Office

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

Note: Unless otherwise indicated, assumes Mars mission scenario

Metrics for Medical Care

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- **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

Human Health & Performance

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  - Performance Readiness
  - Individual & Crew Selection
- **Space Human Factors**
  - Models & simulations
  - Design tools & requirements
  - Performance Measurements
  - Training & Decision Support Systems

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)

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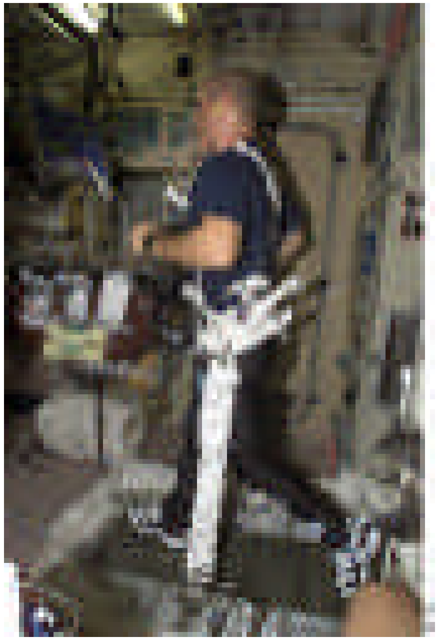
Benefits:

- **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**



Current State-of-the-Art for Human Health Countermeasures

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- Currently used countermeasures have been shown to be effective for flight durations up to 180 days.

Basic Research → Countermeasure Progression → **On-orbit use**

Development

- Pharmacologics
- Gaze, Spatial Orientation Protocols
- Cognitive Tools
- Immune Regulation
- Gait Adaptability Training Program
- Next generation exercise devices

Evaluation

- Vibration Plate Protocols
- Artificial Gravity
- Ultrasound Bone Stimulation
- Enhanced nutrition & exercise protocols
- Exercise prescriptions evaluation & optimization

Validation

- Potassium Citrate (kidney stones)
- Midodrine (orthostatic intolerance)
- Bisphosphonates (Bone Loss)
- EVA Pre-Breathe Reduction Protocols (decompression sickness)
- Exercise hardware devices and prescriptions validation

Operations

- Exercise
  - TVIS
  - BD-1
  - CEVIS
  - SchRED
- Fluid Loading
- Re-entry Anti-G suit
- Liquid Cooling Garment (LCG)
- Recumbent Seat
- Promethazine (SMS)
- Vitamin D and Caloric Counseling
- Acoustics CM Kit
- Prebreathe Protocol
- Circadian Shifting

Requirements /Assumptions for Human Health Countermeasures

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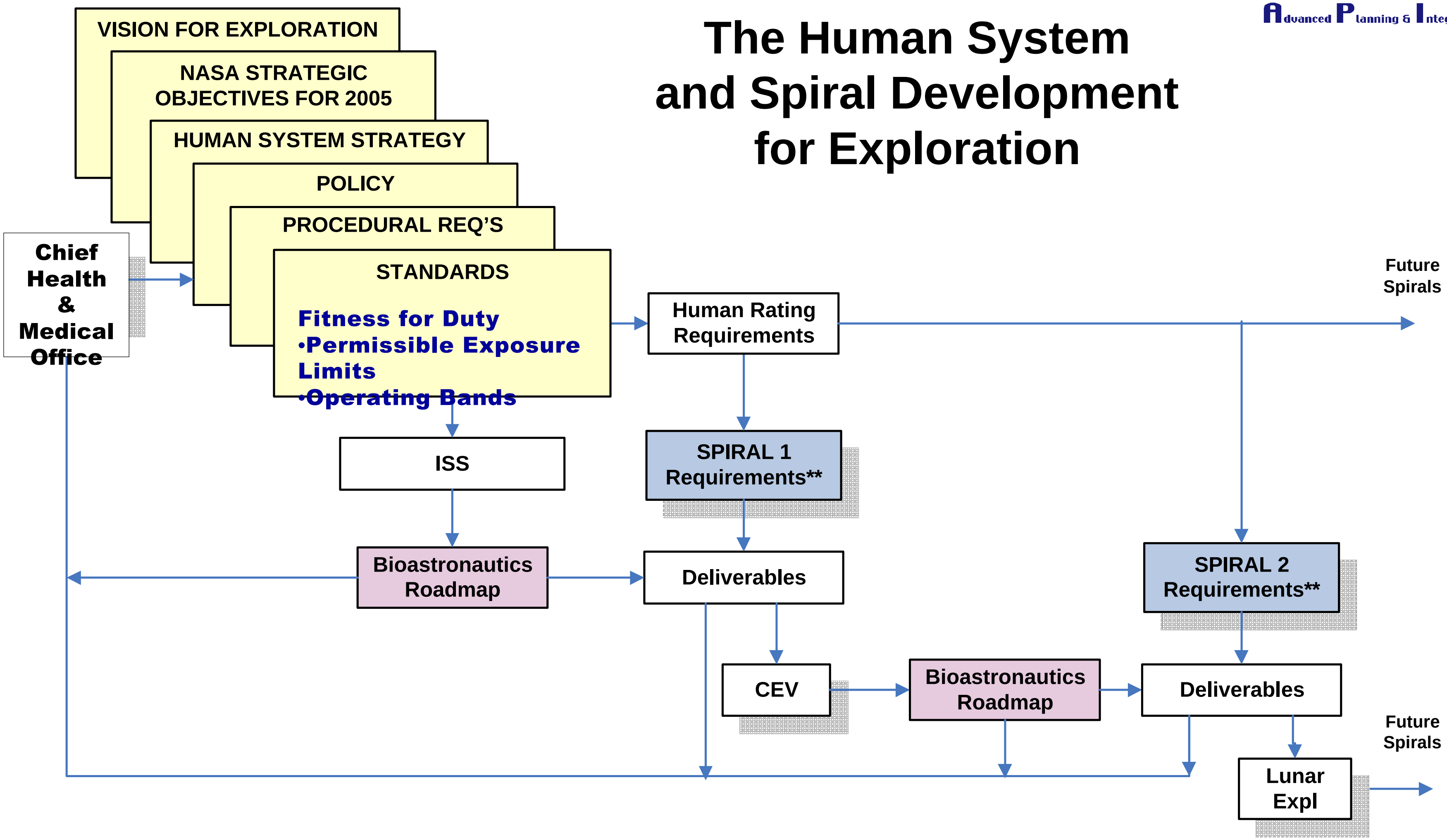
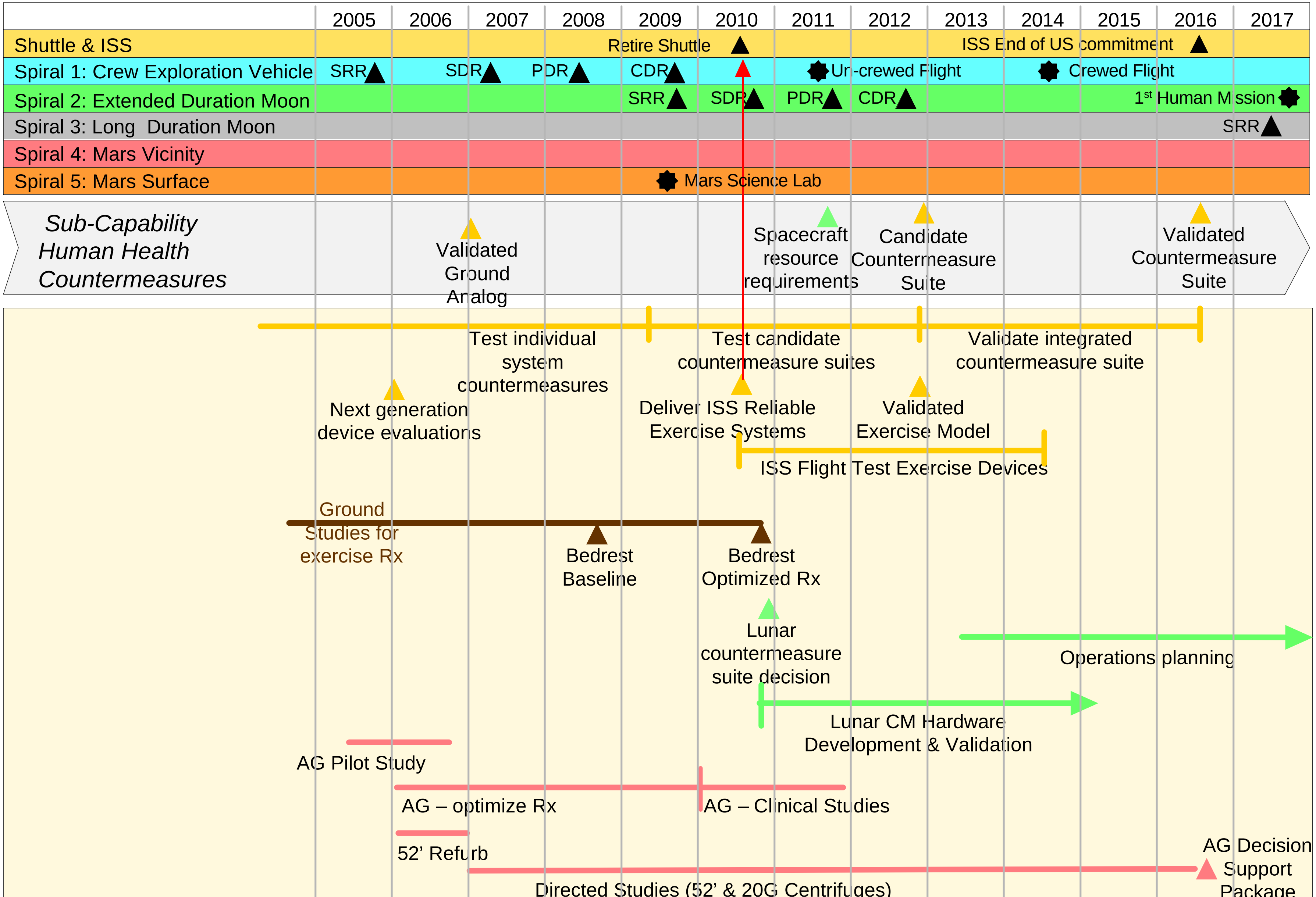
The Human System and Spiral Development for Exploration



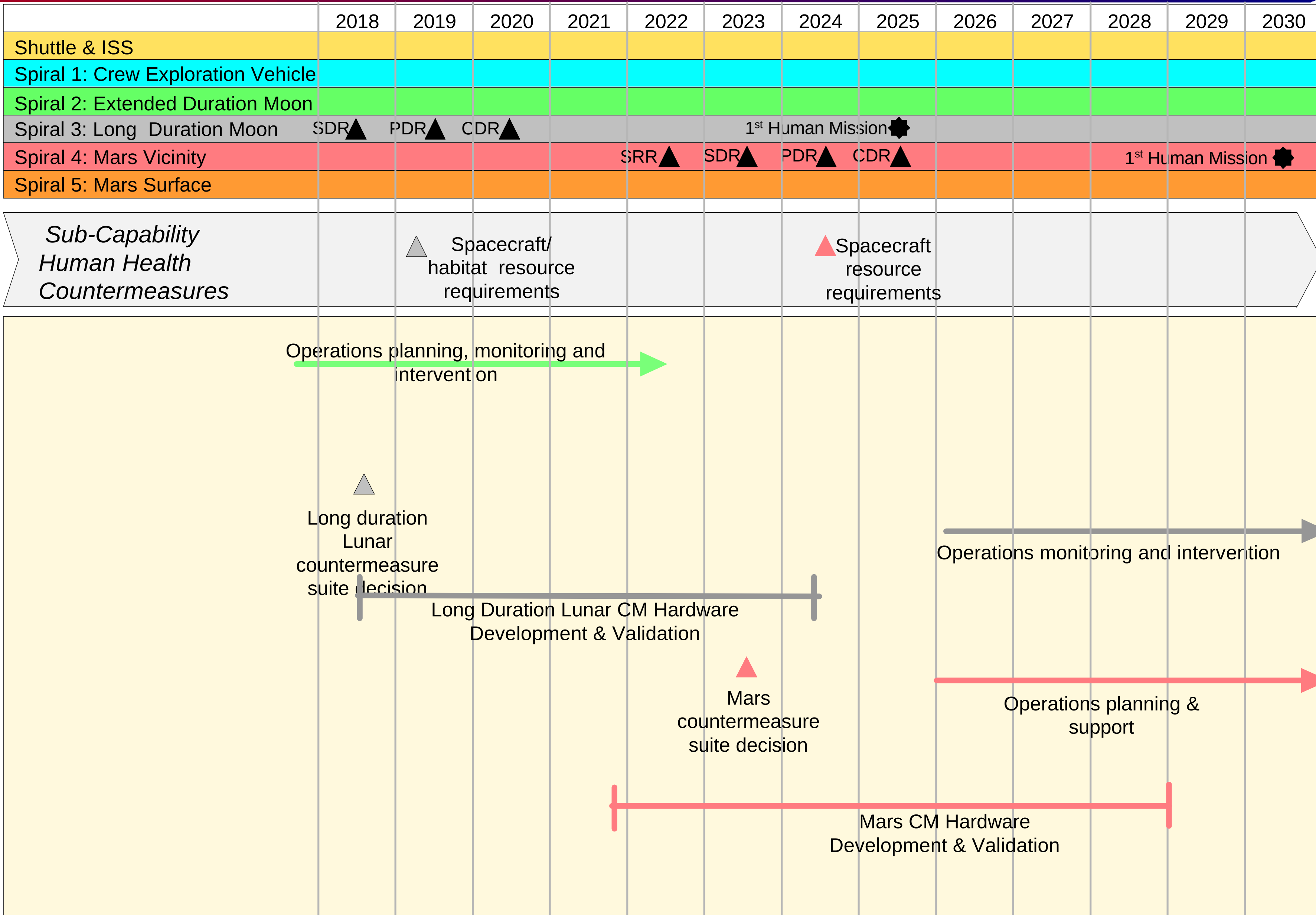
** Includes all program requirements

03/10/05

Human Health Countermeasures Roadmap



Human Health Countermeasures Roadmap



Human Health Countermeasures – Artificial Gravity

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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, …)

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Evidence Base to Guide Program Decisions

Transit Vehicle

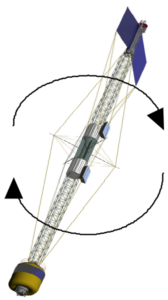
spin CEV ?

yes →

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

no →

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



Surface Ops

3/8 g enough ?

no → Intermittent AG Trade Space

Maturity Level – Capabilities for Human Health Countermeasures

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Integration Approach

Exploration Requirements and Medical Standards & Bioastronautics Roadmap

↓

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

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

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

Maturity Level – Technologies for Artificial Gravity

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

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Exercise

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

*Utilizes ISS as testbed

**Utilizes Moon as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Other Countermeasures

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

*Utilizes ISS as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario

Metrics for Human Health Countermeasures

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

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 Physio-logical 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

- 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

Current State-of-the-Art for Behavioral Health & Performance

Advanced Planning & Integration Office

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

Requirements /Assumptions for Behavioral Health & Performance

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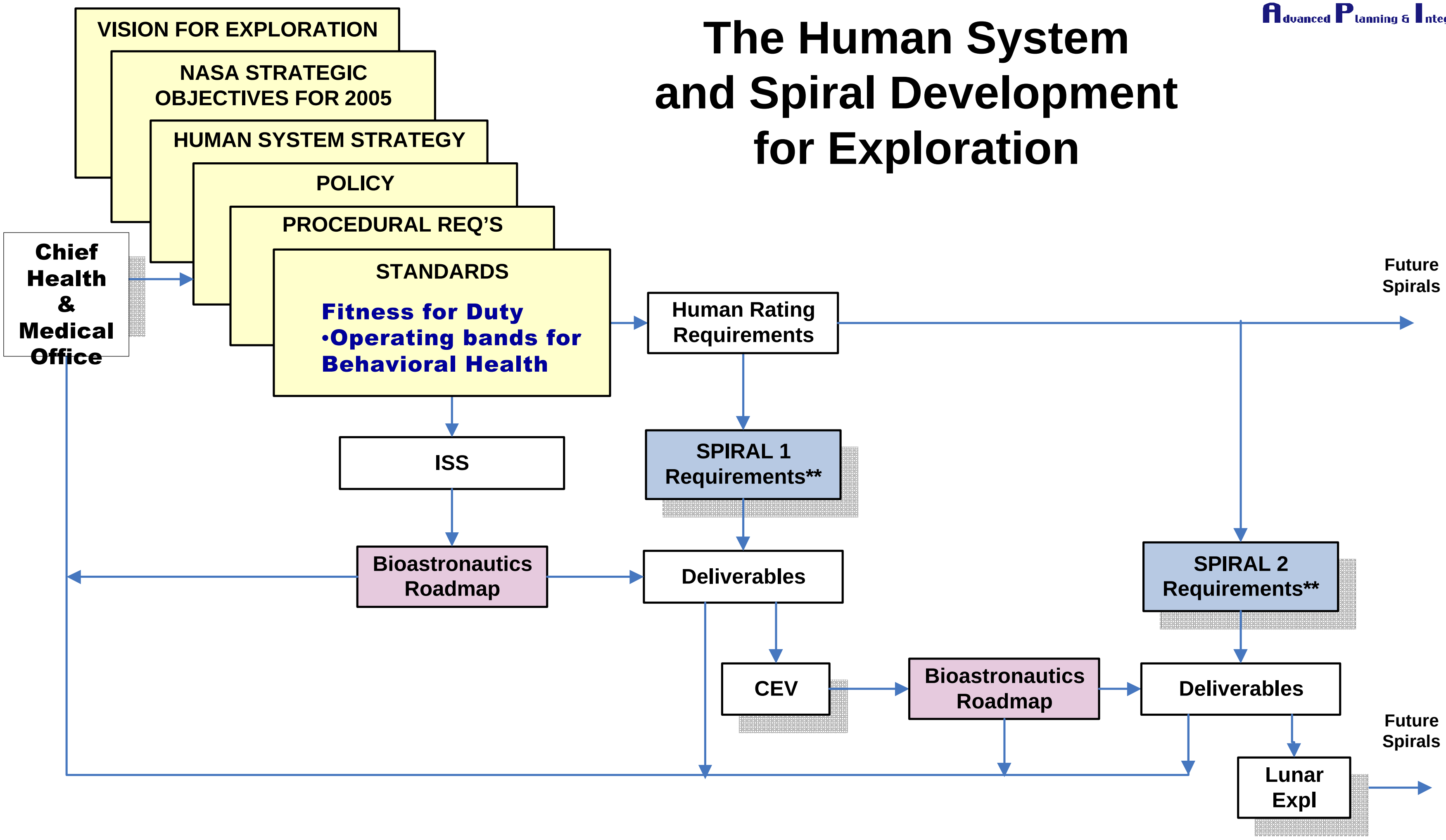
The Human System and Spiral Development for Exploration



** Includes all program requirements

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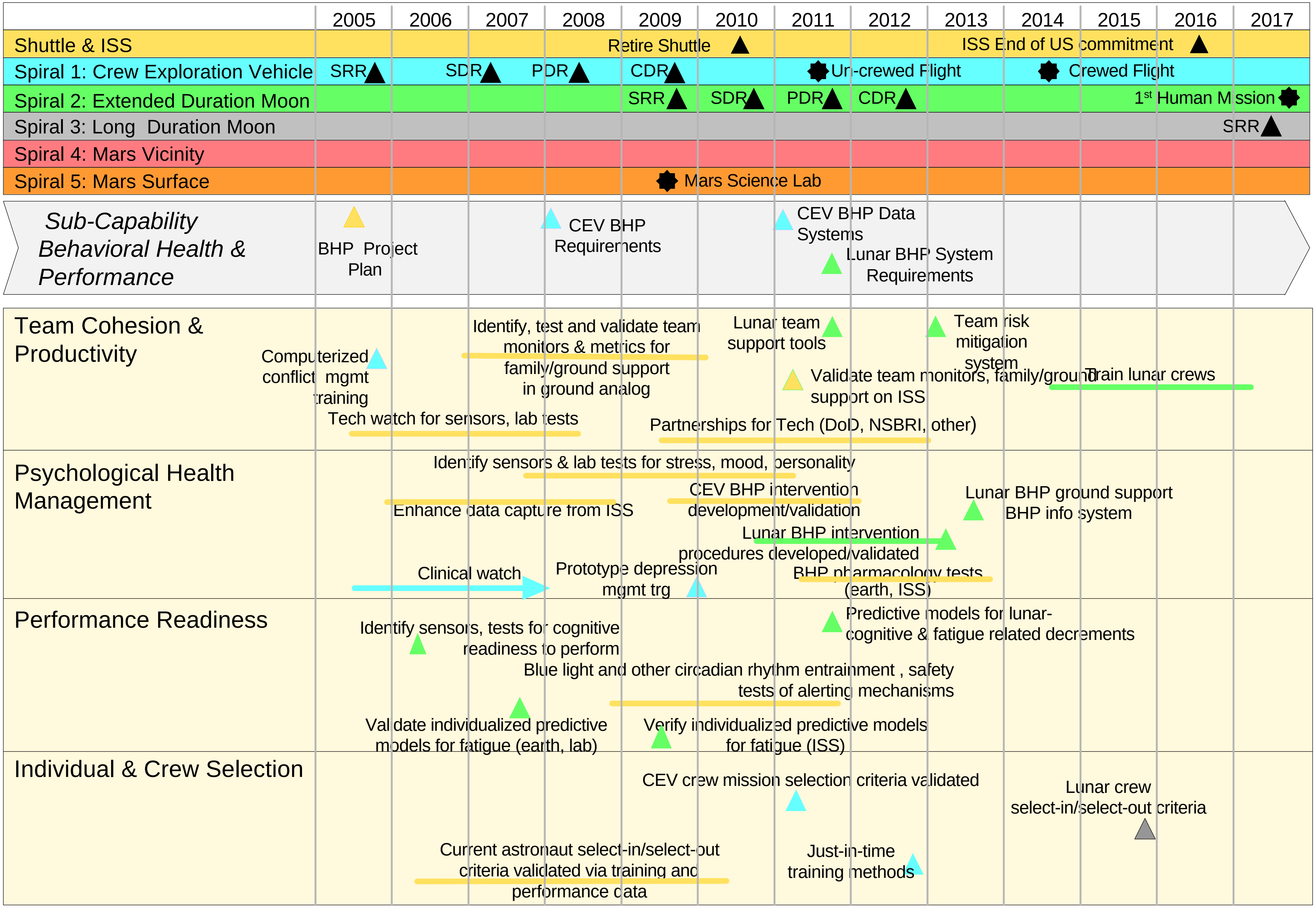
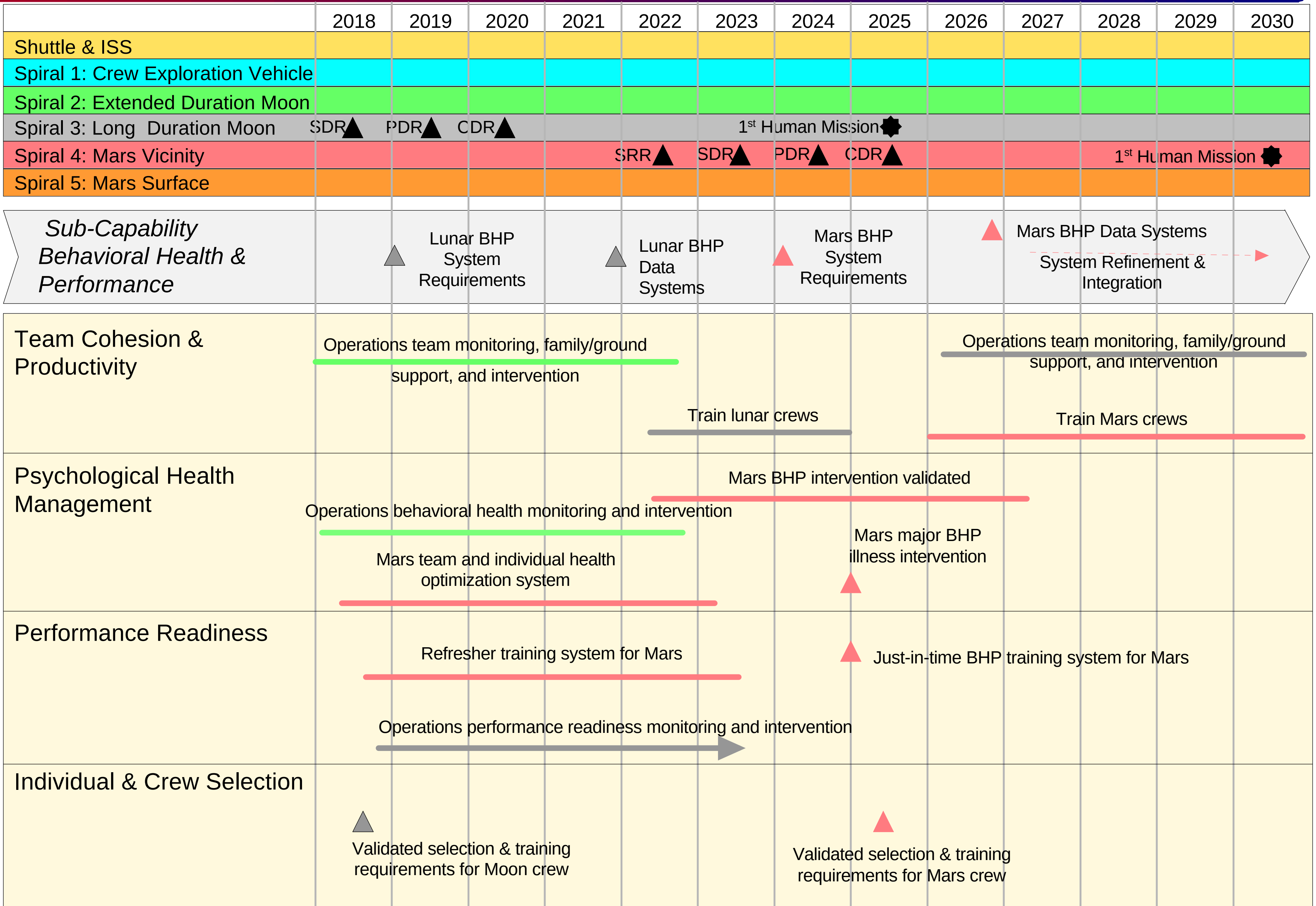
Behavioral Health & Performance Roadmap



Behavioral Health & Performance Roadmap



Maturity Level – Capabilities
Behavioral Health & Performance

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Integration A…

- 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

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

*Utilizes ISS as testbed

**Utilizes Moon as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Psychological Health Management

Gaps	Deliverables	Current TRL/ Need Date
Standards, requirements,operating bands for behavioral health (mood, anxiety)	Standards/requirements/operating bands for mood and anxiety for CEV, lunar, and Mars	2007 (CEV) 2012 (Lunar) 2020 (Mars)
Unobtrusive, ongoing monitoring capabilities	Requirements and validated tech-nologies for unobtrusive monitoring (e.g., optical computer recognition of facial features/ voice analysis; smart clothing or variation thereof) Refinements (lunar, Mars)	2/2008 2014—2025
Biomarker sentinels of mood and anxiety degradation; stress reactions	Biomarkers that are easily obtained and do not require astronaut initiation Refinements for lunar, Mars	2/2012 2014/2022
Just in time training/education for astronaut, ground, flight surgeon	Computerized, modular systems / decision trees Refinements for lunar, Mars	2/2010 2015/2023
Risk mitigation and countermeasures	Tele behavioral health therapy, on-board pharmaceuticals and other countermeasures Refinements for lunar, Mars	2/2012 2015/2025

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Performance Readiness

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

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Individual & Crew Selection

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

Note: Unless otherwise indicated, assumes Mars mission scenario

Metrics for Behavioral Health & Performance

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

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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 Physio-logical 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

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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

Current State-of-the-Art for Space Human Factors

Advanced Planning & Integration Office

State of the Art

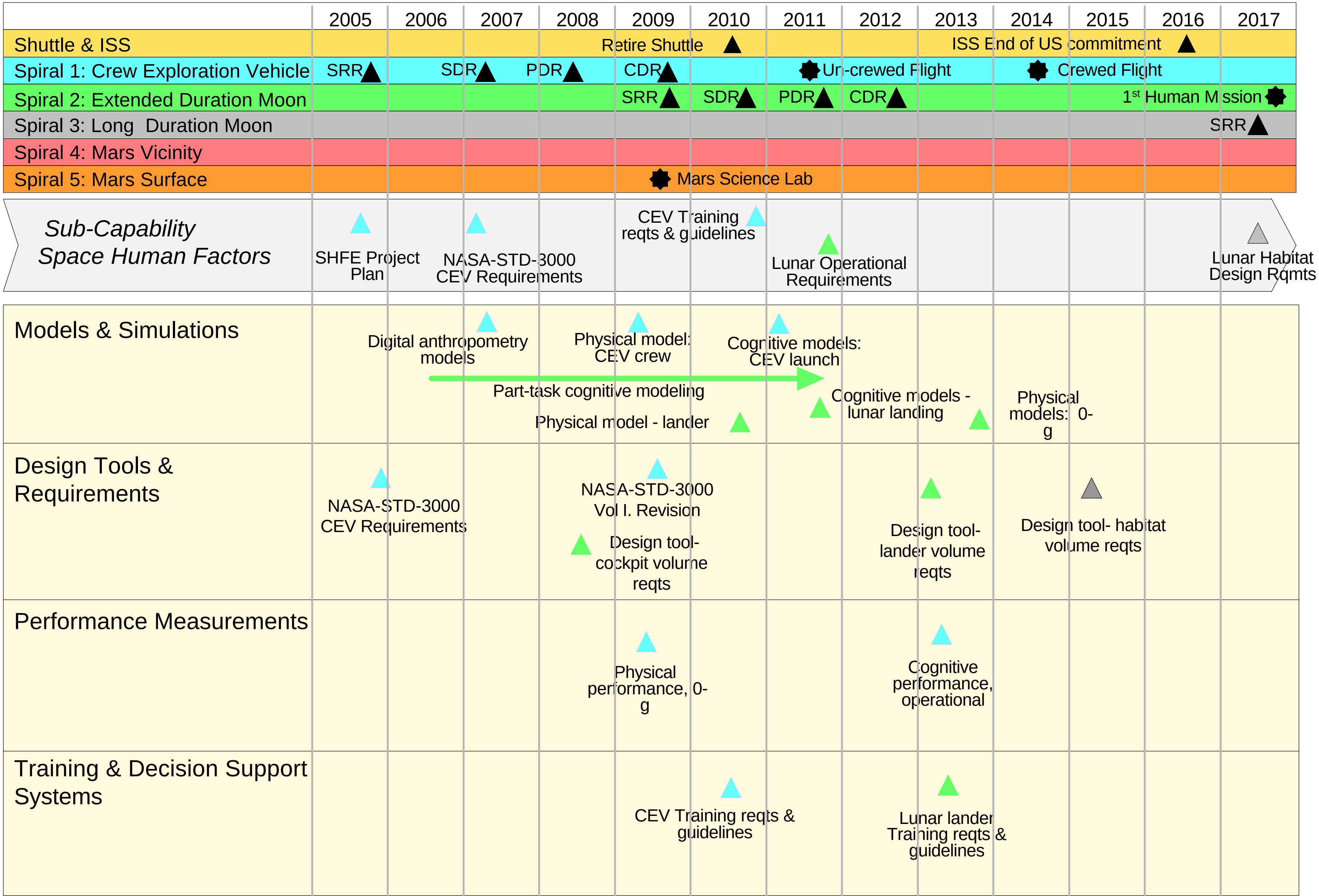
- Anecdotal information from Shuttle, Mir and ISS crews
- Commercial models of 1-g physical performance
- Research models of human cognitive performance
- Commercial CAD design tools do not interface with Human Factors (HF) requirements
- External non-NASA, including DoD, HF knowledge about training, performance measurement, simulations is potentially applicable to some space applications (launch, entry) but not all (microgravity, partial gravity)

Requirements /Assumptions for Space Human Factors

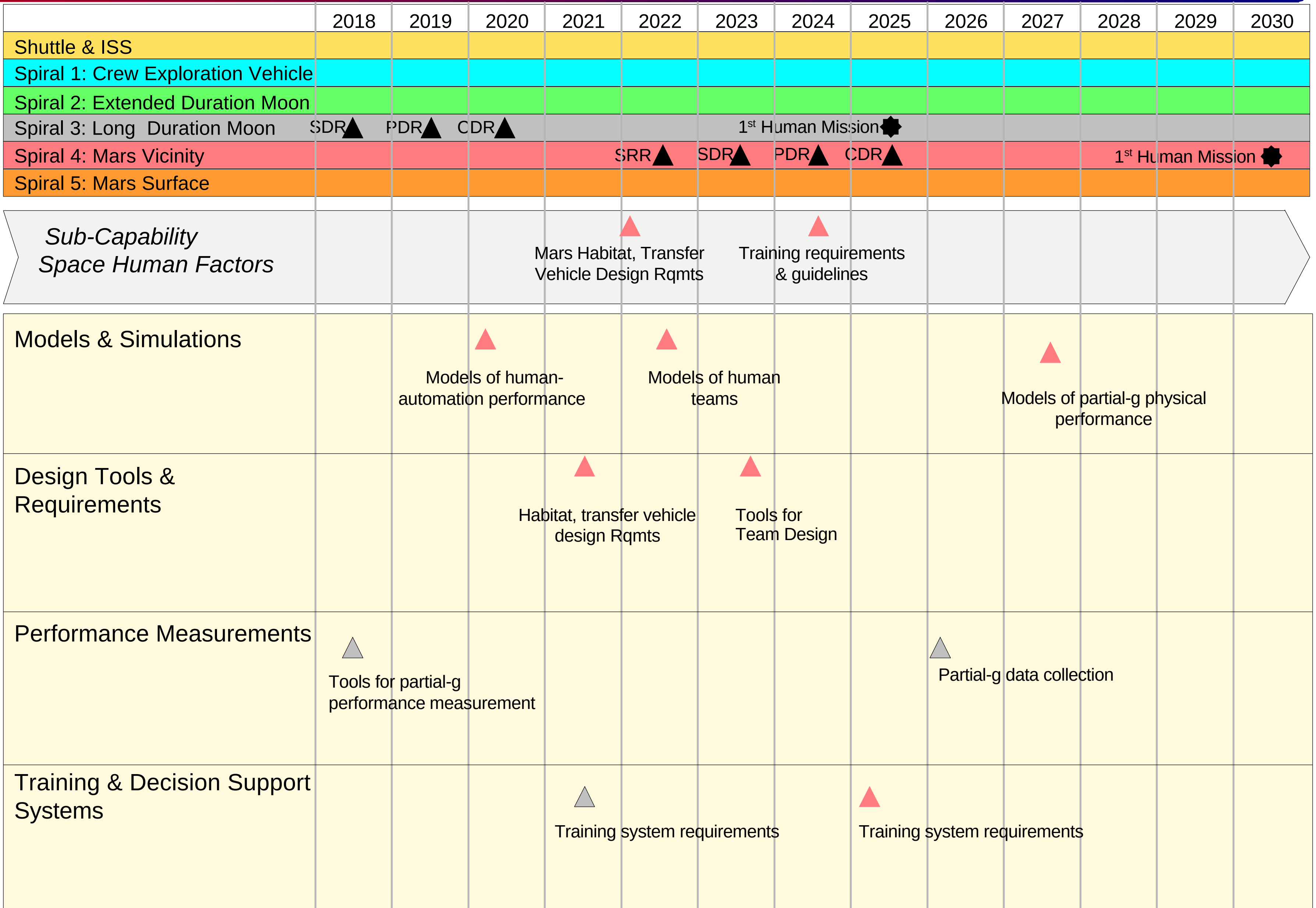
NASA-STD-3000: Human-Systems Integration Standards (HSIS)

- 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



Space Human Factors Roadmap



Maturity Level – Capabilities
Space Human Factors

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Integration A

- 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

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

Maturity Level – Technologies for Team Models & Simulations

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Gaps	Deliverables	Current TRL/ Need Date
Human size data for input to spacecraft designs	Digital anthropometry models	3/2007
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

Gaps	Deliverables	Current TRL/ Need Date
Human-centered design requirements	Updated HSIS standards that are verifiable	5/2009
Volume required for task performance in microgravity	Design tools for cockpit-type volume Design tools for habitable environment: lander Design tools for habitable environment: habitat	3/2011 3/2013 3/2015
Team design requirements & guidelines, including multi-agent teams	Tools for team design Task allocation analysis	8/2023

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Performance Measurements

Gaps	Deliverables	Current TRL/ Need Date
Quantitative performance measurement tools	Validated real-time physical performance measurement tools in zero-g	4/2009
	Validated real-time cognitive performance measurement tools	3/2011
	Validated real-time physical performance measurement tools in partial-g	6/2018

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Training & Decision Support Systems

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

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 heath 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

Life Support and Habitation Capability Breakdown Structure

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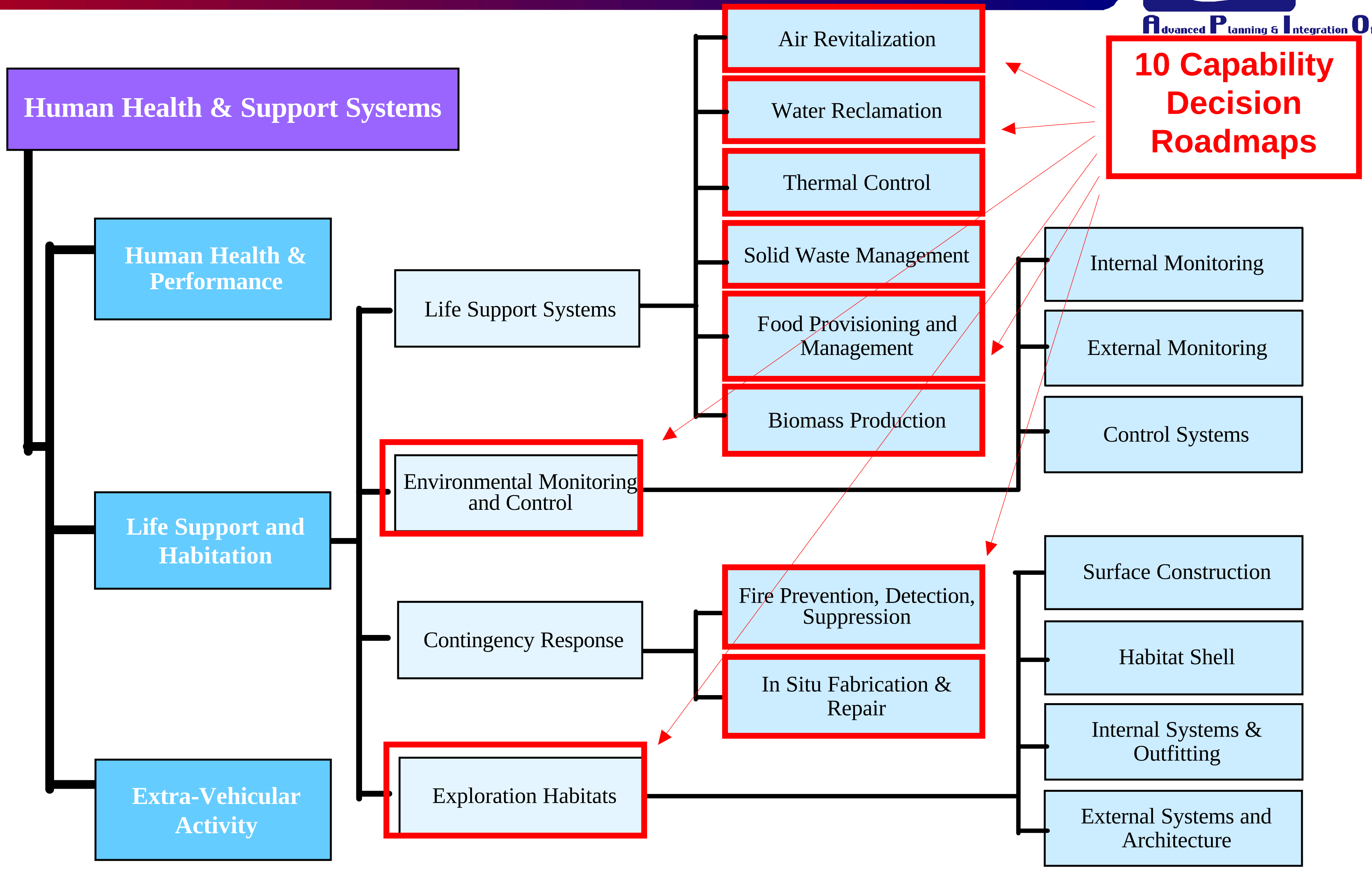
- **Human Health & Support Systems**
  - **Human Health & Performance**
  - **Life Support and Habitation**
    - Life Support Systems
      - Air Revitalization
      - Water Reclamation
      - Thermal Control
      - Solid Waste Management
      - Food Provisioning and Management
      - Biomass Production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

Life Support and Habitation Roadmaps to be Presented

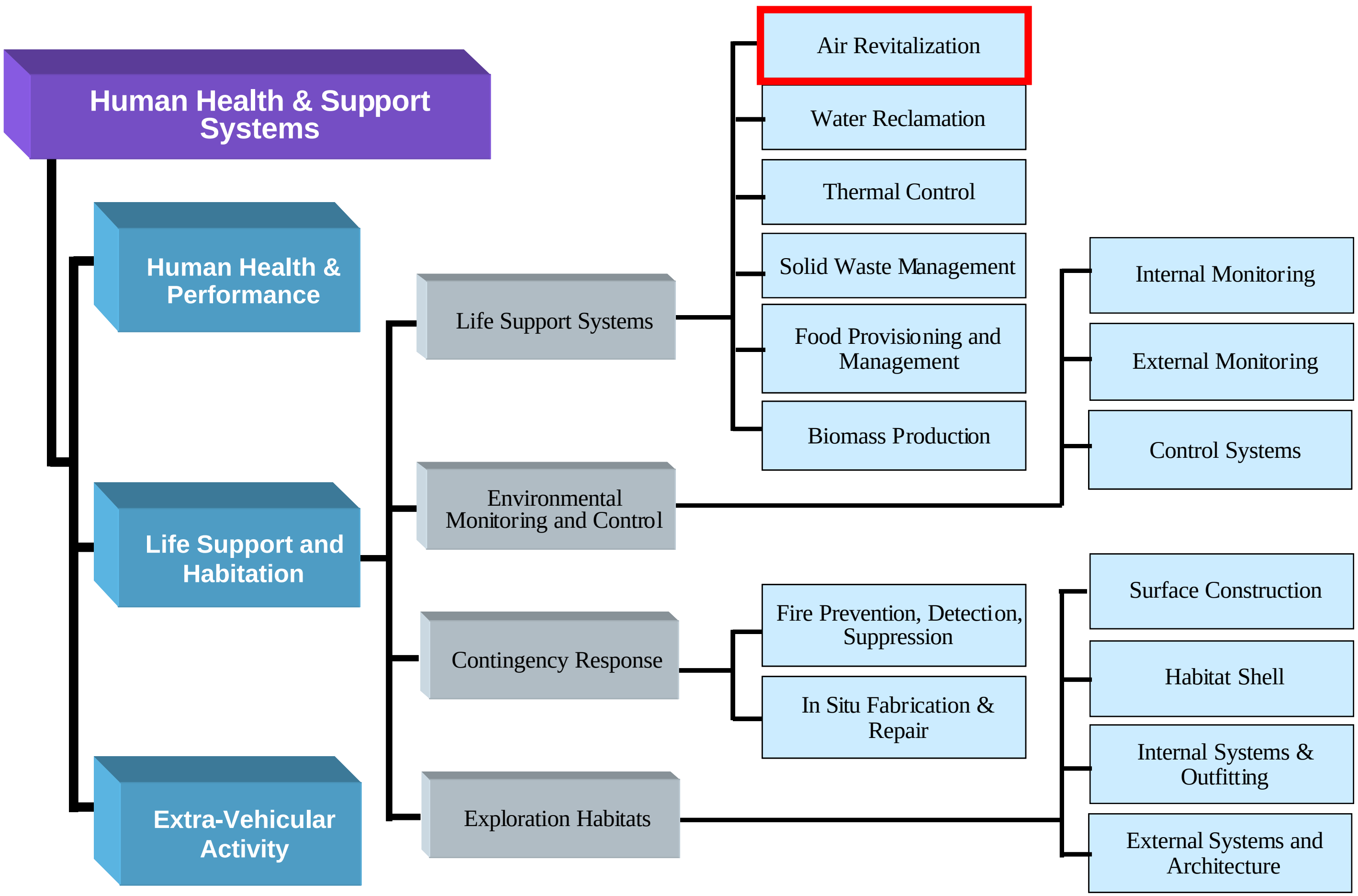


Requirements / Supporting Documents

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**
  - Advanced Life Support Baseline Values and Assumptions Document (2004)
  - Advanced Life Support Requirements Document (2003)
  - Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document (2001)
  - Solid Waste Processing and Resource Recovery Workshop Report (2001)
  - Advanced Food Technology Workshop Final Report (2003)
- **Spacecraft Requirements Documents**
  - Medical Operations and Requirements Documents
  - Manned Systems Integration Standards
- **National Research Council Reports and Guidelines**
  - Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies (2003)
  - Spacecraft Maximum Allowable Concentrations for Selected Airborne Contaminants (1994-)
  - Spacecraft Water Exposure Guidelines for Selected Contaminants (2000-)
  - Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface (2002)
  - Safe Passage: Astronaut Care for Exploration Missions (2001)
  - Advanced Technology for Human Support in Space (1997)

Atmosphere Revitalization



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 H_2; 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 O_2
    - ISS: High pressure storage; Oxygen recharge capability.
  - **Gas Recovery for System Loop Closure**
    - **Presently not on board Shuttle or ISS; CO_2 reduction risk mitigation in work**

Atmosphere Revitalization Requirements & Assumptions

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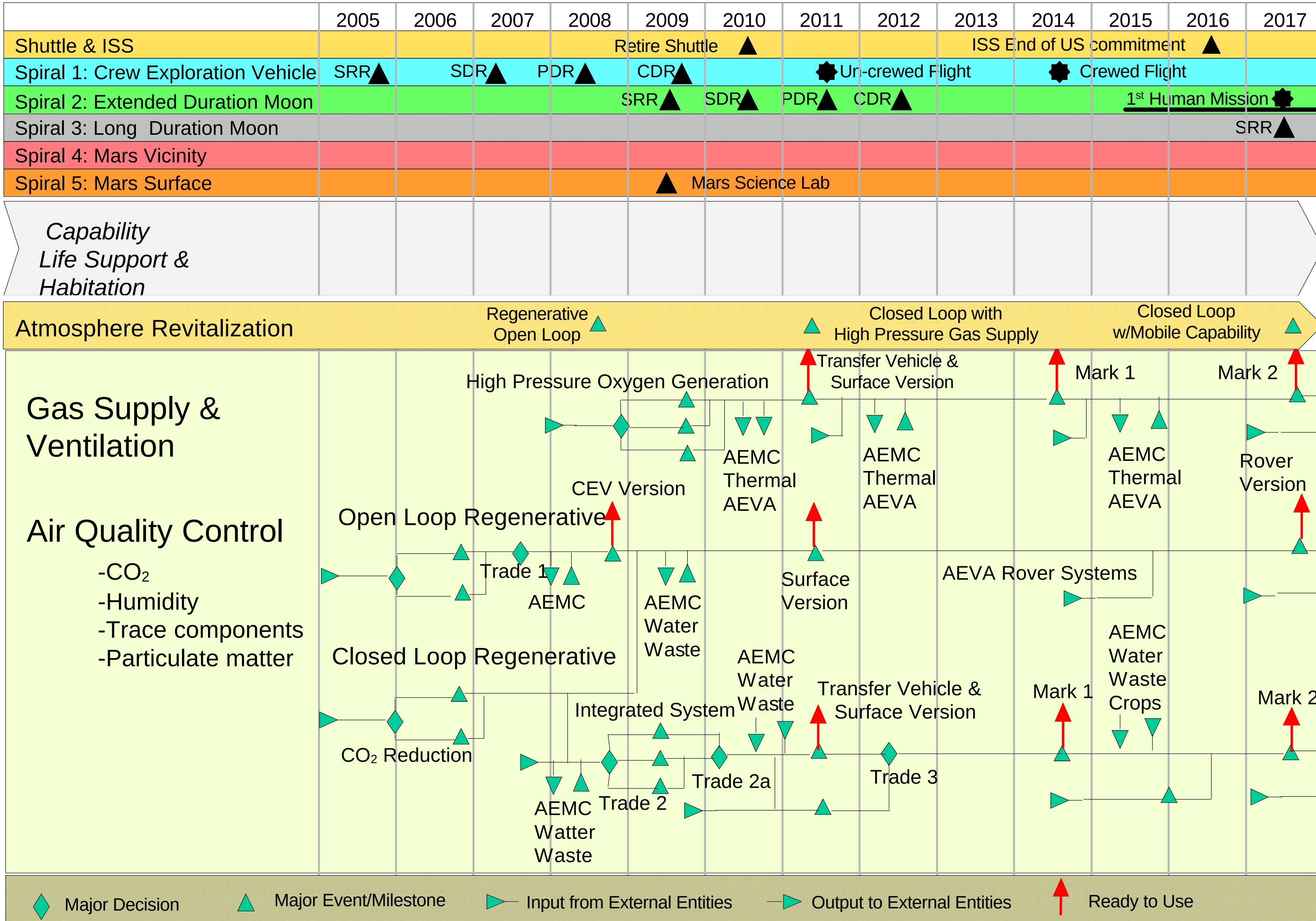
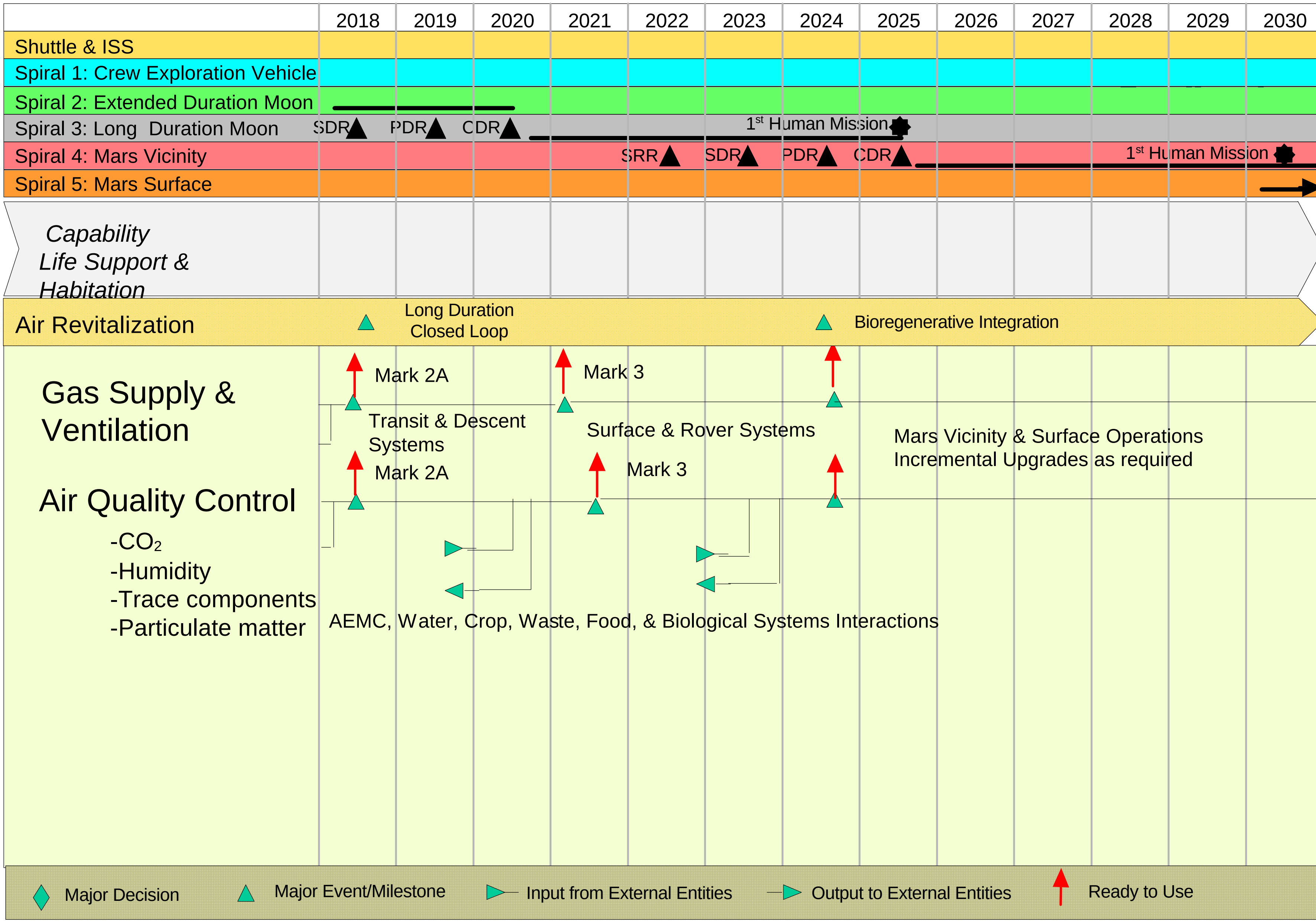
- **Long Duration Missions Drive Requirements**
  - Missions to ISS and other LEO operations can use existing SOA with some modification
    - Potential for extended duration Lunar and Mars transit flight demonstration on ISS
  - Extended duration Lunar missions and Mars transit/Mars vicinity drive technological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



Atmosphere Revitalization Roadmap



Atmosphere Revitalization Maturity Level – Capabilities

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Supply O_2 & N_2 Control O_2 & N_2 partial pressure Regeneratively control CO_2 partial pressure, relative humidity, and remove trace contaminants from cabin atmosphere Remove suspended particulate matter Provide ventilation & atmospheric mixing	No development needed No development needed Improve mass, power, reliability, and maintainability by integrating CO_2, humidity, and trace contaminant control functions; select and characterize adsorbents & catalysts Filter media selection and element configuration Means for pressure drop monitoring Methods for reducing fan noise	6 6 2 6 1 1
Spiral 2 Lunar Surface (2011)	Spiral 1 plus demonstrate closed loop: Provide ambient/high pressure O_2 generation Provide CO_2 reduction/demonstrate loop closure Provide means to control migration of lunar dust into habitat	Mark 1 systems: Extend oxygen generation to high pressures Process design & integration with Spiral 1 regenerable air quality control equipment with scar for CO_2 reduction	2 3 1
Spiral 3 Long Duration Lunar Surface (2014)	Spiral 2 plus full loop closure: Provide ambient/high pressure O_2 generation Open loop systems for EVA support Demonstrate CO_2 reduction to carbon Mark 1 air quality control equipment Improved means to control migration of lunar dust into habitat	Mark 2 systems: Improve mass, power, reliability, and maintainability of Spiral 2 system Extend Spiral 1 systems to mobile applications Develop flight demonstration for carbon formation reactor Improve mass, power, reliability, and maintainability of Spiral 2 system, fully integrated with CO_2 reduction, plus scar for carbon formation Develop habitat isolation and filtration methods/processes	2 1 2 2 1
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	Mark 2A systems: Develop flight carbon formation process Further improve mass, power, reliability, and maintainability of Spiral 2/3 integrated systems	2 1
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	Mark 3 systems: Potential use of in-situ resource (oxygen from CO_2 atmosphere and ground water) Further reduction in weight and/or expendables Improve mass, power, reliability, and maintainability of habitat isolation methods	1 1 1

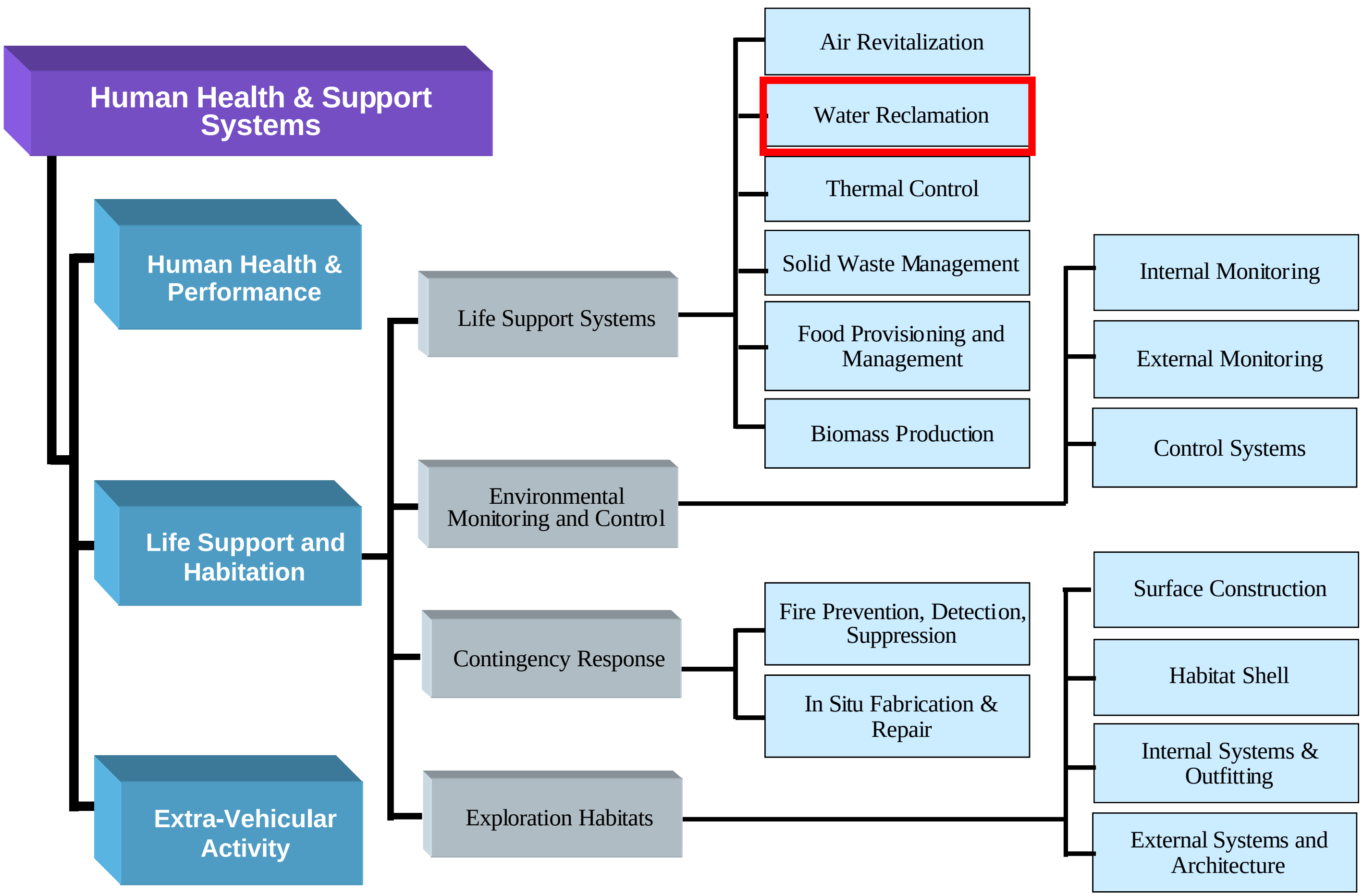
Atmosphere Revitalization Maturity Level – Technologies

Sub-Capability (Level 5/6 CBS)	Leading Technology Candidates	Spiral(s)	Current TRL
Control Carbon Dioxide Partial Pressure	**Expendable chemisorbents (LiOH)** **Vacuum swing adsorption** **Combined temperature/vacuum swing adsorption** **Bioregenerative Systems**	**1-3** **1-5** **1-5** **4-5**	**4-9** **4** **3-9** **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 (CH_4 and light VOCs)** **Ambient temperature catalytic oxidation (CO and H_2)**	**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

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

Water Recovery Systems



Water Recovery Systems Description

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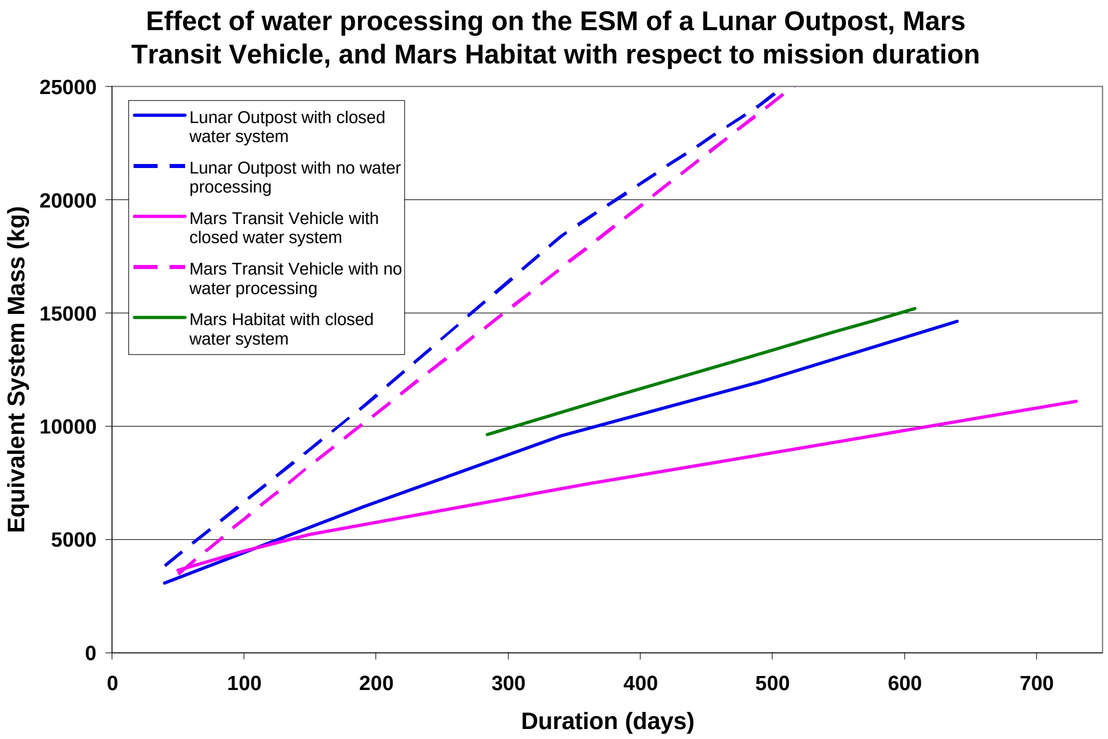
- Water recovery systems transform crew and system wastewater into potable water for crew and system reuse.
- Biological and/or physical/chemical methods employed to remove contaminants
- Biocides added for residual disinfection to inhibit microbial growth in storage tanks.
- Processing strategy
  - 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**



from Ewert, M., Van Buskirk, J. Evaluation of Human Life Support Across Mission Scenarios, SIMA-Lockheed Martin Study, 2004.

Water Recovery Systems Current State-of-the-Art

Advanced Planning & Integration Office

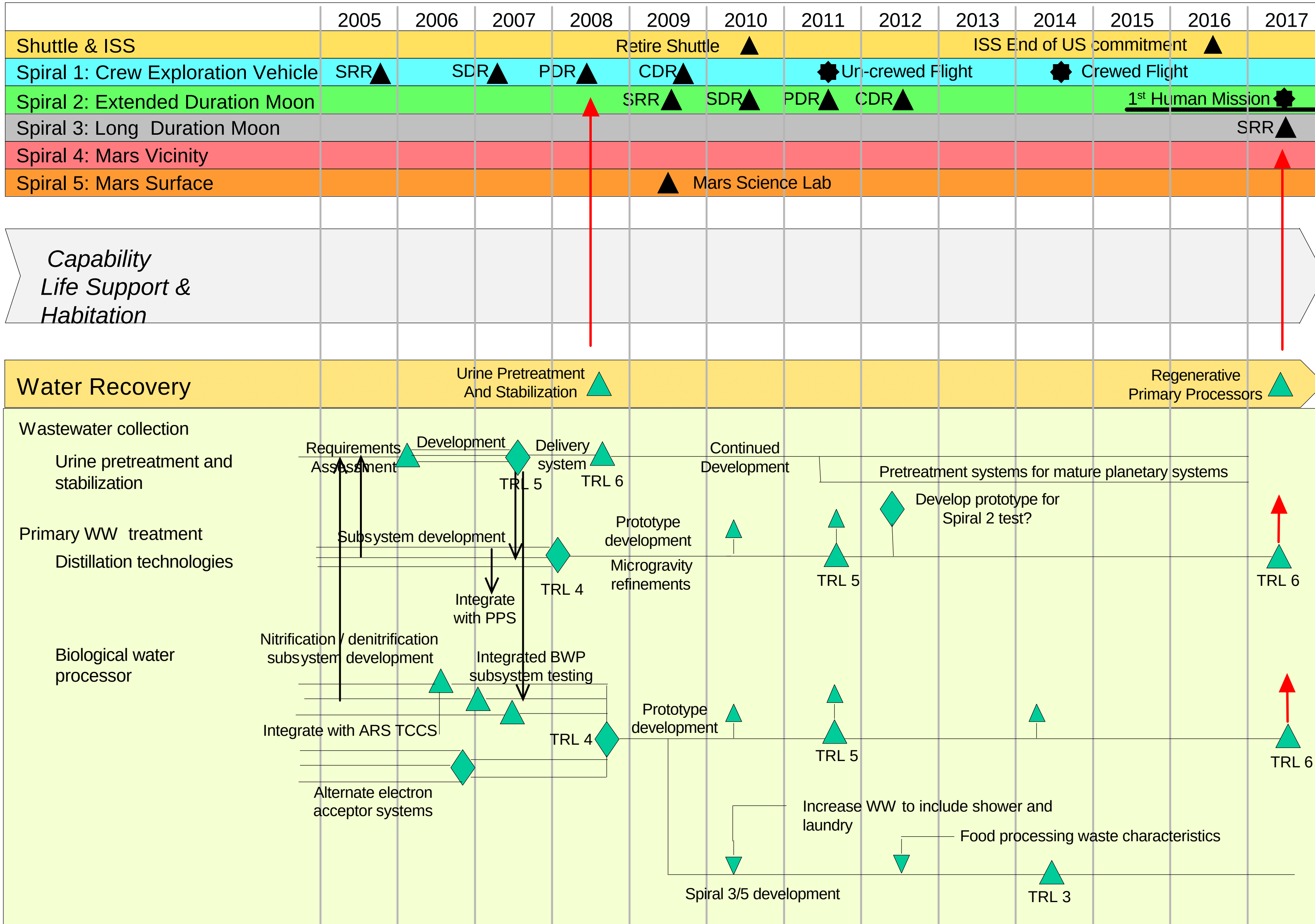
- Vapor compression distillation technology
  - Rotating distillation process
  - Used for urine treatment
  - Organic and inorganic removal
  - Produces brine
  - Distillate requires further treatment to reach potable quality
- Multifiltration beds
  - Organic and inorganic removal
  - Requires consumable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

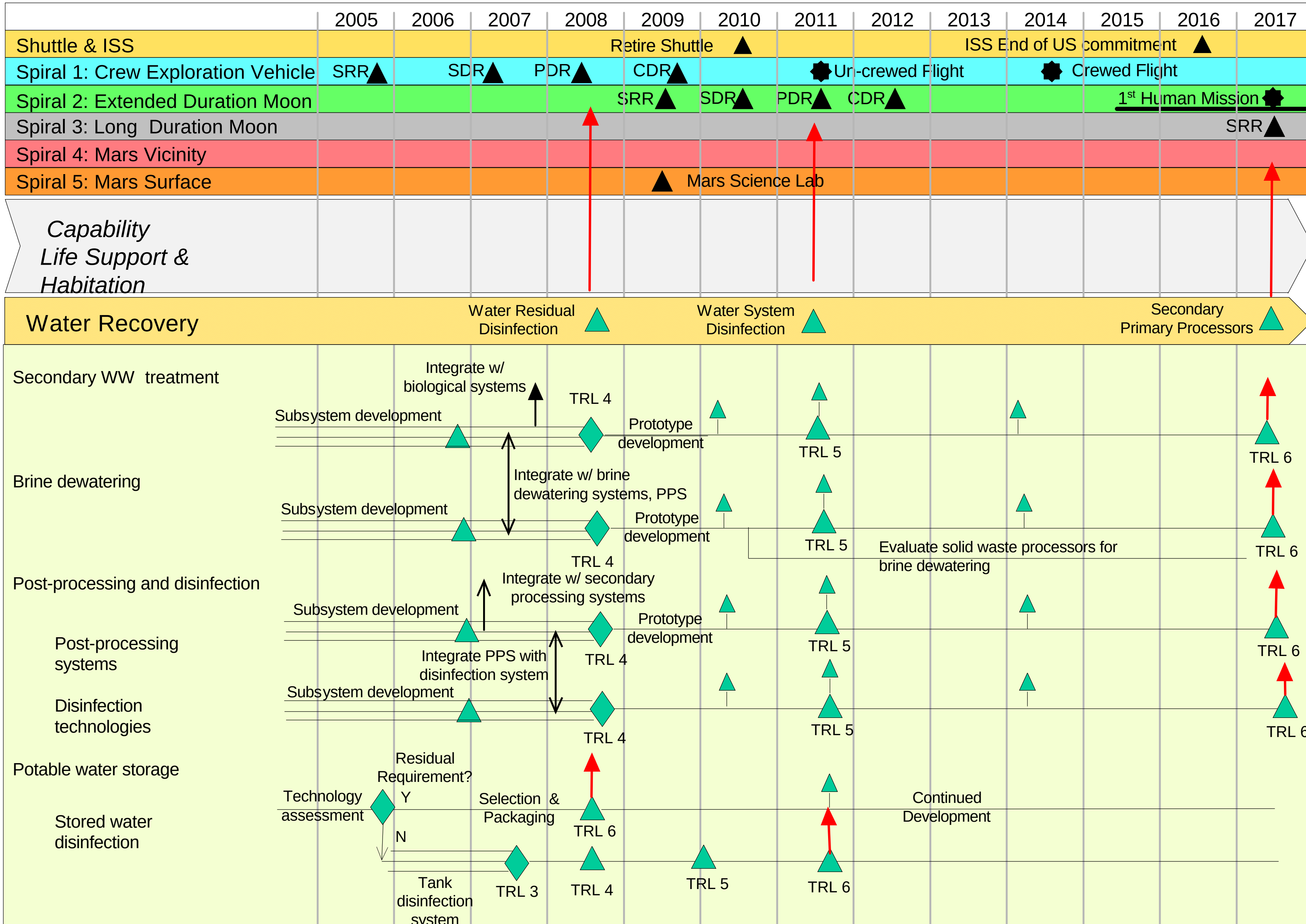
Advanced Planning & Integration Office

- 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

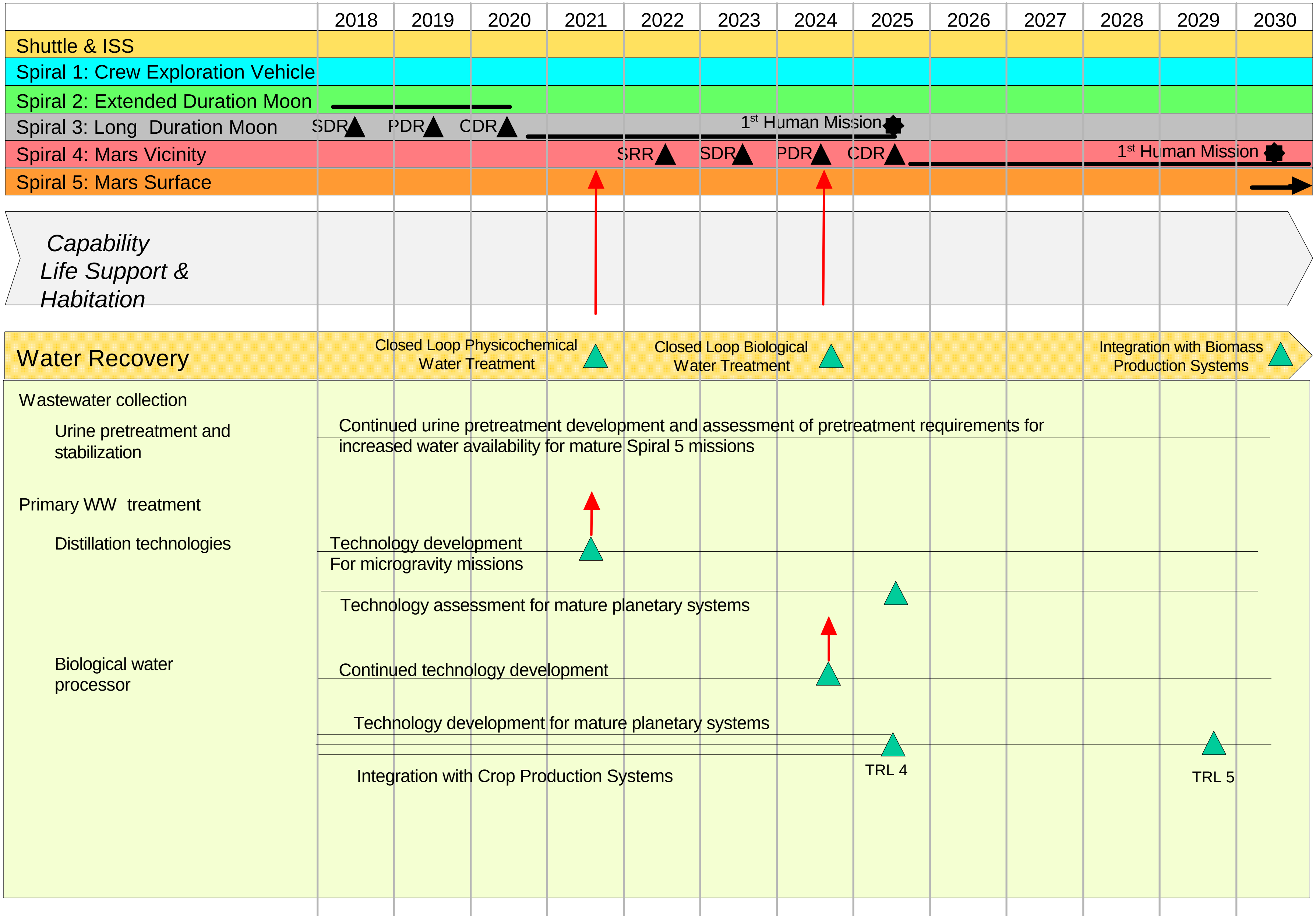
Water Recovery Systems Roadmap



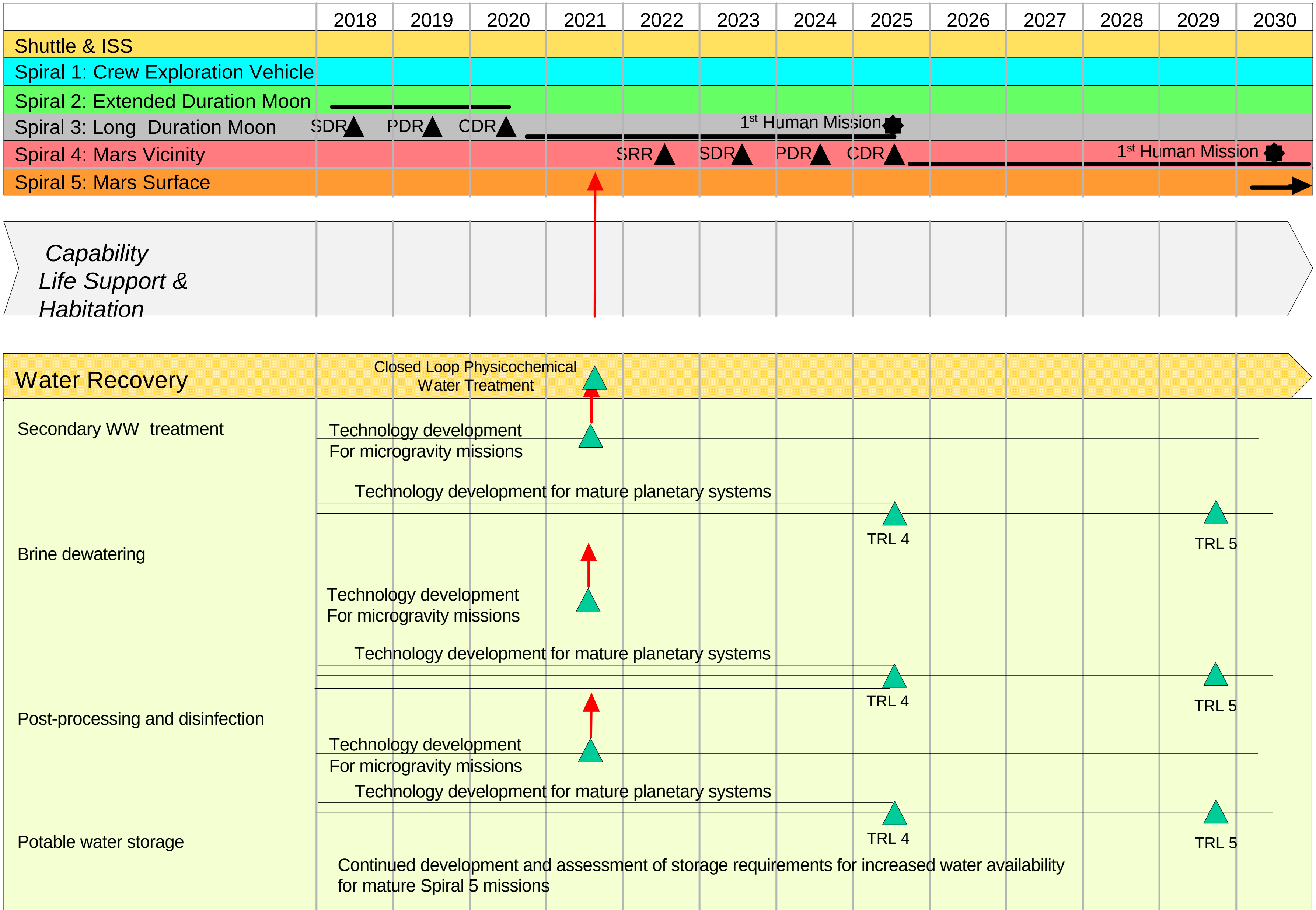
Water Recovery Systems Roadmap



Water Recovery Systems Roadmap



Water Recovery Systems Roadmap



Water Recovery Systems Maturity Level – Capabilities

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Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Pretreat urine for stability Provide residual disinfection for stored water Store potable water	Less toxic urine pretreatment Residual disinfectant that does not require removal prior to water consumption None needed	2 1 3
Spiral 2 Lunar Surface (2011)	Same as Spiral 1	Spiral 1 development supports Spiral 2 except Prototype Spiral 3 distillation system available for testing in Spiral 2	2
Spiral 3 Long Duration Lunar Surface (2014)	Wastewater storage Remove organic contaminants from water Remove inorganic contaminants Recover brine solutions Provide polishing and disinfection Store potable water and provide residual disinfection	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	3 2 2 1 2
Spiral 4 Mars Vicinity (2017)	Same as Spiral 3	Same as Spiral 3 except technologies must operate in a microgravity environment Further reduction in weight and/or expendables	2 1
Spiral 5 Initial Mission Mars Surface (2021)	Same as Spiral 3	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	1 1 1 1

Water Recovery Systems Maturity Level – Technologies

Advanced Planning & Integration Office

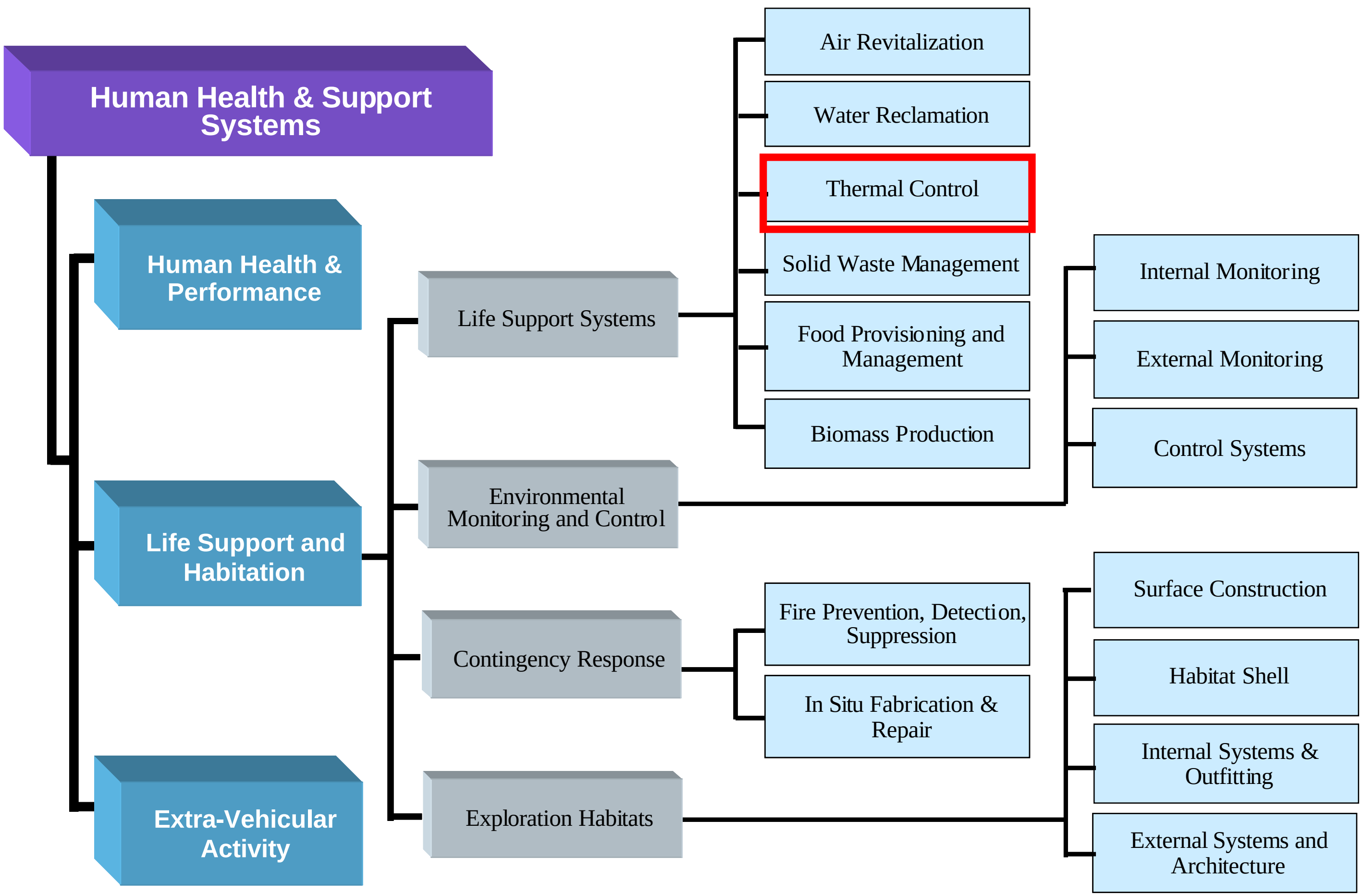
Sub-Capability (Level 5 CBS)	Leading Technology Candidates	Development Needed	Current TRL	Spiral(s)
Urine Pretreatment	Organic acid Increased water flush volume	Effectiveness assessment and delivery system	2 3	1-5
Primary Treatment (organic removal)	Rotating distillation process (combines primary and secondary treatment) Biological systems Crop systems	System integration Microgravity capability Sizing, integration dev. System, integration dev.	3 – 5 3 2	3-5 3-5 5
Secondary Treatment (Inorganic removal)	Membrane process Rotating distillation system	Membrane development System integration	3 3-5	3-5 3-5
Brine recovery	Distillation system Membrane process Solid waste processors		3-5 3 2	3-5 3-5 5
Post-processing and disinfection	Low temperature catalysis Photocatalysis Photolysis Ion exchange	Catalyst development Catalyst and system development System test and integration	3 2 3 5	3-5 3-5 3-5 3-5
Potable water storage	Silver Residual requirement replaced with recirculating tank disinfection and point of use disinfection	Technology assessment and development	6 2	1-5 1-5

Water Recovery Systems Figures of Merit

Advanced Planning & Integration Office

Sub-Capability (Level 5 CBS)	Figures of Merit	
	Description	Units
Waste water storage	Toxicity of urine pretreatment	N/A
Primary processing Secondary processing Brine recovery Post-processing and disinfection	Percent water recovered Power System mass / volume Water quality Consumable mass	% W / liter kg / m^3 Varies kg
Potable water storage	Consumable required for residual disinfection Microbial water quality	kg CFU/ml

Active Thermal Control



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

Advanced Planning & Integration Office

- **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

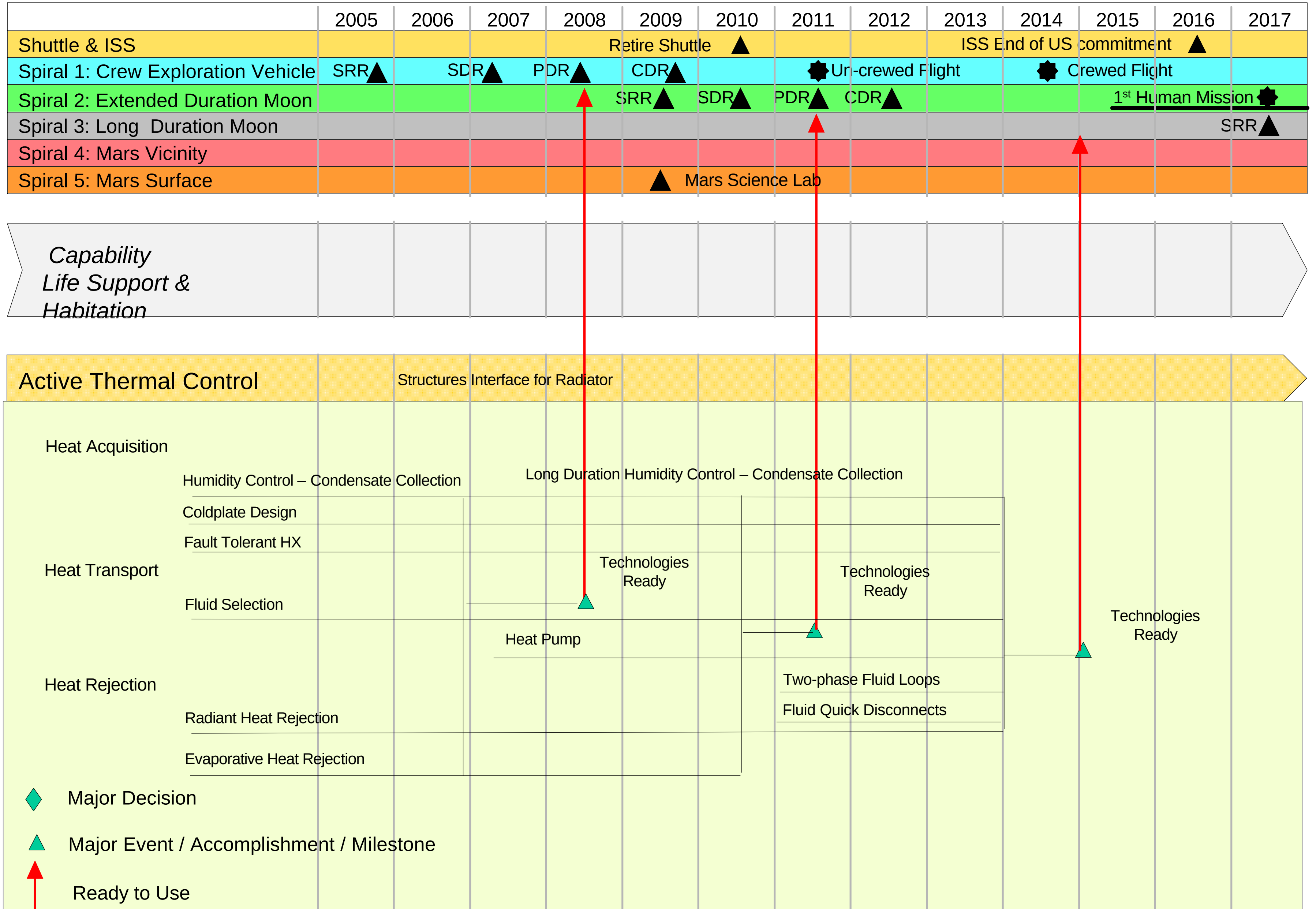
Advanced Planning & Integration Office

- 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

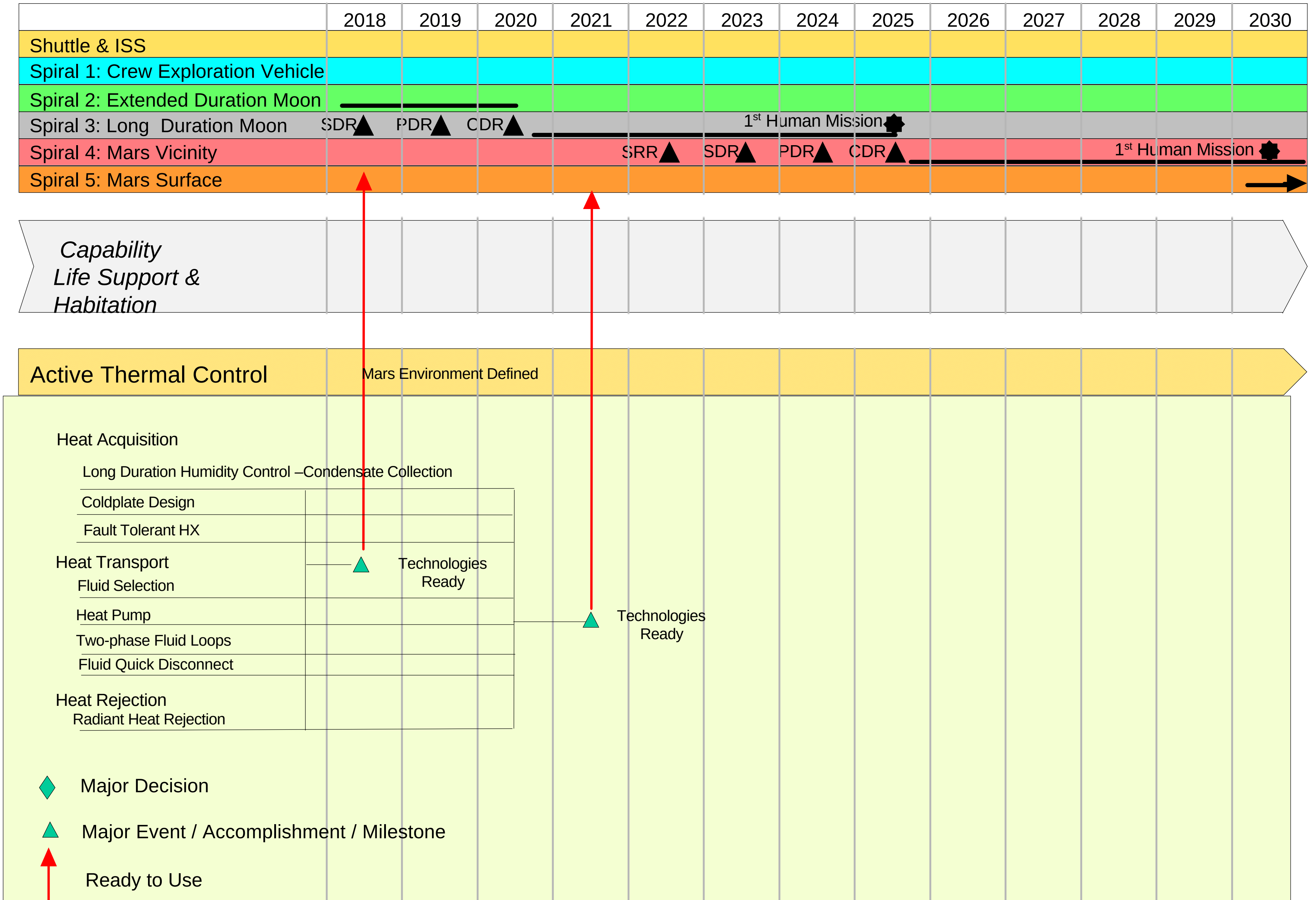
Active Thermal Control Requirements /Assumptions

- **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



Active Thermal Control Roadmap



Active Thermal Control Maturity Level – Capabilities

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Provide cooling to avionics and other heat producing hardware Transfer energy from one fluid loop to another Provide temperature and humidity control for cabin air Transport energy throughout the vehicle Provide radiant heat rejection Provide evaporative heat rejection	Mass reduction for coldplates Fault tolerance for interpath leakage No development needed Fluids that can be used inside the cabin and in radiators Mass reductions and ability to handle mission transients for radiators Extended operating range that included vacuum and post landing; decreased sensitivity to feedwater contamination	1 2 7 2 2 2
Spiral 2 Lunar Surface (2011)	Same as Spiral 1 except Provide heat rejection in hot Lunar environments	Same as Spiral 1 except Heat pump systems are needed	2
Spiral 3 Long Duration Lunar Surface (2014)	Same as Spiral 1 except Evaporative heat rejection is not required Requirements for assembly and maintenance during the mission Increased heat loads	Same as Spiral 1 except Long duration systems are needed for humidity control and condensate collection Fluid Quick disconnect Two-phase fluid loops	1 1 2
Spiral 4 Mars Vicinity (2017)	Same as Spiral 3	Same as Spiral 3	
Spiral 5 Initial Mission Mars Surface (2021)	Same as Spiral 3	Same as Spiral 3	

Active Thermal Control Maturity Level – Technologies

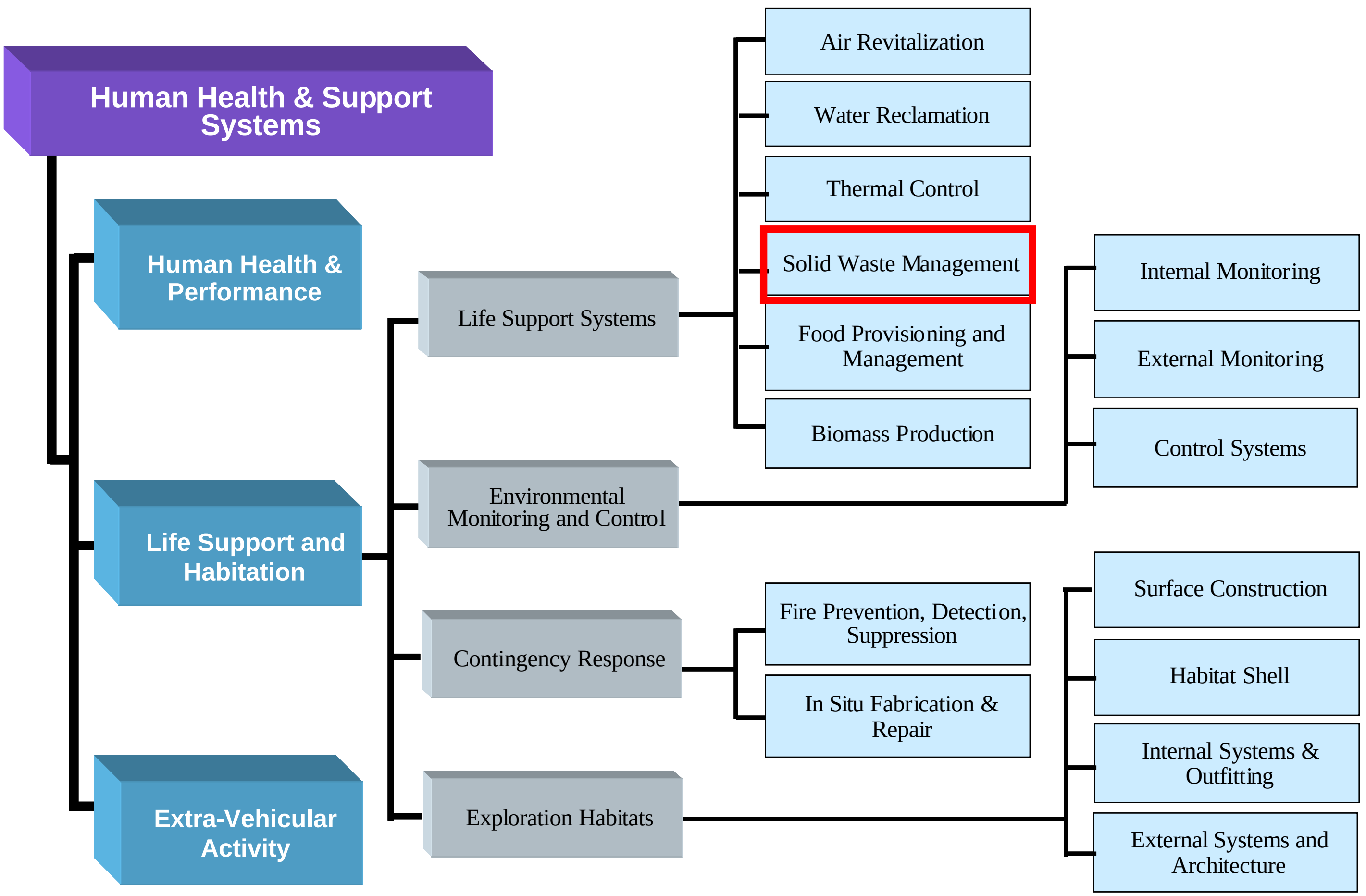
Sub-Capability (Level 5 CBS)	Leading Technology Candidates	Development Needed	Current TRL	Spiral(s)
Heat Acquisition				
Provide cooling to avionics and other heat producing hardware	Composite Coldplate Shelf	Mass reduction	3	1-5
Transfer energy from one fluid loop to another	Fault Tolerant Heat Exchanger	Additional barrier for interpath leakage	4	1-5
Provide temperature and humidity control for cabin air	Porous Media Condensing Heat Exchanger; Vortex Dehumidification	Long duration humidity control and condensate collection	3; 4	3-5
Heat Transport				
Transport energy throughout the vehicle	Fluids that enable single loop systems	Performance, safety, compatibility	3	1-5
Provide heat rejection in hot Lunar environments	Vapor Compression Heat Pump	Gravity independent performance	3	2-5
Increased heat loads	Low Power Two-phase ATCS	Decrease mass and power	3	3-5
Requirements for assembly and maintenance during the mission	none	Reliable and EVA compatible	-	3-5
Heat Rejection				
Provide radiant heat rejection	Lightweight radiator; structural radiator	Mass reduction; ability to handle mission transients	5; 3	1-5
Provide evaporative heat rejection	Multi-environment evap; Contamination Insensitive Sublimator	Larger operating envelope; longer life	3; 3	1, 2

Active Thermal Control
Figures of Merit

Advanced Planning & Integration Office

Sub-Capability (Level 5 CBS)	Figures of Merit	
	Description	Units
Heat Acquisition Provide cooling to avionics and other heat producing hardware Transfer energy from one fluid loop to another Provide temperature and humidity control for cabin air	Heat transfer per coldplate mass Barriers between fluids Operational life	W/kg Number of barriers Hours
Heat Transport Transport energy throughout the vehicle Provide heat rejection in hot Lunar environments Increased heat loads Requirements for assembly and maintenance during the mission	Heat transfer per system mass Radiator fluid temperature Heat transfer per power input Reliability	W/kg K W_{th}/W_{power} Time between failure
Heat Rejection Provide radiant heat rejection Provide evaporative heat rejection	Mass per surface area Operating pressure range Operational life	Kg/m^2 kPa Hours

Waste Management



Waste Management Description

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.

Waste Management Benefits

Advanced Planning & Integration Office

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.

Name	ISS ESM	ALS ESM	delta	comment
Waste (clothing,feces, food packaging, scraps, etc.) safener - e.g. container vs. mineralizer	3,933	1,000	2,933	assume containers for ISS - processor for ALS
Waste Disposal on Mars surface	5,899	1,000	4,899	savings on return propulsion
Water in feces and waste	2,000	500	1,500	water saving vs cost
Clothing	6,780	1,200	5,579	clothing washer
Compaction	3,000	1,000	2,000	assume crewed vol=200 kg/m^3, ISS is 1/2 compact by hand

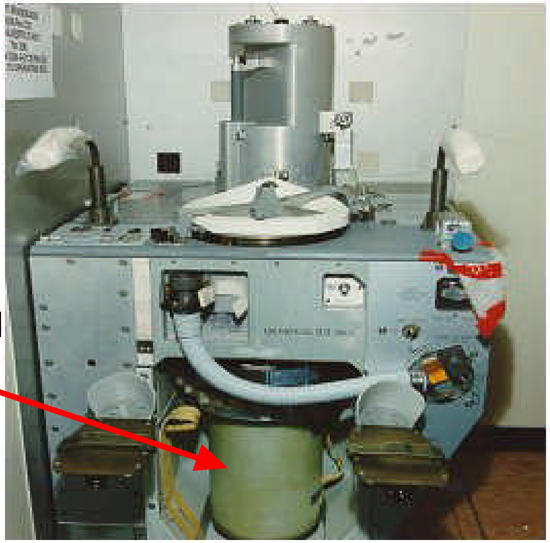
Waste Management
Current State-of-the-Art

Advanced Planning & Integration Office

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.

Disposable
Feces container
Untreated



Waste Collection System

Hand Compacted Waste - Shuttle

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**

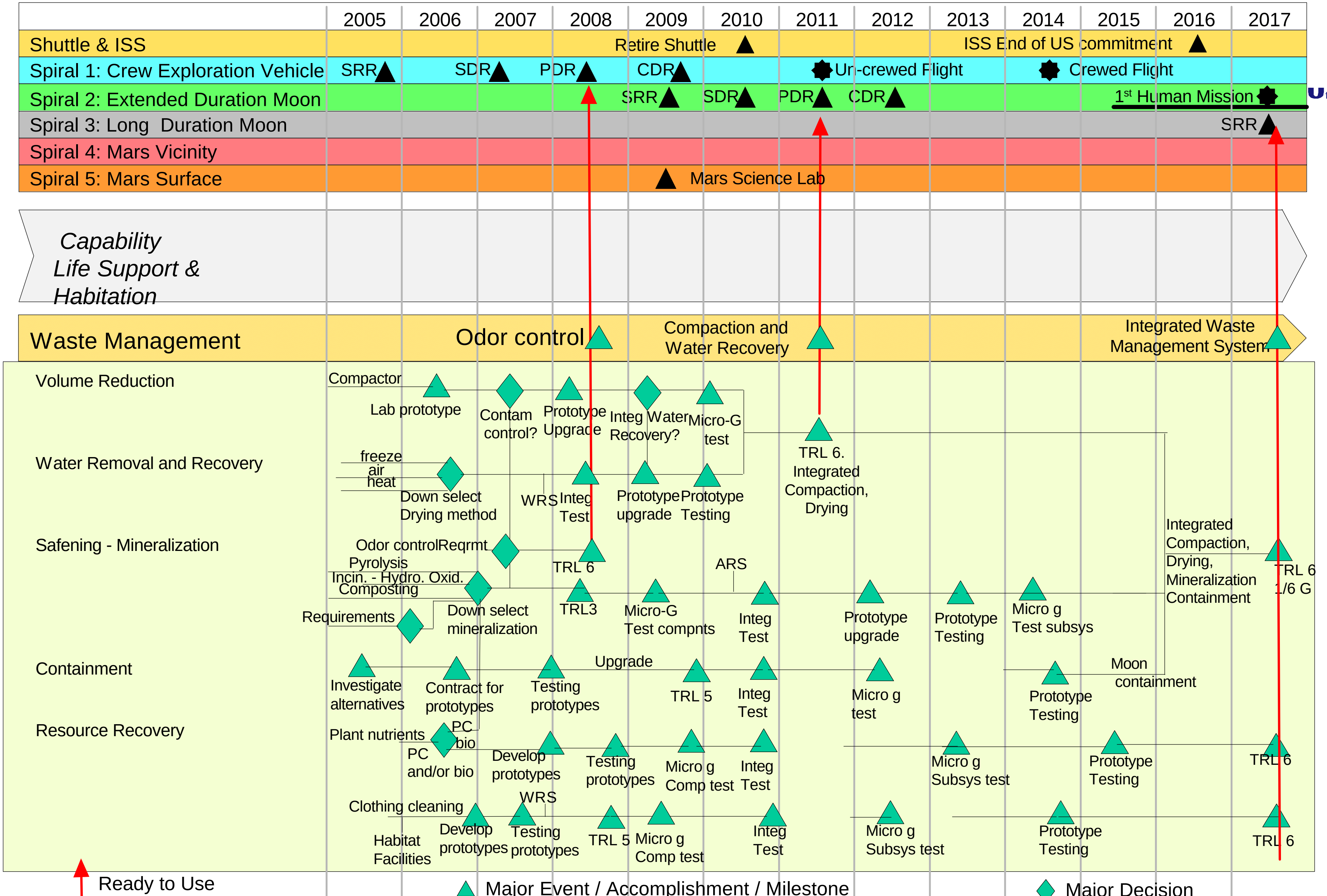
    Odor, clutter, and other qualities of waste can negatively affect crew outlook and performance. Detailed requirements for waste are not yet established. It is assumed that this requirement supports the need for improved management of waste via deodorization, compaction, drying, and mineralization.
  - **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.

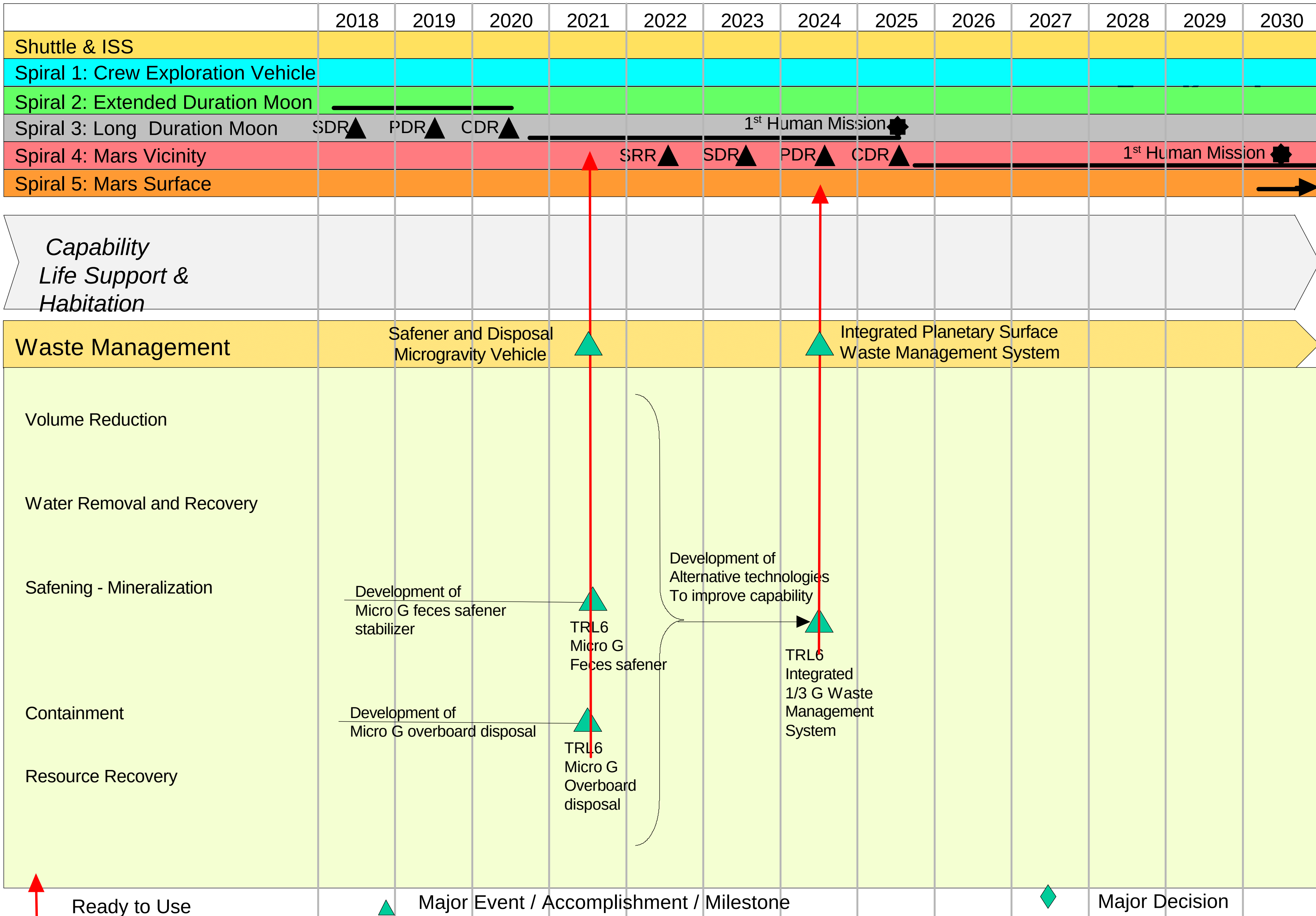
Waste Management Requirements /Assumptions

- **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



Waste Management Roadmap



Waste Management Maturity Level – Capabilities

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs - Gaps	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Volume reduction and stabilization	Existing waste management can support spiral 1, although some benefits could be obtained from odor control	2
Spiral 2 Lunar Surface (2014)	Volume reduction Stabilization	There is no automated or mechanical volume reduction capability ready for flight Odor control and some vacuum drying stabilization may be needed	2 1
Spiral 3 Long Duration Lunar Surface (2017)	Volume reduction Water Recovery Safening- stabilization (mineralization) Containment and Disposal Resource Recovery	Need flight ready mechanical volume reduction Need flight ready capability for water recovery from solid waste Need to test advanced prototypes for safening and stabilization of waste on long duration missions Need flight ready moon containment and test prototype for Mars containment and disposal Need flight ready capability as clothing cleaning and advanced test prototype for nutrient recovery	2 2 2 1 1
Spiral 4 Mars Vicinity (2021)	Same as Spiral 3	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 Overboard disposal is in space	 1 1
Spiral 5 Initial Mission Mars Surface (2024)	Same as Spiral 3	Same as Spiral 3 except Operation on 1/3 rather than 1/6 g Operational rather than test prototypes	 1

Waste Management Maturity Level - Technologies

Advanced Planning & Integration Office

Sub-Capability (Level 5/6 CBS)	Leading Technology Candidates	Spiral(s)	Current TRL
Volume reduction Safening - Stabilization	Plastic heat melt compactor	2,3,4,5	2
Water removal and recovery Safening - Stabilization	Lyophiliization	3,4,5	3
Water removal and recovery Safening - Stabilization	Air drying	3,4,5	2
Water removal and recovery Safening - Stabilization	Vacuum drying	3,4,5	1
Volume reduction Water removal and recovery Safening - Stabilization	Pyrolysis	3,4,5	3
Volume reduction Water removal and recovery Safening - Stabilization Resource recovery - nutrients	Incineration	3,4,5	3
Volume reduction Water removal and recovery Safening - Stabilization Resource recovery - nutrients	Hydrothermal oxidation	3,4,5	3

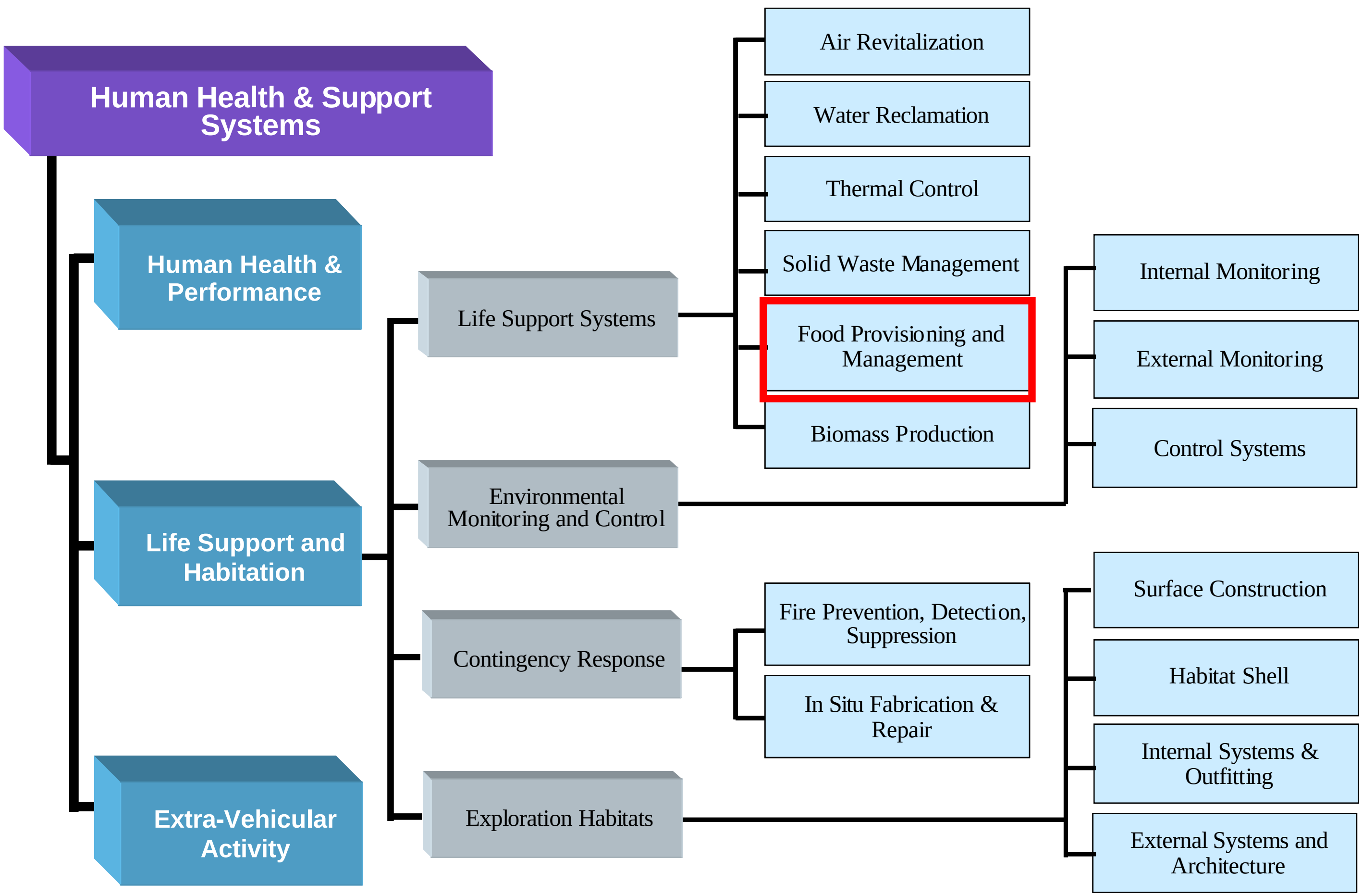
Waste Management
Maturity Level - Technologies

Sub-Capability (Level 5/6 CBS)	Leading Technology Candidates	Spiral(s)	Current TRL
Volume reduction Water removal and recovery Resource recovery - nutrients Safening - Stabilization	Composting - aerobic	3,4,5	2
Volume reduction Resource recovery - nutrients Safening - Stabilization	Composting - anaerobic	3,4,5	2
Resource Recovery -clothes	Clothes washer	3,4,5	1
Containment	Containers	3,4,5	1

Waste Management Figures of Merit

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

Food Provisioning and Management



Food Provisioning and Management Description

Advanced Planning & Integration Office

- **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

Advanced Planning & Integration Office

- 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

Advanced Planning & Integration Office

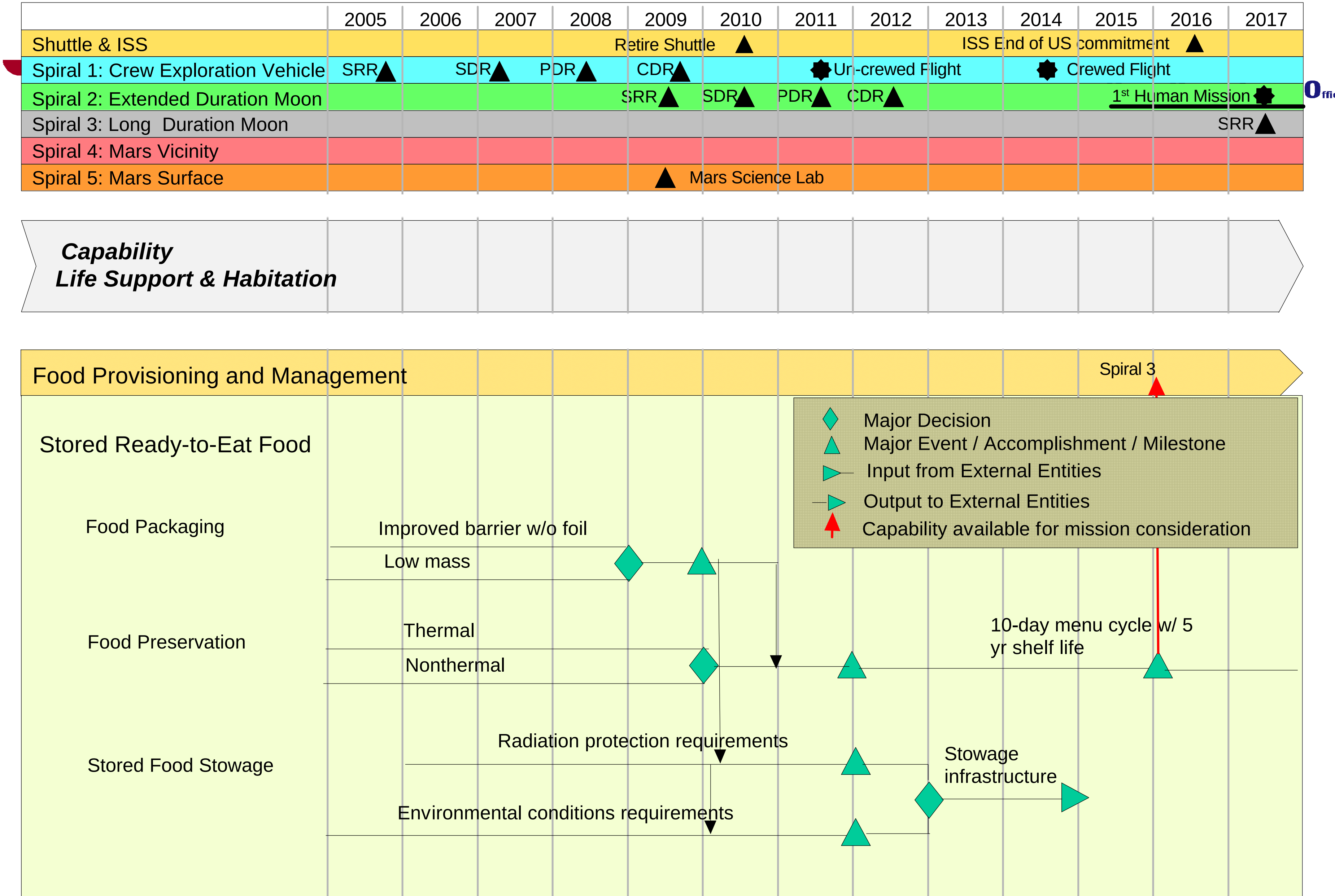
- Stored Ready-to-Eat Foods
  - Food packaging
    - MRE pouch used for thermostabilized and irradiated foods has a high barrier to moisture and oxygen due to the aluminum layer. However, it is dense and hard to process by solid waste processing team
    - Poly material used for freeze dried foods and 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

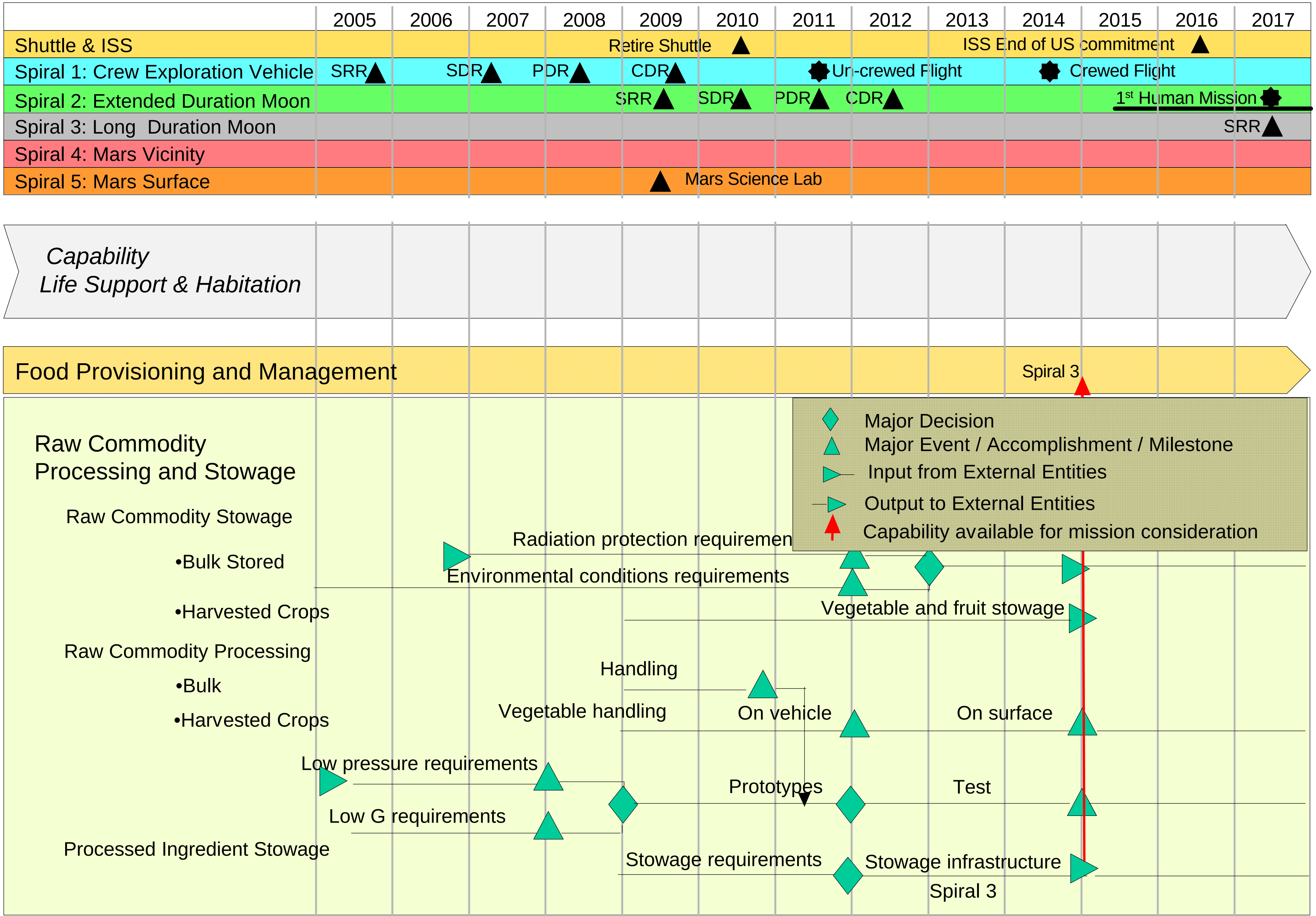
Advanced Planning & Integration Office

- 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

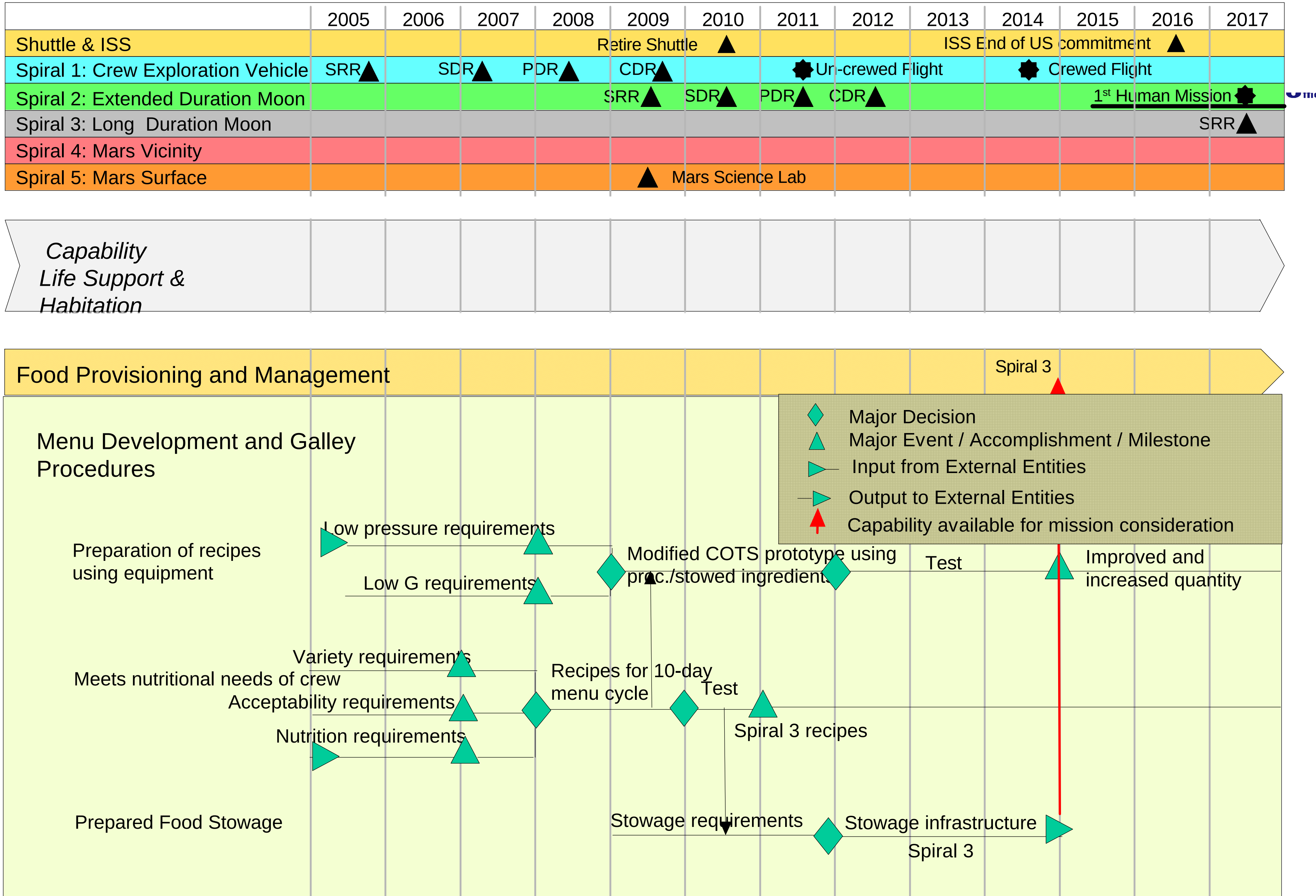
Food Provisioning and Management Roadmap



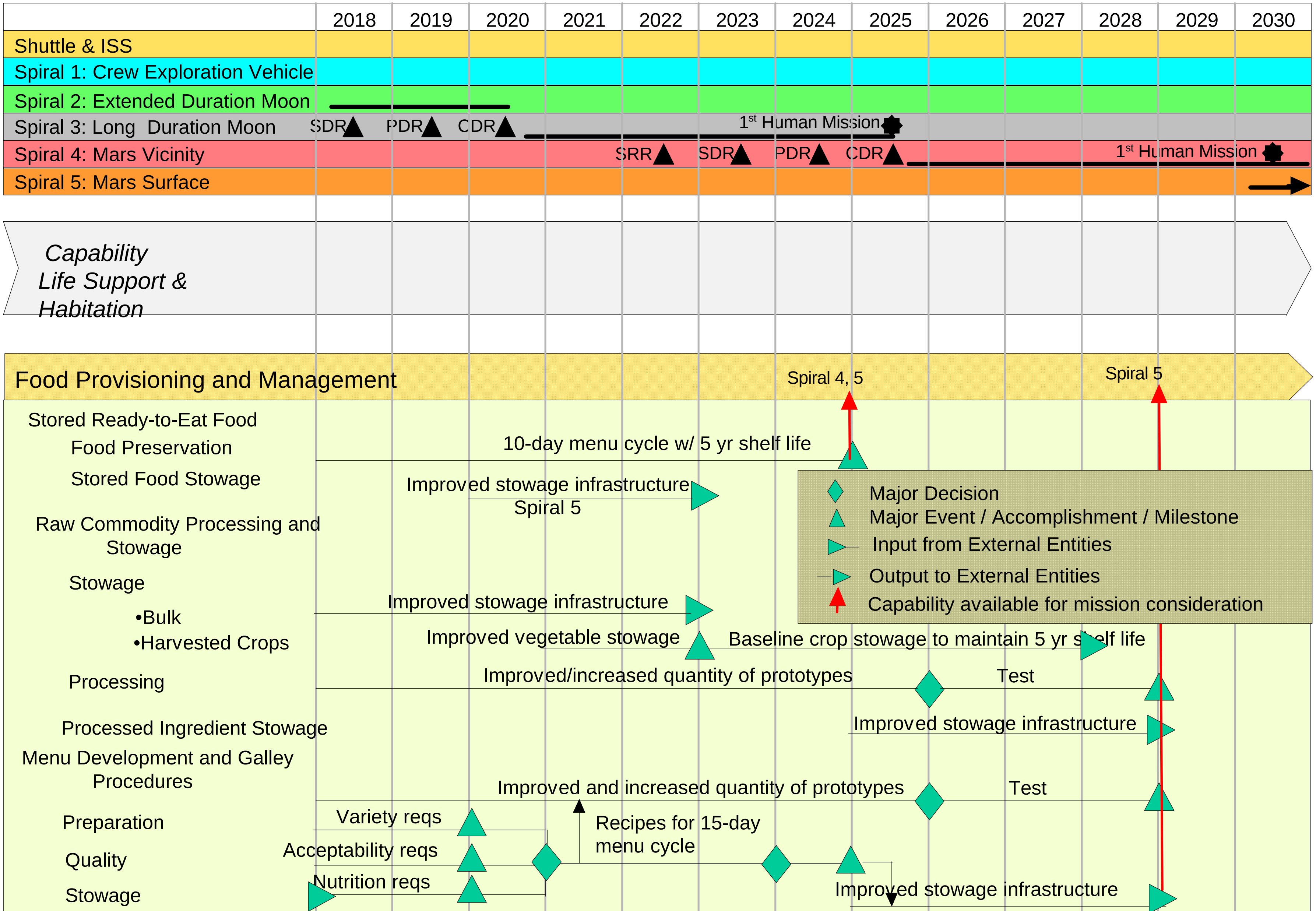
Food Provisioning and Management Roadmap



Food Provisioning and Management Roadmap



Food Provisioning and Management Roadmap



Food Provisioning and Management Maturity Level - Capabilities

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Stored Ready-to-Eat Food	Improved barrier packaging with easier solid waste processing capability. Current food preservation and stowage capabilities supports Spiral 1.	1 7
Spiral 2 Lunar Surface (2011)	Same as Spiral 1	Spiral 1 development supports Spiral 2	1, 7
Spiral 3 Long Duration Lunar Surface (2014)	Stored Ready-to-Eat Food Raw commodity processing and stowage Menu development and galley procedures	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	2 1 2 2
Spiral 4 Mars Vicinity (2017)	Stored Ready-to-Eat Food	Same as Spiral 2 except 5-yr shelf life stored food system with 10-day menu cycle	2
Spiral 5 Initial Mission Mars Surface (2021)	Stored Ready-to-Eat Food Raw commodity processing and stowage Menu development and galley procedures	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	2 1 2 2

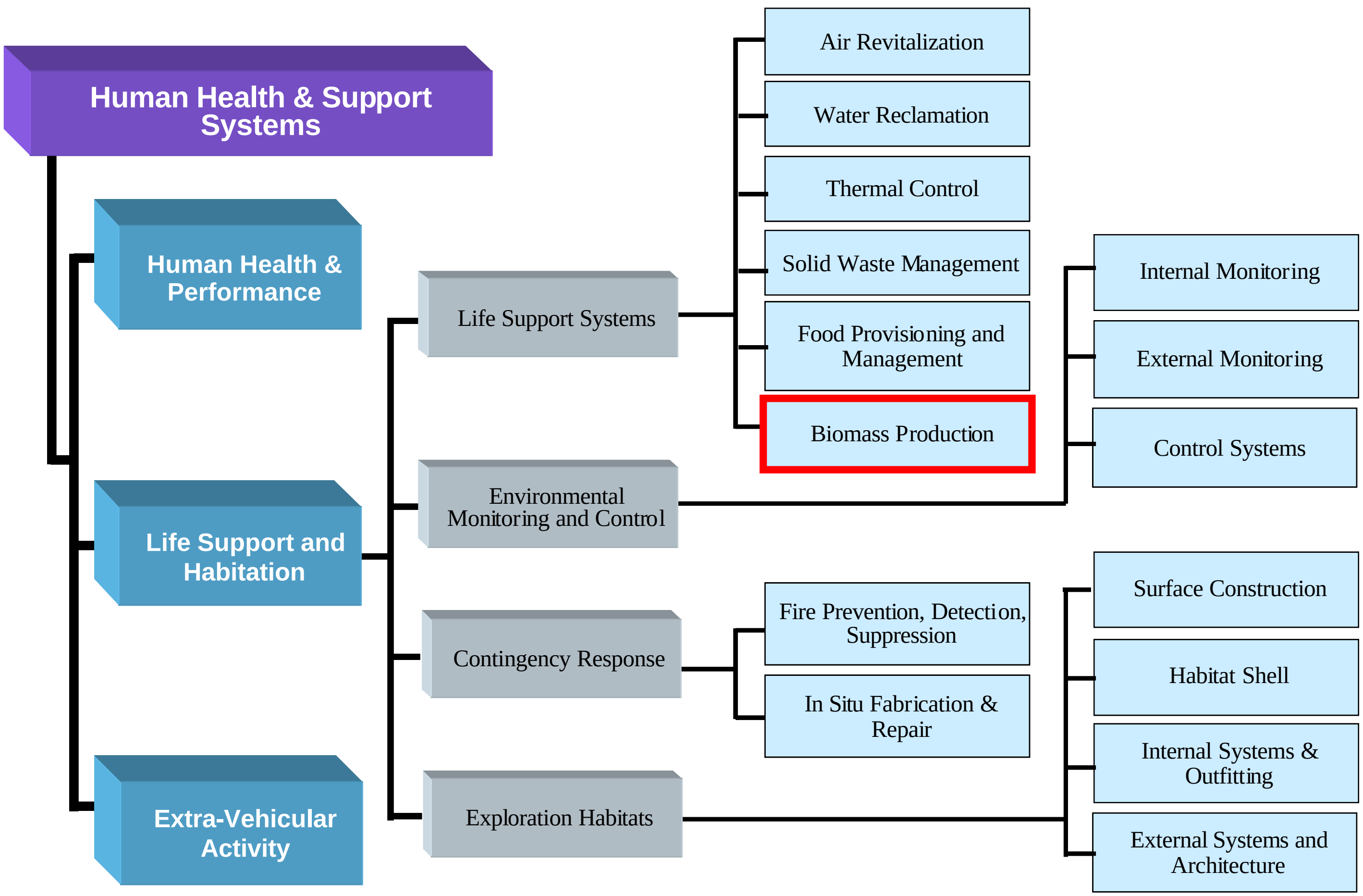
Food Provisioning and Management Maturity Level - Technologies

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

Food Provisioning and Management Figures of Merit

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

Biomass Production



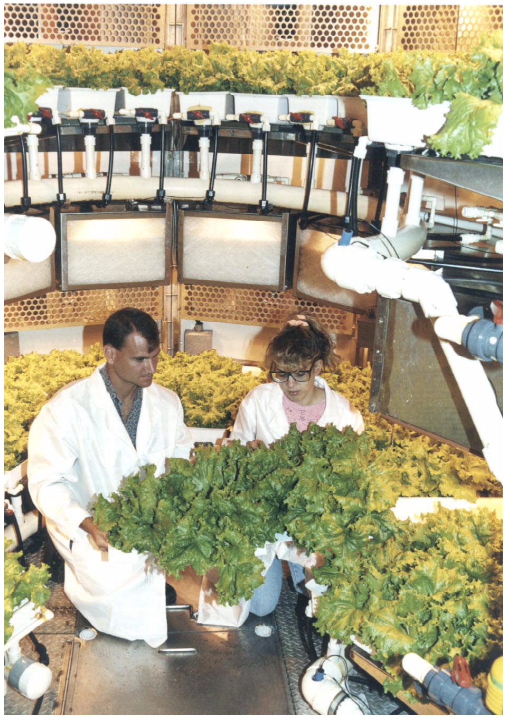
Biomass Production Description

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 O_2 needs and 20% of the CO_2 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_2 reduction, O_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

Advanced Planning & Integration Office

- **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 m- 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 m^2 growing area, and most < 0.1 m^2.*

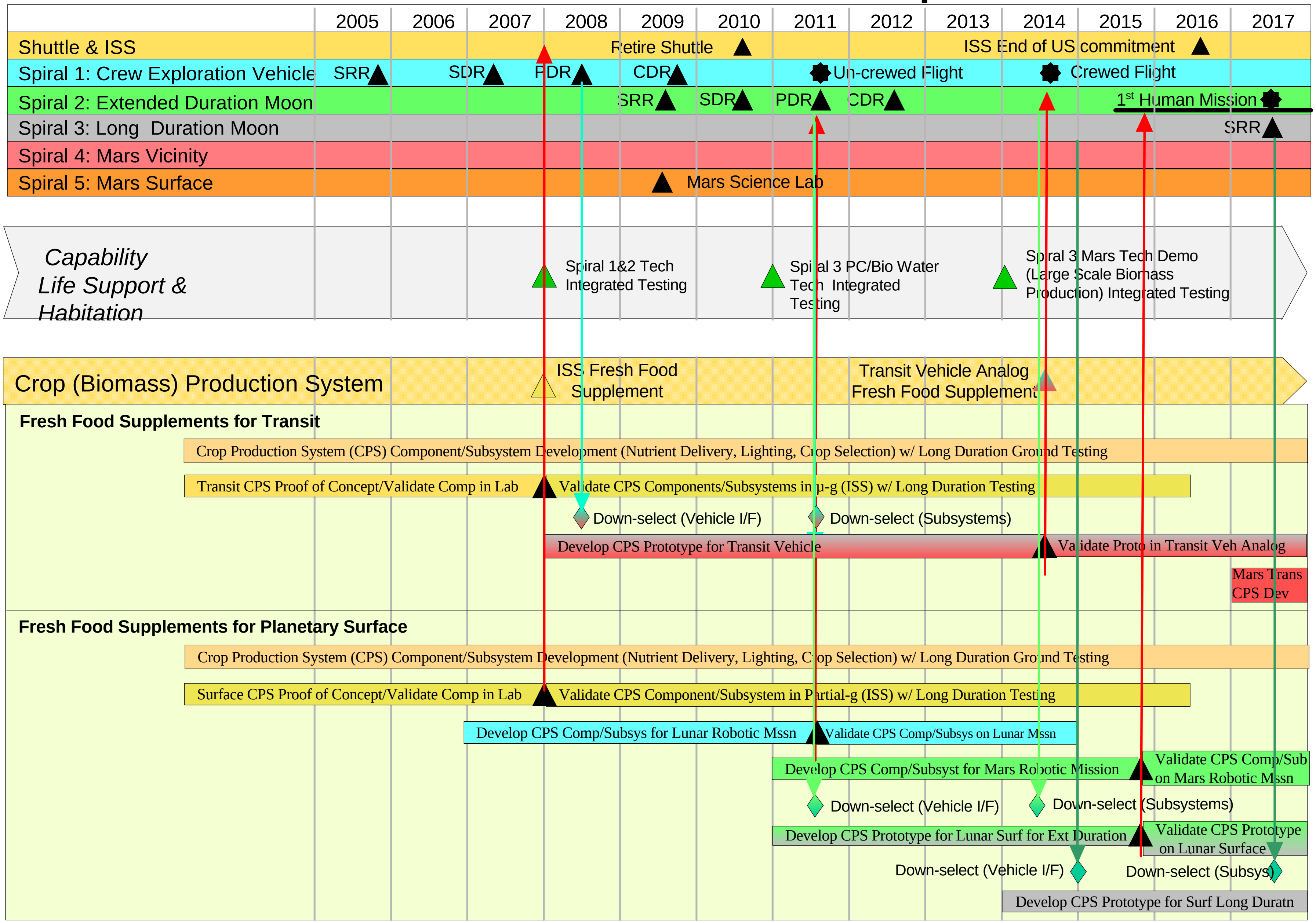
Biomass Production Requirements /Assumptions

Advanced Planning & Integration Office

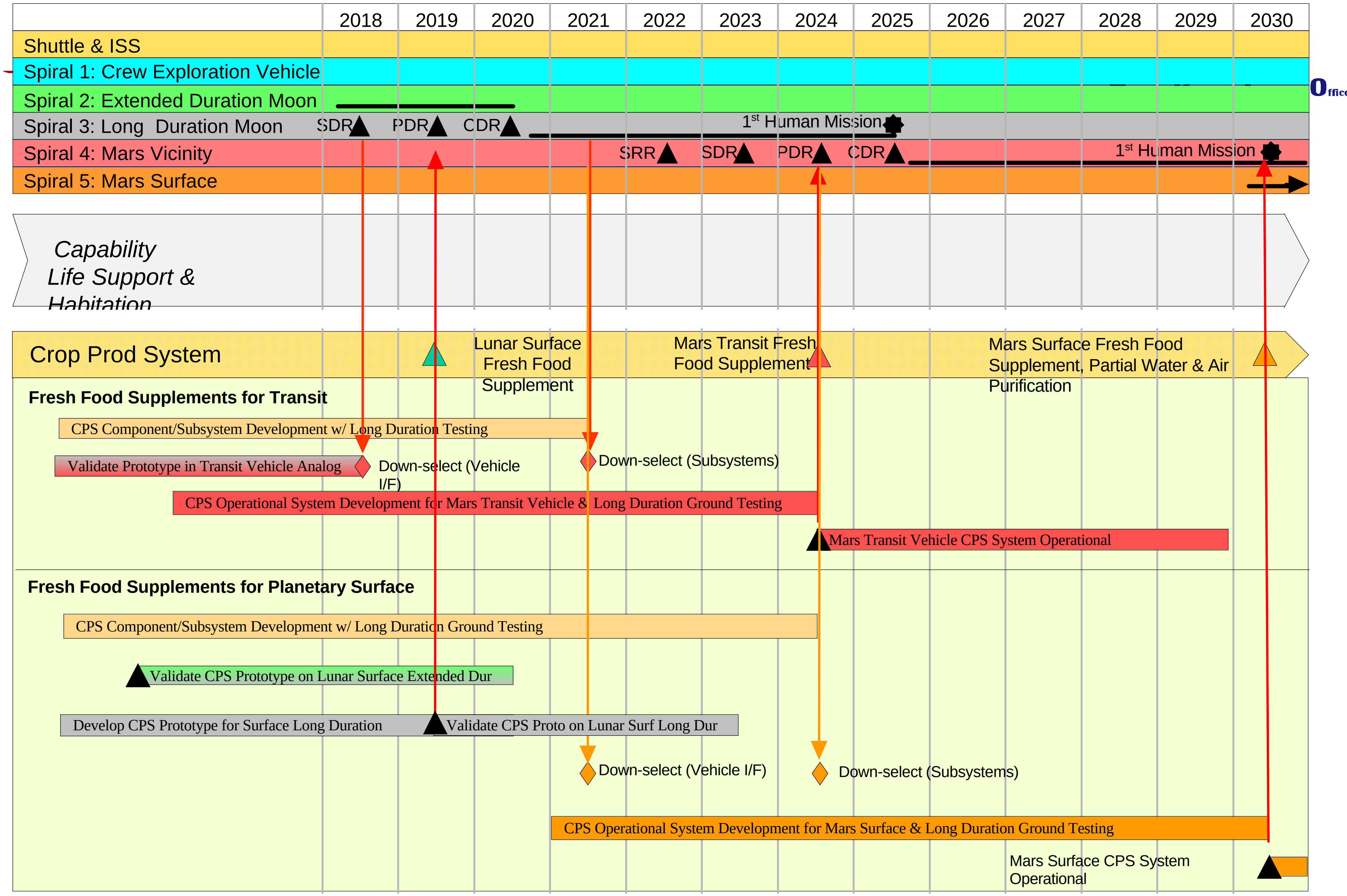
- **Assumptions that drove the need for the capability**
  - **Continuous need for fresh foods in the crew's diet.**
  - **Positive effects of living plants on crew well-being and performance.**
  - **Eventual need to rely on bioregenerative technologies for food, air, and water regeneration for true 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 m–g crop production system.**
  - **Spiral 5 (Mars Surface), operational planetary surface crop production system. Expansion of bioregenerative life support capability.**

Biomass Production Roadmap



Biomass Production Roadmap



Biomass Production Maturity Level – Capabilities

Mission	Capability (Level 4 CBS)	Leading Capability Candidates	CRL	Date Needed
Spiral 1	**Robotic Lunar Mission Payload (CPS Component Testing)**	**Integration with Lunar Surface Lander Mission**		**2008**
Spiral 2 Extended Duration Lunar Surface	**Robotic Mars Mission Payload (CPS Component Testing)**	**Integration with Mars Surface Lander Mission**		**2010**
Spiral 3 Long Duration Lunar Surface	**Production of Fresh Food for Surface (Prototype CPS)**	• **CPS Inside the Lander** • **CPS Attached to Lander** • **CPS Deployed on Surface**	**2** **1** **1**	**2014**
Spiral 4 Mars Vicinity	**Production of Fresh Food for Transit (Operational VPU)**	**Closed, fixed-volume chamber** **Open, fixed-volume chamber** **Open, expandable volume chamber** **Open, conveyor system**	**3** **4** **2** **2**	**2019**
Spiral 5 Initial Mission Mars Surface	**Production of Fresh Food for Surface (Operational CPS)** **Bioregenerative Integrated Crop Production System (ICPS)**	• **CPS Inside the Lander, Electric or Solar Lighting** • **CPS Attached to Hab Module, Electric or Solar Light** • **CPS Deployed on Surface, Electric or Solar Lighting** • **Multiple CPS Modules**	• **2** • **1** • **1** • **1**	• **2024** • **2024**

Biomass Production Maturity Level – Technologies

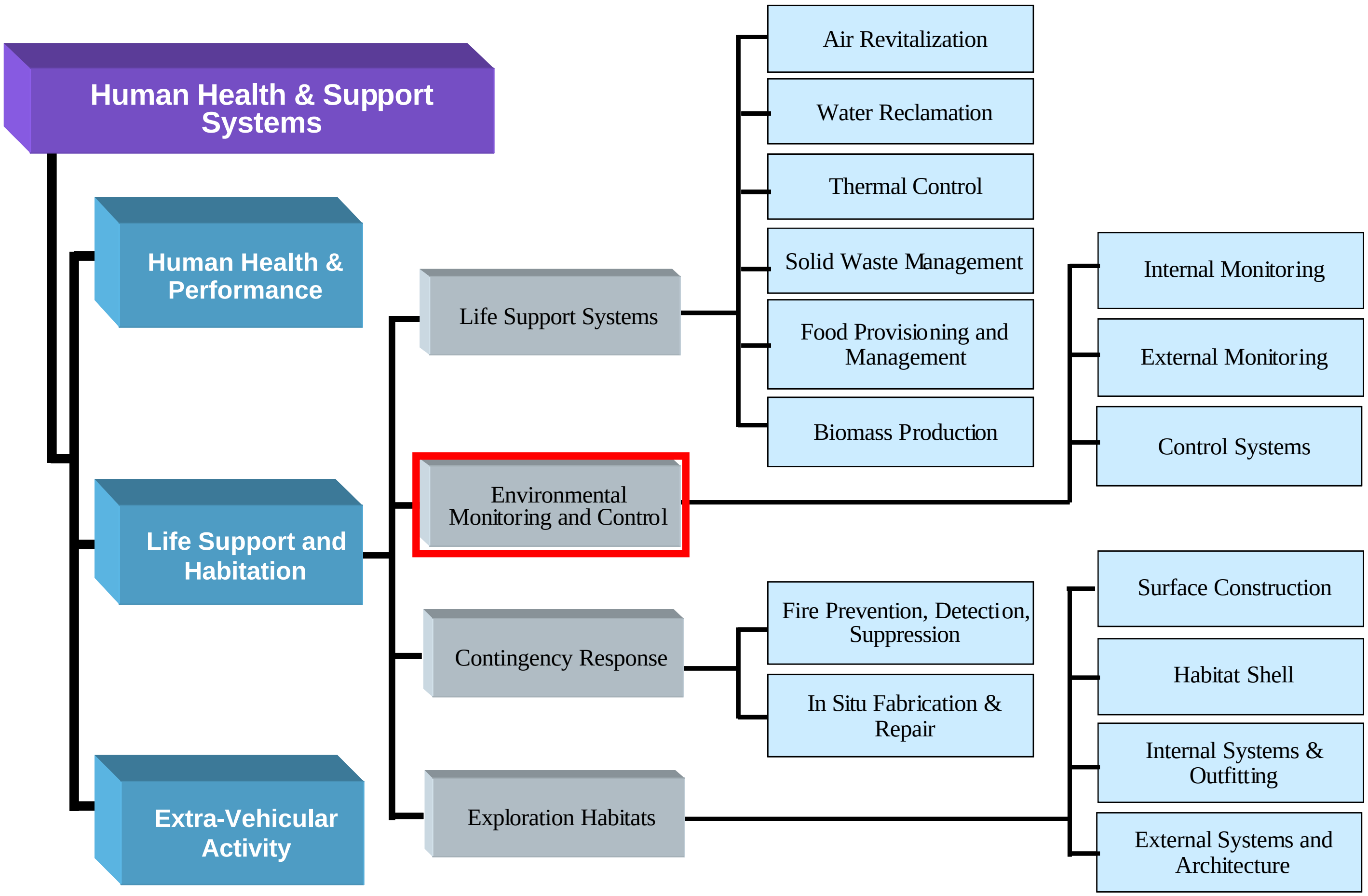
Advanced Planning & Integration Office

Mission	Capability (Level 4 CBS)	Leading Technology Candidates	Current TRL	Date Needed (TRL 6)
Spiral 1	**Robotic Lunar Mission Payload (CPS Component Testing)**	**Transparent materials** **Regolith for crop rooting** **Remote operations**		**2008**
Spiral 2 **Extended Duration Lunar Surface**	**Robotic Mars Mission Payload (CPS Component Testing)**	**Transparent materials** **Regolith for crop rooting** **Remote operations** **Predeployment potential**		**2010**
Spiral 3 **Long Duration Lunar Surface**	**Production of Fresh Food for Surface (Prototype CPS)**	• **LEDs and μ-wave sulfur lamps lighting** • **Surface solar collectors and light conduits** • **Recirculating hydroponics** • **Salad and staple crop cultivars**	**3** **2** **3**	**2014**
Spiral 4 **Mars Vicinity**	**Production of Fresh Food for Transit (Operational Transit CPS)**	**LEDs for lighting** **Transit solar collectors and light conduits** **Porous tube watering with or without media** **Dwarf salad crop cultivars**	**4** **2** **4** **2**	**2019**
Spiral 5 **Initial Mission Mars Surface**	**Production of Fresh Food for Surface (Operational Surface CPS)** • **Bioregenerative Integrated Crop Production System (ICPS)**	• **LEDs and μ-wave sulfur lamps lighting** • **Surface solar collectors and light conduits** • **Recirculating hydroponics** • **Salad and staple crop cultivars** • **Mechanized / automated planting and harvesting** • **Integrated crop / water system** • **Integrated crop / air system**	• **2** • **1** • **2** • **2** • **1** • **2** • **2**	• **2024**

Biomass Production Figures of Merit

Mission	Capability (Level 4 CBS)	Figures of Merit				
		Description	Units	+/-	Current Level	Required Level
Spiral 1 **Lunar Capable Low Earth Orbit CEV**	**Robotic Lunar Mission Payload**	**ESM**	**kg**			
Spiral 2 **Extended Duration Lunar Surface**	**Robotic Mars Mission Payload**	**ESM**	**kg**			
Spiral 3 **Long Duration Lunar Surface**	**Prototype of Planetary Surface Crop Production System (CPS)**	**ESM Edible Productivity Biomass / Unit Energy Efficiency Elec. Lamps**	**kg $g\ m^{-2}\ d^{-1}$ $g\ MJ^{-1}$ %**			
Spiral 4 **Mars Vicinity**	**Operational Vegetable Production Unit (VPU) for Transit**	**ESM Edible Productivity Biomass / Unit Energy Efficiency Elec. Lamps Eff. Solar Collectors**	**kg $g\ m^{-2}\ d^{-1}$ $g\ MJ^{-1}$ % %**		**-- $7\ g\ m^{-2}\ d^{-1}$ $0.4\ g\ MJ^{-1}$ 20% 30%**	**-- $5\ g\ m^{-2}\ d^{-1}$ $0.3\ g\ MJ^{-1}$ 30% 40%**
Spiral 5 Initial Mission Mars Surface	• **Operational Crop Production System (CPS) for Surface** • **Bioregenerative Integrated Crop Production System (ICPS)**	**ESM Edible Productivity Biomass / Unit Energy Efficiency Elec. Lamps Eff. Solar Collectors ESM Edible Productivity Biomass / Energy**	**kg $g\ m^{-2}\ d^{-1}$ $g\ MJ^{-1}$ % % kg $g\ m^{-2}\ d^{-1}$ $g\ MJ^{-1}$**		**• -- • $12\ g\ m^{-2}\ d^{-1}$ • $0.4\ g\ MJ^{-1}$ • 20 % • 30 % • -- • $12\ g\ m^{-2}\ d^{-1}$ • $0.4\ g\ MJ^{-1}$**	**• -- $25\ g\ m^{-2}\ d^{-1}$ • $1.0\ g\ MJ^{-1}$ • 40 % • 50% • -- $25\ g\ m^{-2}\ d^{-1}$ • $1.0\ g\ MJ^{-1}$**

Environmental Monitoring & Control



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

Advanced Planning & Integration Office

- 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

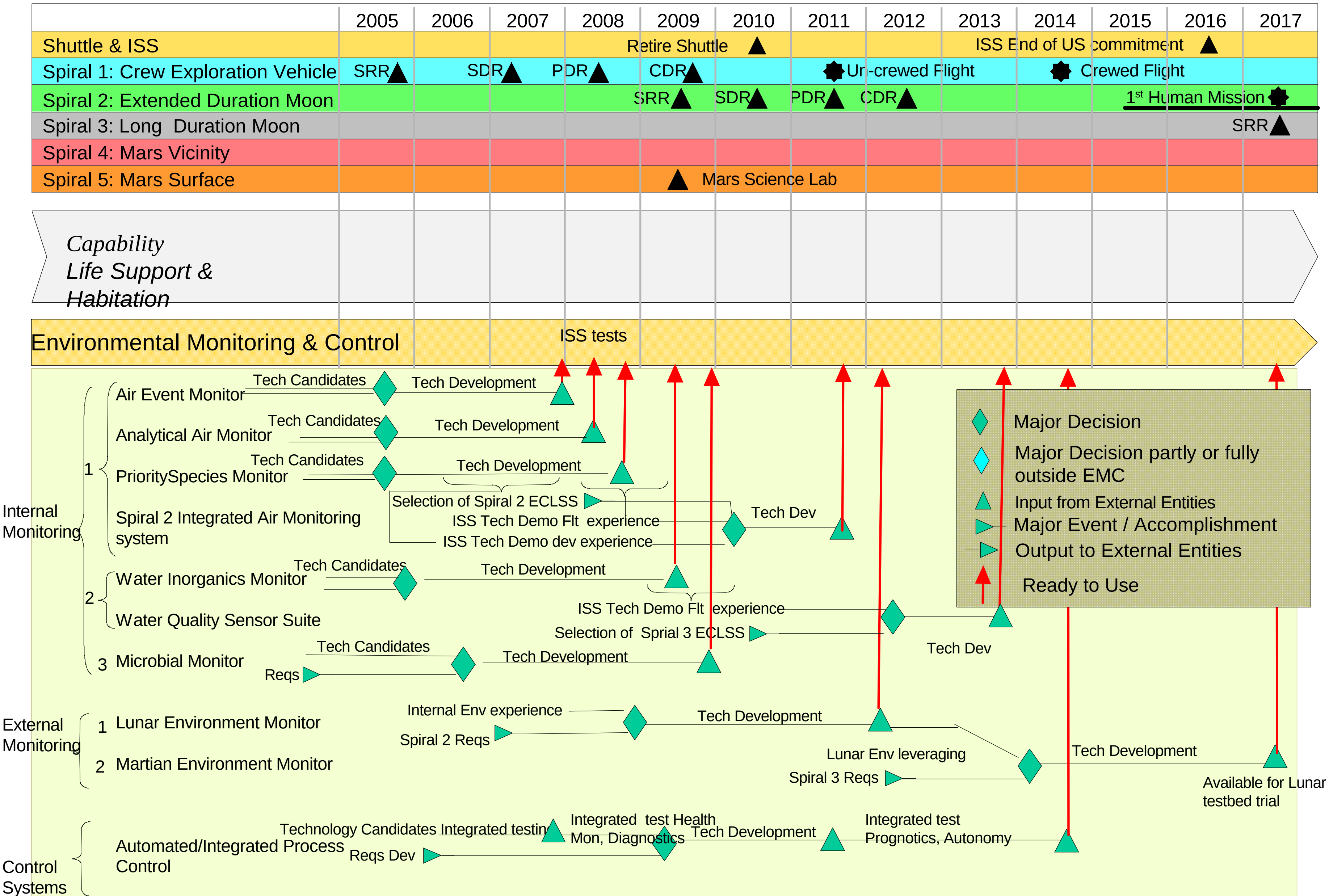
Environmental Monitoring & Control Current State-of-the-Art

- **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

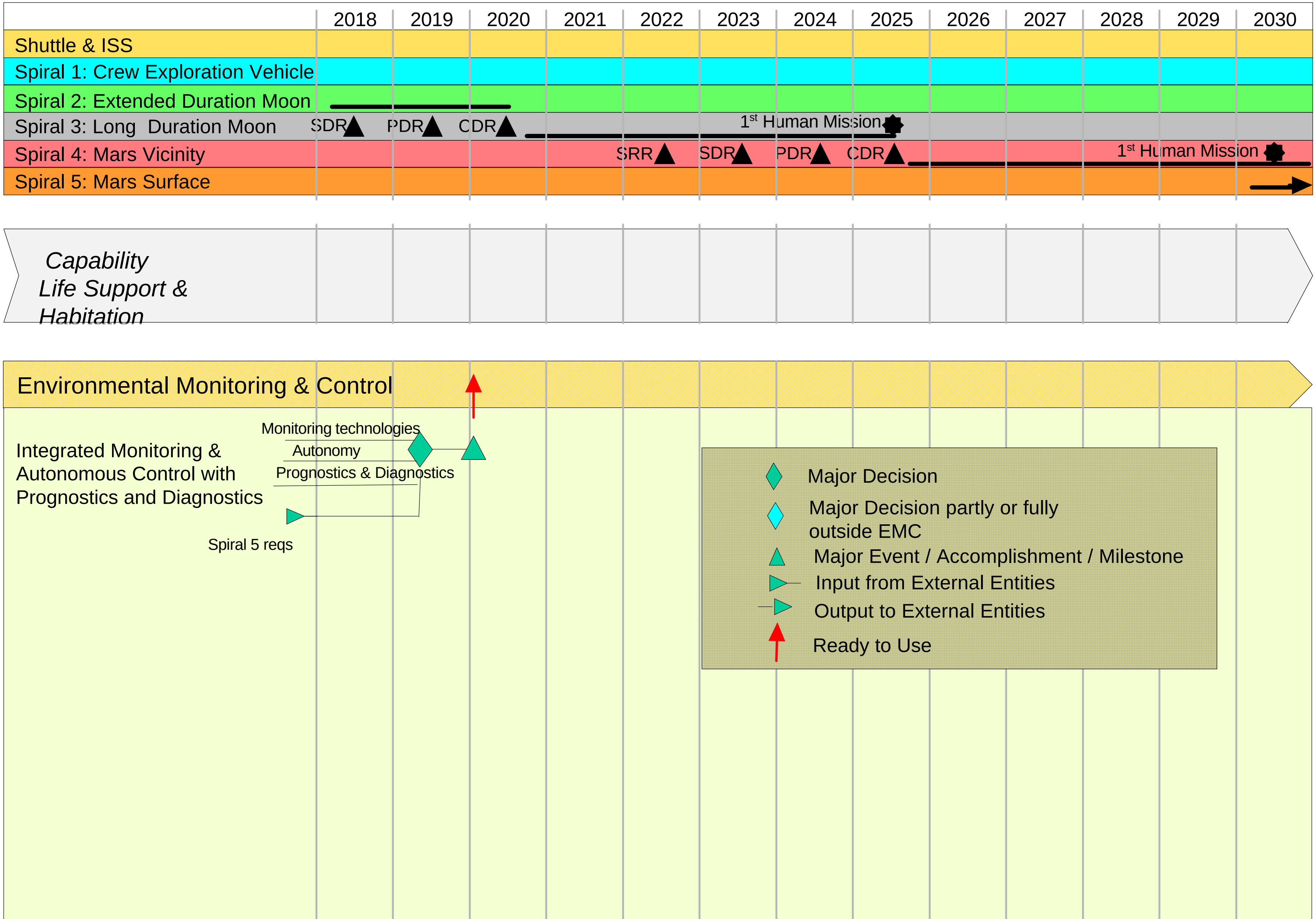
Environmental Monitoring & Control Requirements /Assumptions

- 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



Environmental Monitoring & Control Roadmap



Environmental Monitoring & Control Maturity Level – Capabilities

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Event monitoring Air analysis non-realtime	Detection of Hg and SO_2, other gases doable Grab sample bottle technology in use	1-5 7
Spiral 2 Lunar Surface (2011)	Event monitoring Water inorganics monitor Integrated realtime air monitoring Lunar Environment monitor	Same as above Flight hardware addressing micro-G operation Reliability of chemical analyzer Requirements, lunar surface operation	1-5 3 3 1
Spiral 3 Long Duration Lunar Surface (2014)	Event monitoring Integrated realtime air analysis Water quality suite Lunar Environment Monitor Autonomous Integrated Process Control	Same as above Same as above Organics analysis Above plus tests of simulated Martian conditions if possible Assisted diagnostics and operation	1-5 3 2 1 1
Spiral 4 Mars Vicinity (2017)	As above, tailored to Mars mission Longer communication lags	As above, tailored to Mars mission More autonomous operation	As above
Spiral 5 Initial Mission Mars Surface (2021)	• As above, tailored to Mars surface mission –Martian environment	• As above, tailored to Mars surface mission •Chemically reactive dust	As above

Environmental Monitoring & Control Maturity Level – Technologies

Advanced Planning & Integration Office

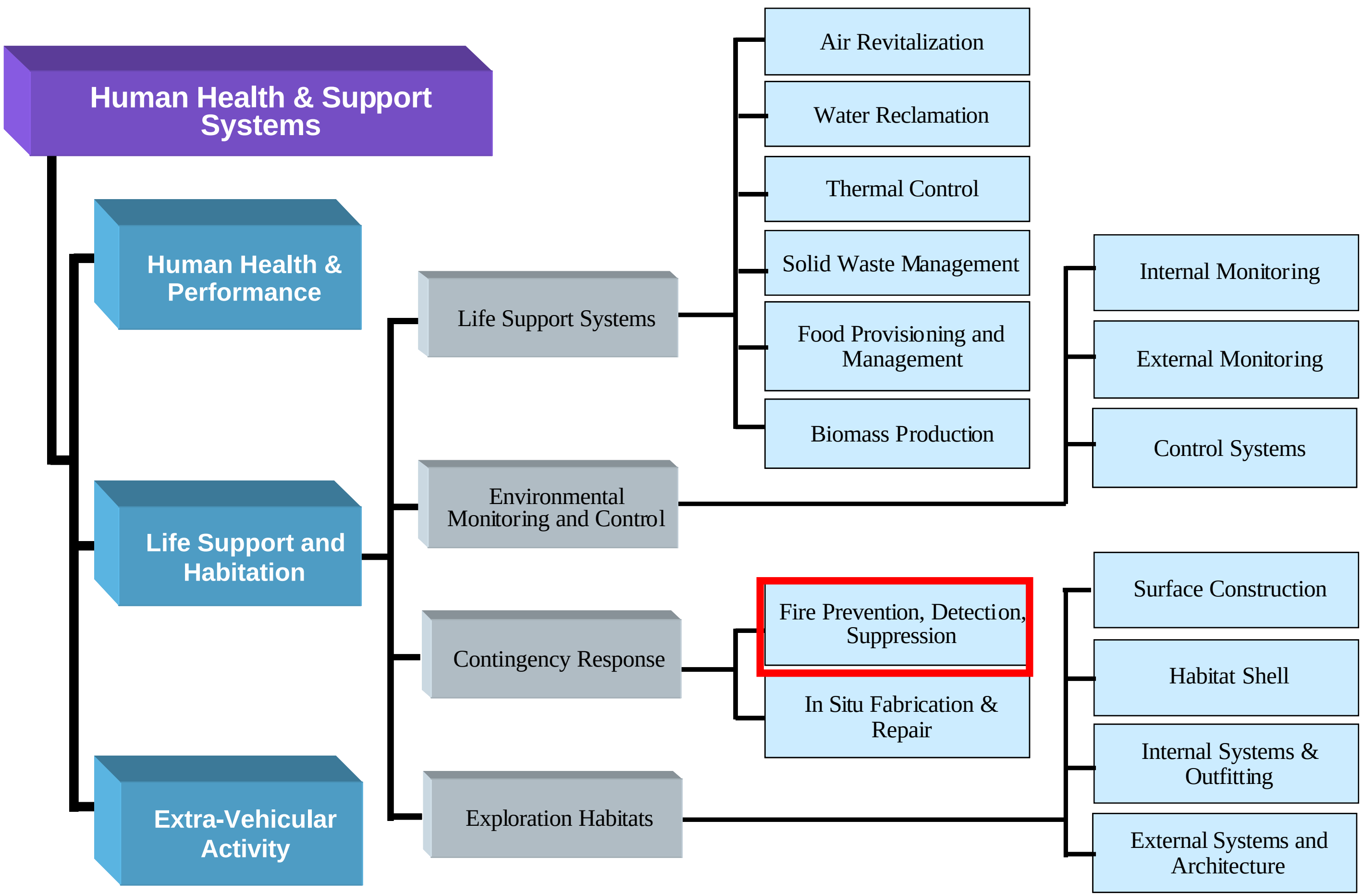
Sub-Capability (Level 5 CBS)	Leading Technology Candidates	Development Needed	Current TRL	Spiral(s)
Event monitoring	Electronic Nose	Additional target gases	5	1-5
Integrated realtime air analysis	GCMS FTIR GCIMS TDL, to be used with one of the above	Test in relevant environment Flight testing Reliability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

Environmental Monitoring & Control Figures of Merit

Advanced Planning & Integration Office

Sub-Capability (Level 5 CBS)	Figures of Merit	
	Description	Units
Event monitoring Integrated realtime air analysis Water quality suite Lunar Environment Monitor	% priority targets measured Number of targets/resource demands Mean Time Between Failure Mean Time Between Maintenance	% #targets/mass months months
Autonomous Integrated Process Control	Reduced Number of human interactions Reduced resource req'ts Reduced downtime Reduced time to detect fault	#events or hours Mass, power Time Time

Fire Prevention, Detection, & Suppression (FPDS)



Fire Prevention, Detection, and Suppression Description & Introduction

Advanced Planning & Integration Office

Critical Issue

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

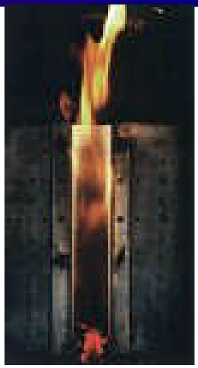
Advanced Planning & Integration Office

- 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

- **NASA-STD-6001: Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion**
  - **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**

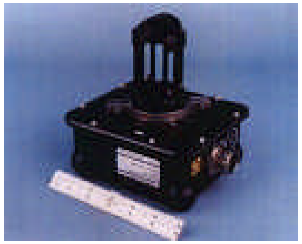
> ➢ All existing technology and requirements are based on 1-g fire behavior
>
> ➢ Effectiveness in low-g is unproven as evidenced by the inconsistent approaches



Sample failing NASA-STD-6001: Test 1

STS SD

FGB SD



US SD

SM SD

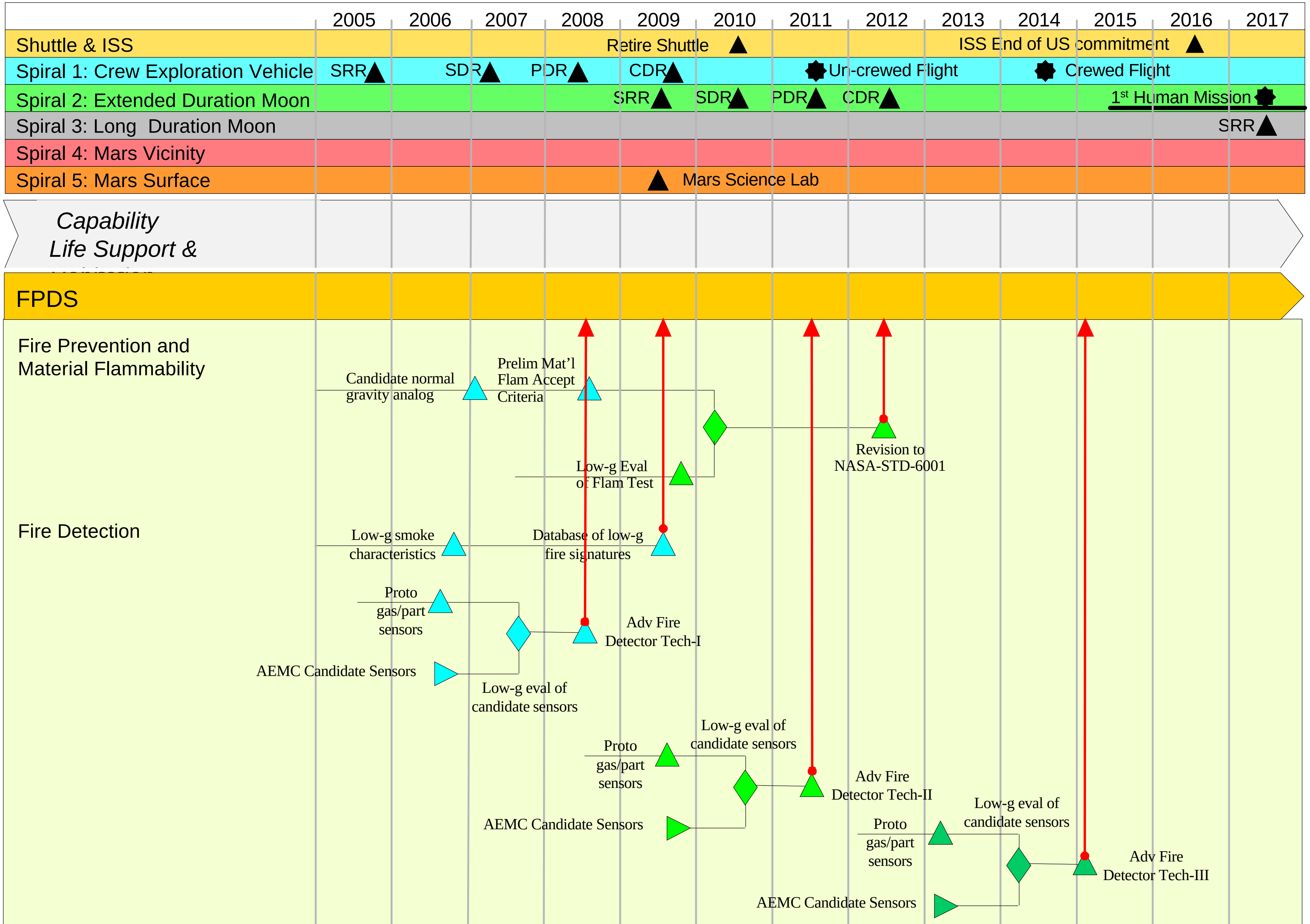
US CO_2 fire extinguisher

Requirements/Assumptions for Fire Prevention, Detection, and Suppression

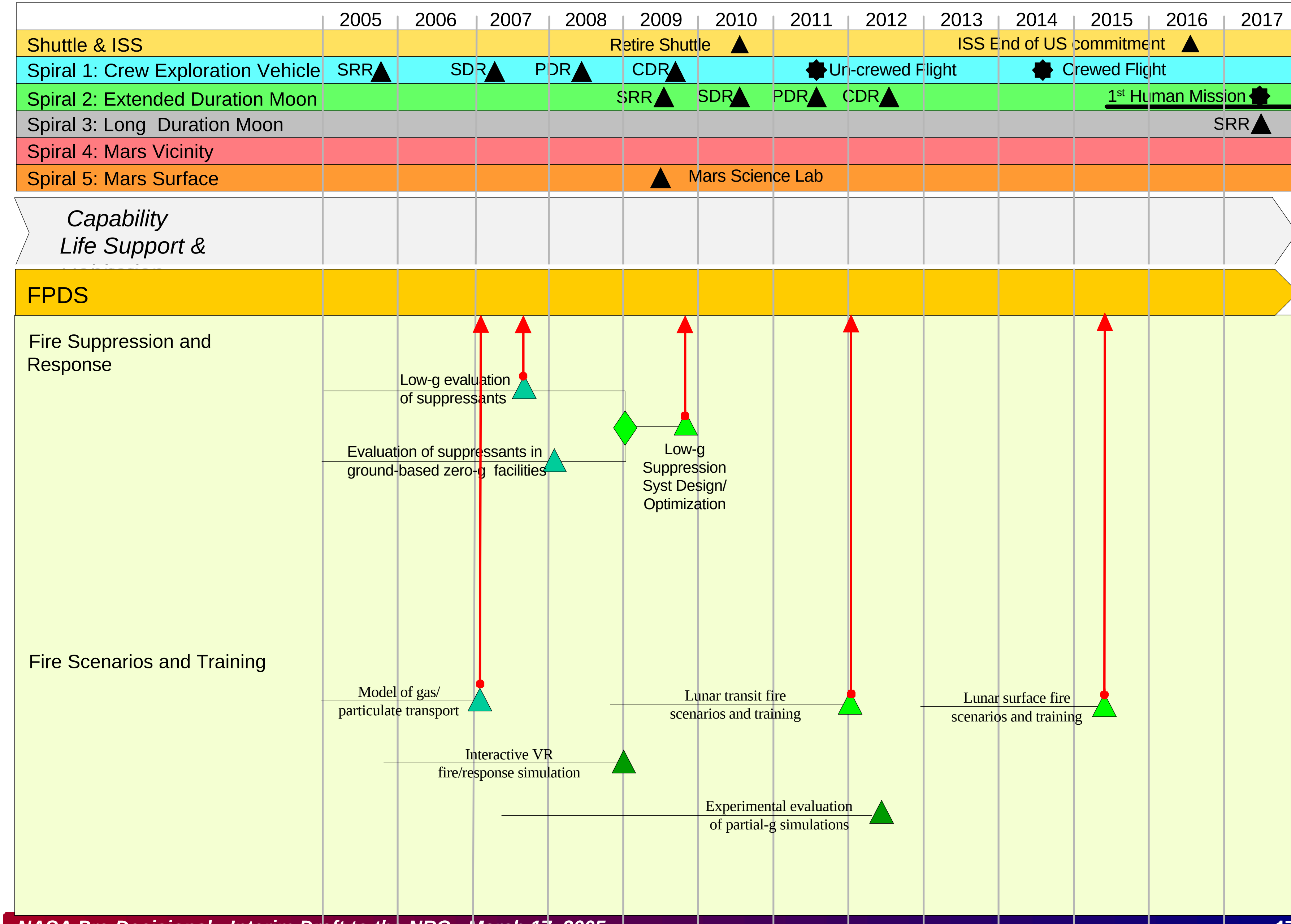
- **FPDS capability is driven by the mission requirements of all spirals**
  - **Fire Prevention and Material Flammability**
    - Selection of atmosphere for habitable volumes
    - Flammability in partial gravity (Spirals 3, 5: Lunar and Martian habitats) is different than zero-gravity (Spirals 1-5: 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

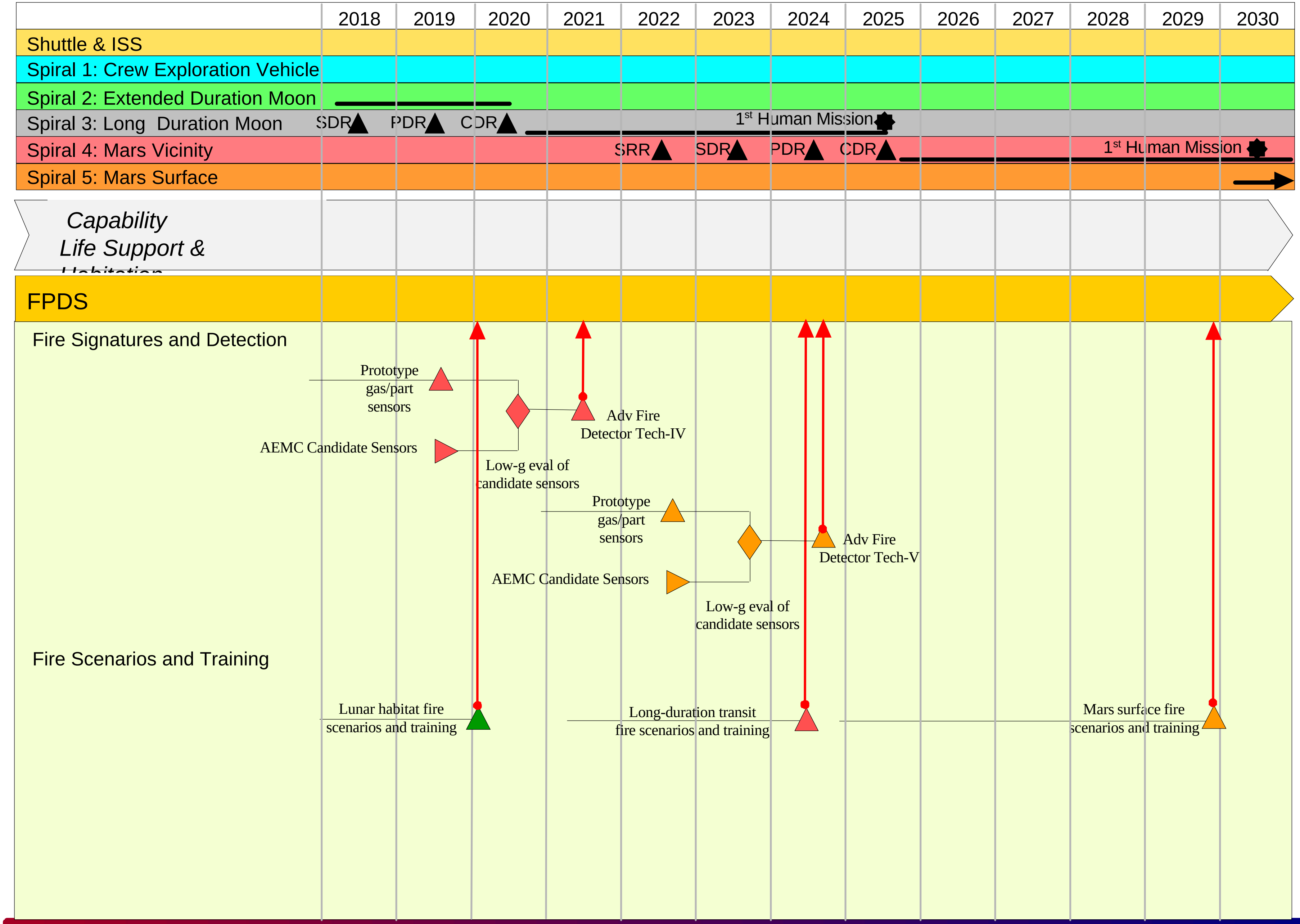
Fire Prevention Detection & Suppression Roadmap



Fire Prevention Detection & Suppression Roadmap



FPDS Road Map



Maturity Level – Fire Prevention, Detection, and Suppression

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	• 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 Lunar Surface (2011)	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
Spiral 3 Long Duration Lunar Surface (2014)	Same as Spiral 1	• Advanced fire detection system (assessment and implementation of future sensor technology)	1
Spiral 4 Mars Vicinity (2017)	Same as Spiral 1	Same as Spiral 3	1
Spiral 5 Initial Mission Mars Surface (2021)	Same as Spiral 1	Same as Spiral 3	1 1

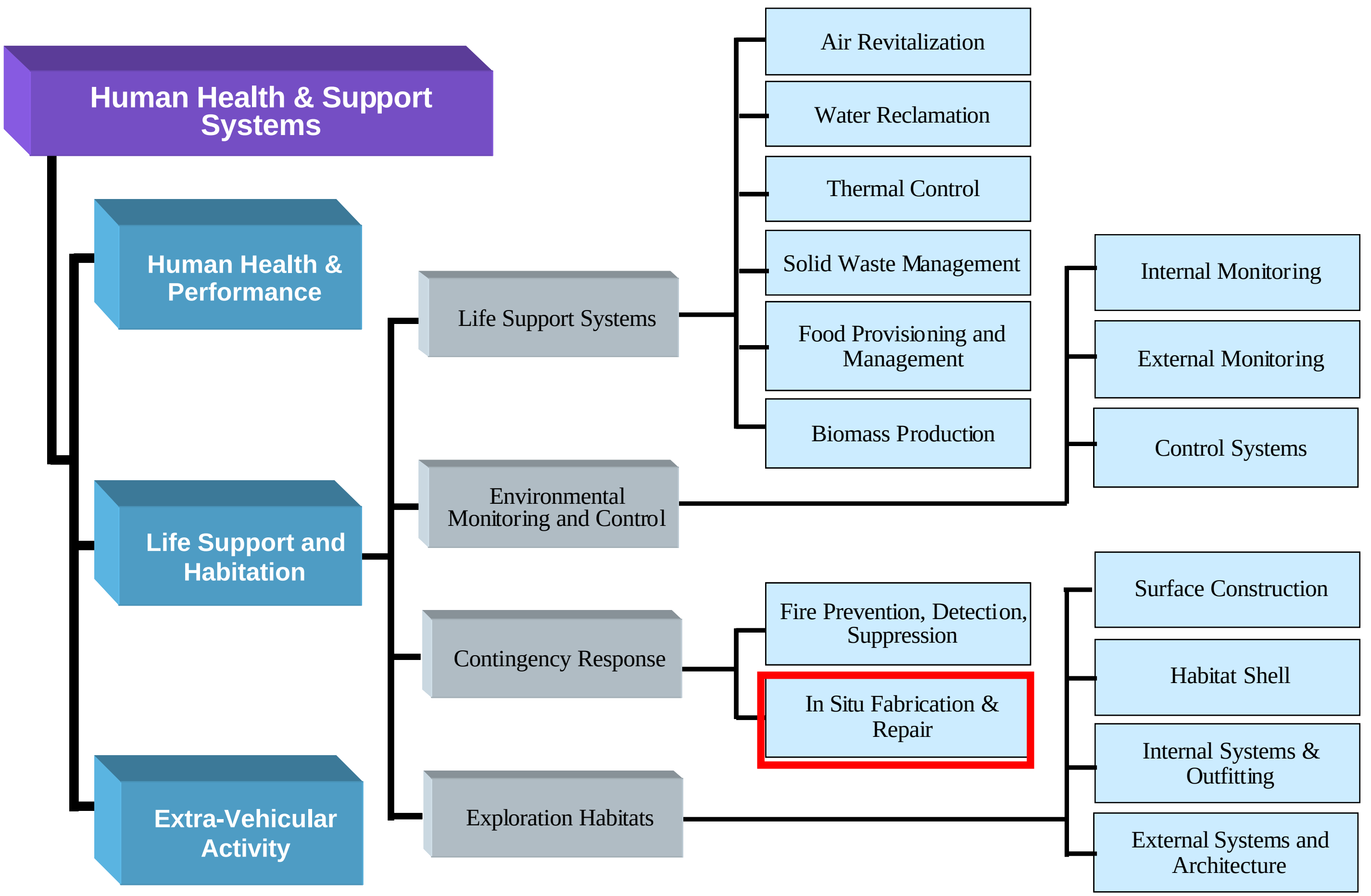
Maturity Level – Technologies
Fire Prevention, Detection, & Suppression

Capability (Level 5 CBS)	Leading Technology Candidates	TRL	Products (Spirals Needed)
Fire Prevention and Material Flammability	**Low-stretch scaling of ignition delay, mass loss rate, heat release, production of toxic products**	**2**	**Low gravity material flammability acceptance criteria (Spirals 2-5)**
	Flight hardware to validate scaling of ignition delay, flame spread, heat release, and release of toxic products (FEANICS/Combustion Integrated Rack (CIR)	**6**	
	Normal gravity analog for reduced gravity flammability	**2**	
Fire Signatures and Detection	**MEMS chemical sensors for species measurements**	**4**	**Fire signatures in reduced gravity (Spirals 2-5)** **Advanced fire detector and detection logic Verified models of fire precursor transport in low gravity (Spirals 1-5)**
	Electronic nose technology for detection of pre-fire signatures	**4**	
	Particulate sensors and size classifiers	**3**	
	Database of reduced gravity fire signatures	**3**	
	Flight hardware to quantify reduced gravity signatures of pre-fire particulate (Smoke Aerosol Measurement Experiment)	**6**	
Fire Suppression and Response	**Low-gravity evaluation of candidate fire suppressants**	**3**	**Design rules for reduced gravity fire suppression system (Spirals 1-5)**
	Flight hardware for initial screening of effectiveness of fire suppressants (Flame Extinguishment Experiment/CIR)	**6**	
Fire Scenarios and Training	**Simulation of relevant fire scenarios in a low-g habitable volume**	**4**	• **Simulation and evaluation of relevant fire scenarios** • **Realistic crew training modules (Spirals 2-5)**
	Realistic visualization of fire/smoke transport	**2**	
	Development of fire response training module	**2**	

Metrics
Fire Prevention, Detection, & Suppression

Sub-Capability (Level 5 CBS)	Figures of Merit	
	Description	**Units**
Fire Prevention and Material Flammability	Reduce mass Decrease risk of fire	kg %
Fire Signatures and Detection	Reduce mass Reduce power Reduce detection time	kg W sec
Fire Suppression	Reduce system mass Reduce suppressant mass released Reduce response time Reduce consumables for clean-up/recovery	kg kg (or ppm) sec kg
Fire Scenarios and Training	Decrease risk of fire Decrease response time	% sec

In Situ Fabrication & Repair



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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

Benefits of In Situ Fabrication & Repair

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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 In Situ Fabrication & Repair

- 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

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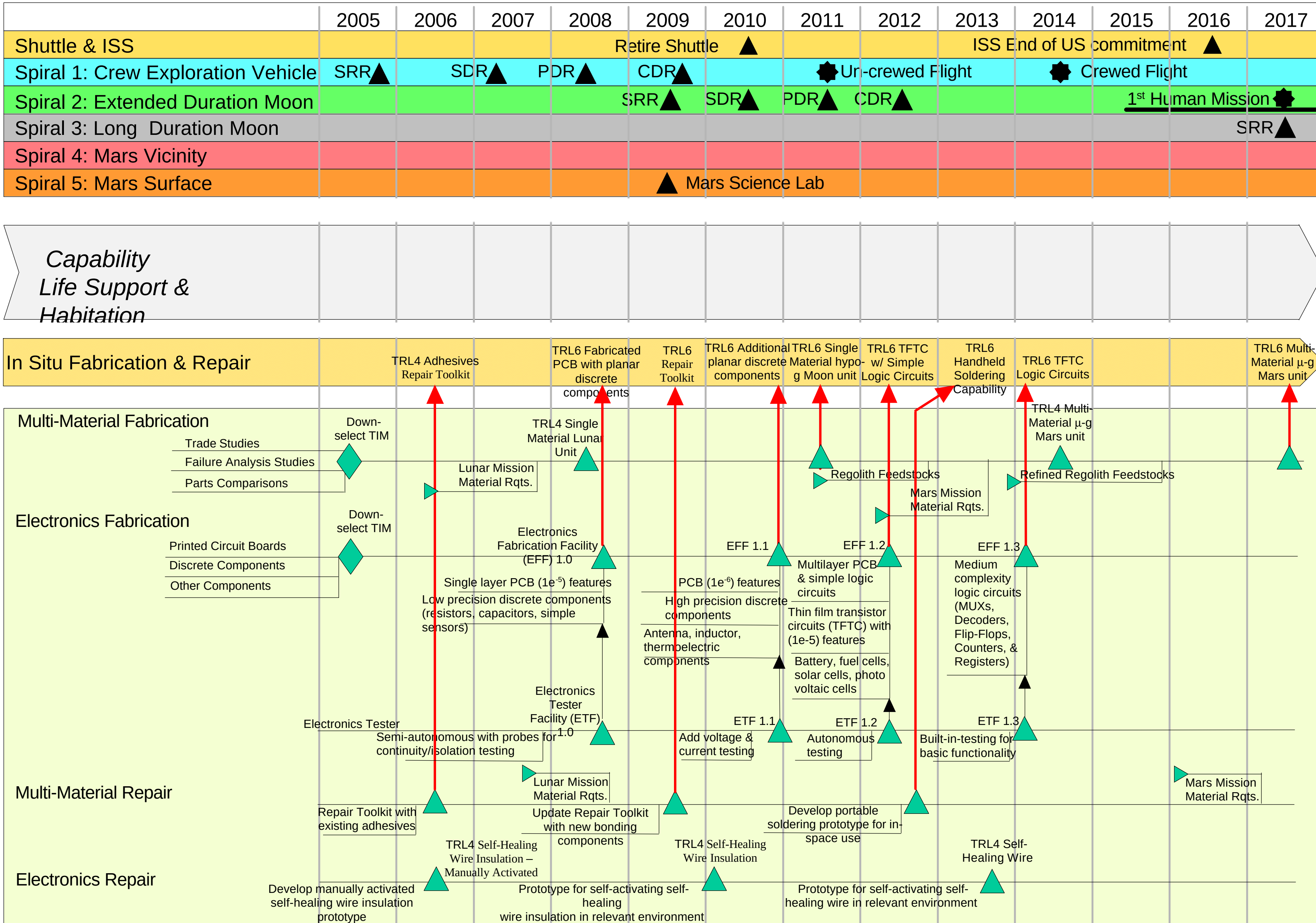
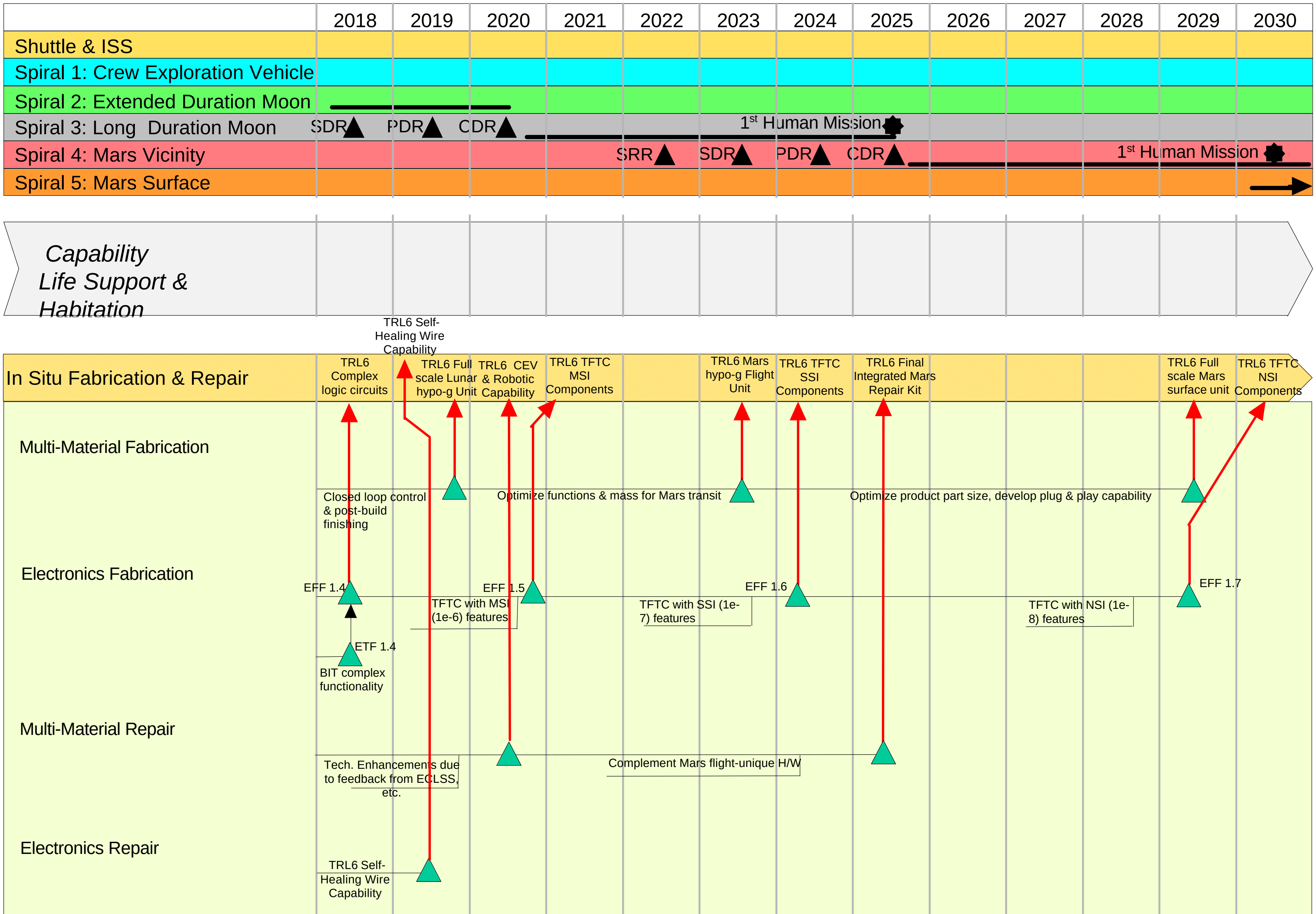
- **Design Framework/Reference Missions**
  - **Infrastructure Characteristics**
    - **Operational Gravity: Hypo-g (Lunar 1/6-g & Martian 1/3-g) for Spiral 2**
    - **Operational Gravity: Hypo-g *and Micro-g* for Spirals 3-5**
    - **Operational Environment: Cabin IVA; T=10-35C, P=10-15psia**
    - **Operating Mode:**
      - **Crew tended for Fabrication capability (exchange feedstock, transfer parts, perform parts cleaning, etc.)**
      - **Crew or robotic operation for Repair capability**
    - **System Reliability:** ^{3} **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



In Situ Fabrication & Repair Road Map



Maturity Level – In Situ Fabrication & Repair

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 2 Lunar Surface (2011)	Multi-Material Patching, Filling, Joining	Develop Adhesives Repair Toolkit Demo with existing adhesives for demo on ISS and/or lunar surface	4
Spiral 3 Long Duration Lunar Surface (2014)	Multi-Material Fabrication - Fabricator	Multi-material fabricator with closed loop control in hypo-g moon capability.	1
	Multi-Material Fabrication - Fabricator	Full scale lunar hypo-g flight unit with closed loop control and post-build finishing for pressurized cargo module launch to moon	1
	Multi-Material Fabrication - Fabricator	Full scale system stand alone cargo element testbed for lunar surface for independent deployment ahead of manned expedition	1
	• Multi-Material Patching, Filling, Joining	Identify, develop & apply new in-situ bonding components press & unpress areas.	1
	Multi-Material Patching, Filling, Joining	Apply learned soldering methods & technology to development of prototype portable soldering equipment for ISS	1
	Repair – Self-Healing Wire	Develop manually activated self-healing wire insulation prototype	1
Spiral 4 Mars Vicinity (2017)	Multi-Material Fabrication - Fabricator	Breadboard of Mars transit μ-g for CEV cabin	2
	Multi-Material Fabrication - Fabricator	Full scale μ-g Mars transit TRL6 unit for controlled CEV cabin w/ closed loop control & post finishing; μ-g Mars transit flight unit with restricted part size up to 12x12x12	2
	Multi-Material Fabrication - Fabricator	Full scale system stand alone cargo element testbed for lunar surface for independent deployment ahead of manned expedition	2
	Electronics Fabrication	Single layer printed circuit boards (PCB) with 10 micron (1e-5) features and low precision planar discrete components (resistors, capacitors, and simple sensors)	2
	Electronics Fabrication	Single layer PCBs with 1 micron (1e-6) features and high precision planar discrete components (resistors, capacitors, and simple sensors)	1
	Electronics Fabrication	Addition of antenna and inductor components, thermoelectric components	1
	Electronics Fabrication	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)	1
	Electronics Fabrication	Addition of energy components (batteries, fuel cells, and solar cells)	1
	Electronics Fabrication	Addition of LSI of medium complexity logic TFTC components with 10 micron (1e-5) features (MUX, Decoders, Flip-flops, Counters, and Registers)	1
	Electronics Fabrication	Addition of LSI of complex logic TFTC components with 10 micron (1e-5) features (PLA, ROM, and FPGA)	1
	Electronics Fabrication	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	1
	Electronics Fabrication	Autonomous Built-in-Test (BIT) test/verification and validation tester with probes for electrical testing and basic functionality of PCB boards	1
	Electronics Fabrication	Autonomous test/verification and validation tester with probes for electrical testing and complex functionality testing of PCB boards	1

Maturity Level – In Situ Fabrication & Repair (cont.)

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Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 4 Mars Vicinity (2017)	Multi-Material Patching, Filling, Joining	Evaluate Program flight H/W development status for new applications. Assemble multi-flight h/w repair kit. Perform validation of lunar repair kit. ECLSS, lander integration demo	2
	Multi-Material Patching, Filling, Joining	CEV/Robotic performance feedback for design deltas. Technology enhancement due to ECLSS, logistics, or lander variations, etc. Complement Mars flight-unique H/W.	1
	Multi-Material Patching, Filling, Joining	Apply ISS lessons learned to portable flight prototype soldering equipment for Mars flight	2
	Repair – Self-Healing Wire	TRL6 Self-activating self-healing wire demo for Mars Flight	1
Spiral 5 Initial Mission Mars Surface (2021)	Multi-Material Fabrication - Fabricator	• Optimize functions & mass of μ-g design for Mars transit; build & test ground unit modified for transition from lunar to Mars surface gravity	1
	Multi-Material Fabrication - Fabricator	Full scale Mars version w/ optimized functionality for independent deployment ahead of manned Mars expedition	1
	Electronics Fabrication	• 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	1
	Multi-Material Patching, Filling, Joining	• Final integrated Mars adhesive kit contents. Flight H/W and environment compatibility.	2

Maturity Level – Technologies
In Situ Fabrication & Repair

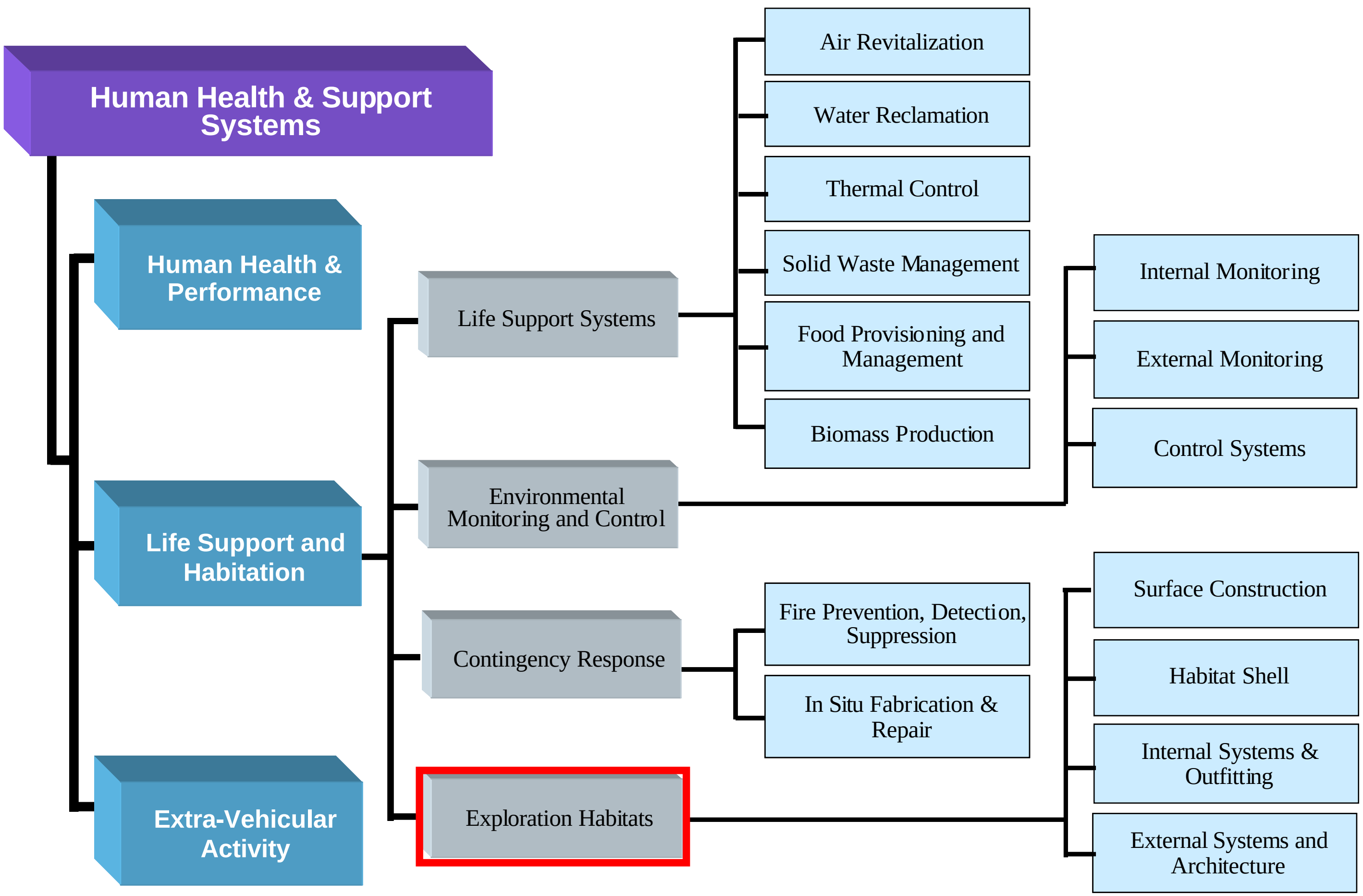
Advanced Planning & Integration Office

Sub-Capability (Level 5 CBS)	Leading Technology Candidates	Current TRL	Spiral(s)
Multi-Material Fabrication	Multi-Material Fabricator	2	3-5
Electronics Fabrication	Printed Electronics	2	3-5
Multi-Material Repair	Amalgams Adhesives Soldering	3 5 3	3-5 2-5 3-5
Electronics Repair	Self-Healing Wire Self-Healing Wire Insulation	1 1	4-5 3-5

Metrics In Situ Fabrication & Repair

Sub-Capability (Level 5 CBS)	Figures of Merit	
	Description	**Units**
Multi-Material Fabrication	**Product Strength** **Product Surface Finish** **Product Tolerances**	**%** **m-in RMS** **in/in**
Electronics Fabrication	**Trace Width** **Fabrication Tolerance**	**mm** **mm**
Multi-Material Repair	**Strength** **Temperature Tolerance**	**%** **Degrees**
Electronics Repair	**Strength** **Environmental Compatibility of repair**	**%** **%**

Exploration Habitats



Exploration Habitats
Introduction & Definition

- 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)

Exploration Habitats Introduction & Definition

Advanced Planning & Integration Office

- 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)

Exploration Habitats Capability Breakdown Structure

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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)

Exploration Habitats Benefits

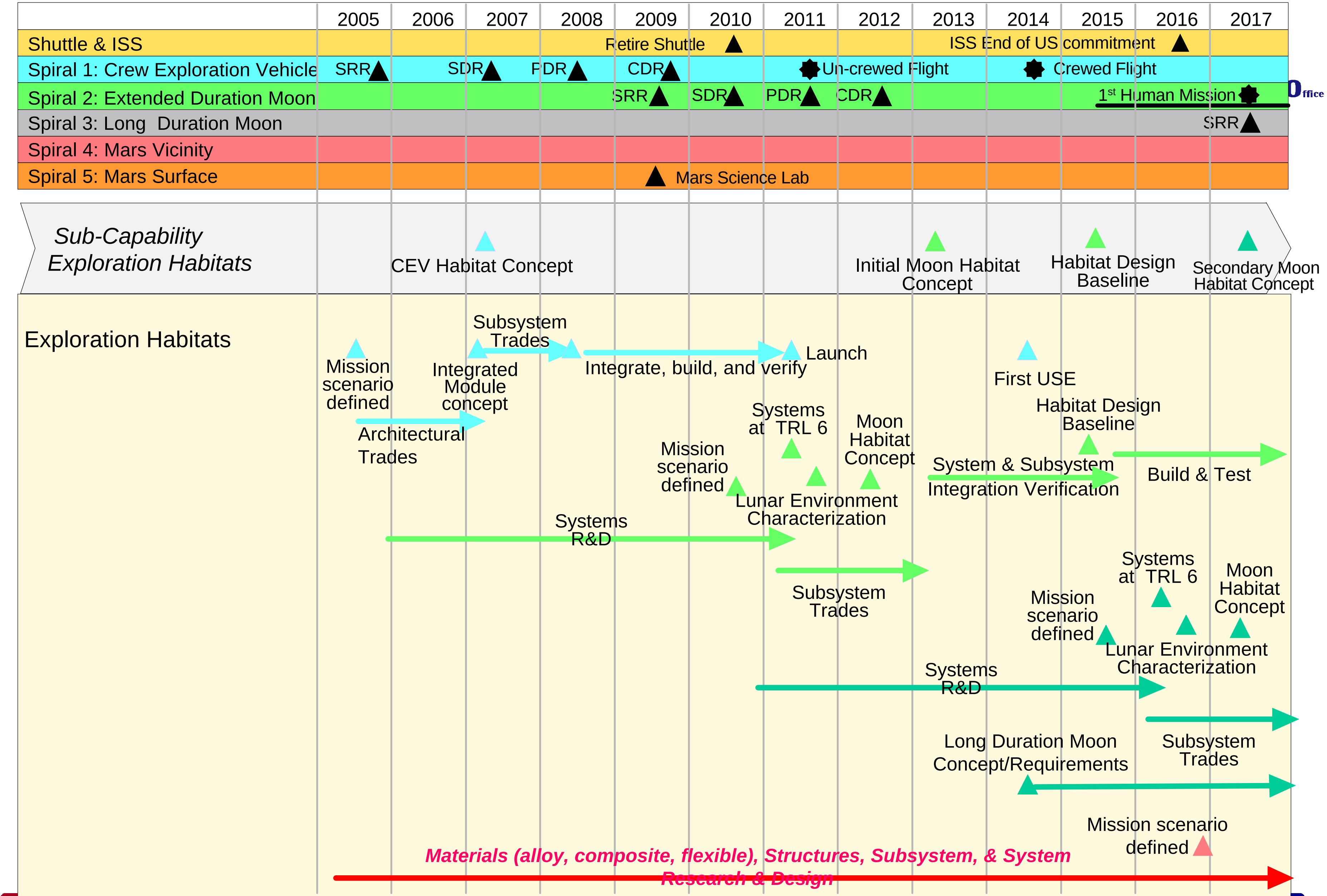
Benefits

- 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)

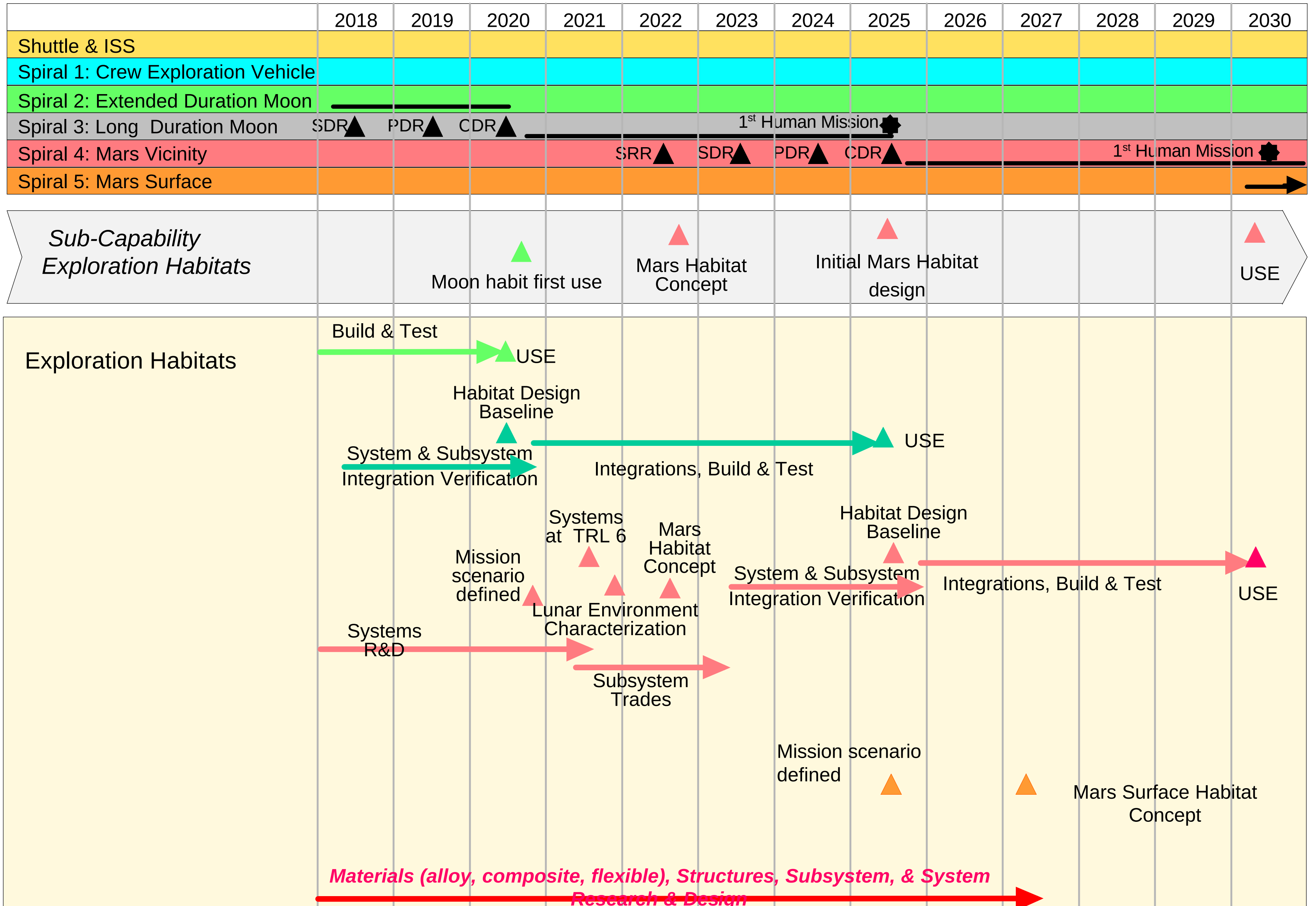
Exploration Habitats
Current State-of-the-Art

- 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

Exploration Habitats Roadmap



Exploration Habitats Roadmap



Exploration Habitats Maturity Level - Capabilities

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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

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Integrated Vehicle habitat 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 Lunar Surface (2011)	Initial Lunar Surface Habitat with airlock 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 Long Duration Lunar Surface (2014)	Expanded Lunar Surface Habitat utilizing ISRU capabilities 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 Mars Vicinity (2017)	Long term Vehicle habitat Closed loop life support systems Crew habitation facilities	Above plus: Lighter weight structural materials	1
Spiral 5 Initial Mission Mars Surface (2021)	Initial Mars Surface Habitat	Above plus: Automated setup/construction Logistical supply Surface launch support system Seal technology	1

Exploration Habitats - Habitat Shell Maturity Level - Technologies

Advanced Planning & Integration Office

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

Assumes need date as date of mission to first use capability

Habitats – Internal Systems & Outfitting Maturity Level - Technologies

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

Note: Assumes mission worst case scenario (Mars)

Habitats – External Systems and Architecture Maturity Level - Technologies

Advanced Planning & Integration Office

Gaps (not identified on other roadmaps)	Deliverables	Current TRL/ Need Date
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 Summary

Advanced Planning & Integration Office

- 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.

Life Support and Habitation Acknowledgements

The draft content within this progress report includes content from many different individuals within the NASA community

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Public Workshop

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

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Advanced EVA Systems

Presenter:

Kerri Knotts

The brains behind the words…

Advanced Planning & Integration Office

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:

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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

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- 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 Facilites
      - Simulators
      - Ground Processing Facilites

Requirements /Assumptions for Advanced EVA Systems

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- 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 Facilites
  - Simulators
  - Ground Processing Facilites

Suits

- **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

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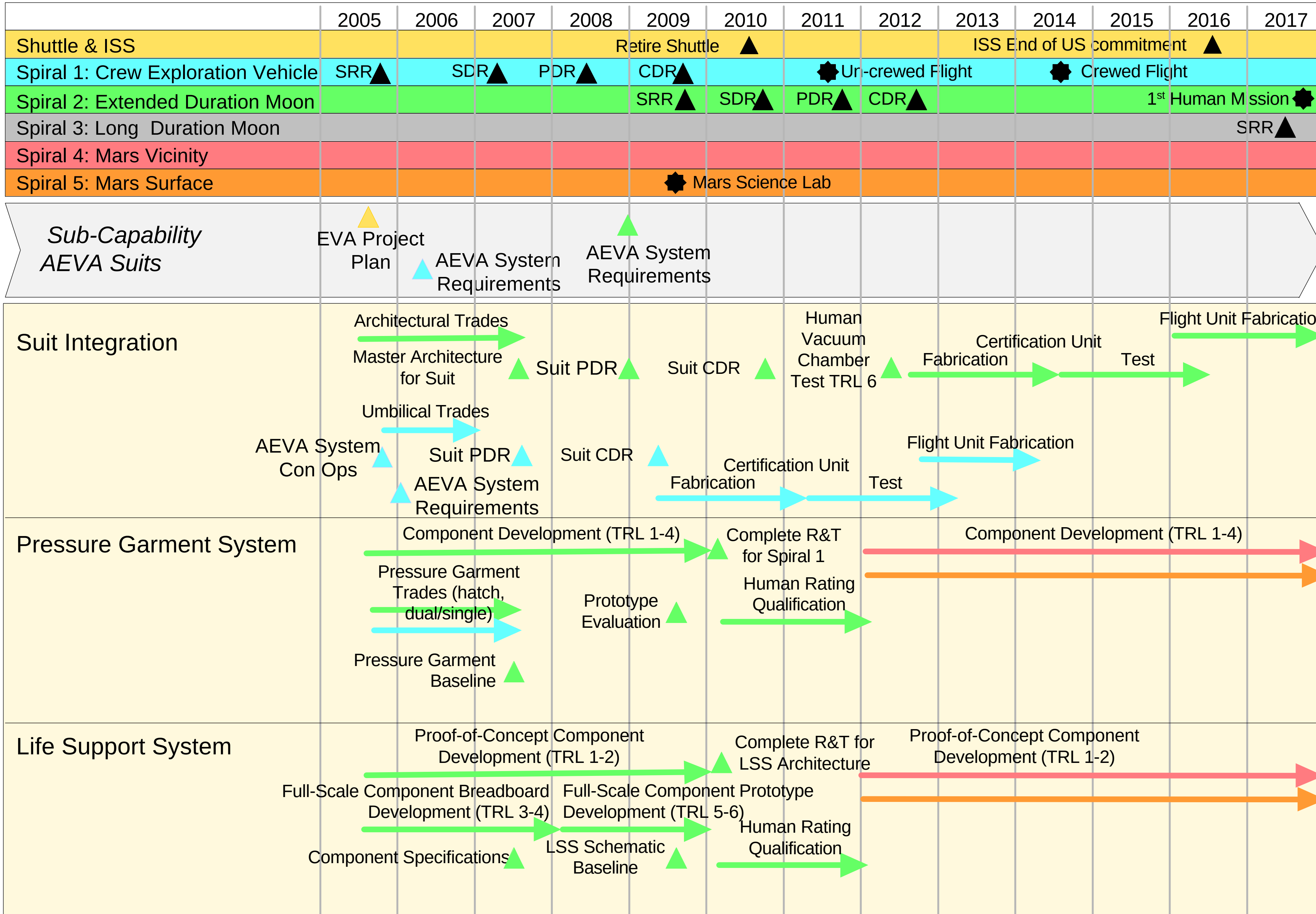
- An in-space suit (s) will support launch and entry crew survivability and CEV-based on-orbit operations
- A surface EVA suit will be based on a flexible, open architecture which will support multi-destination operation with minimal system reconfiguration
- Benefits of maximizing commonality between 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

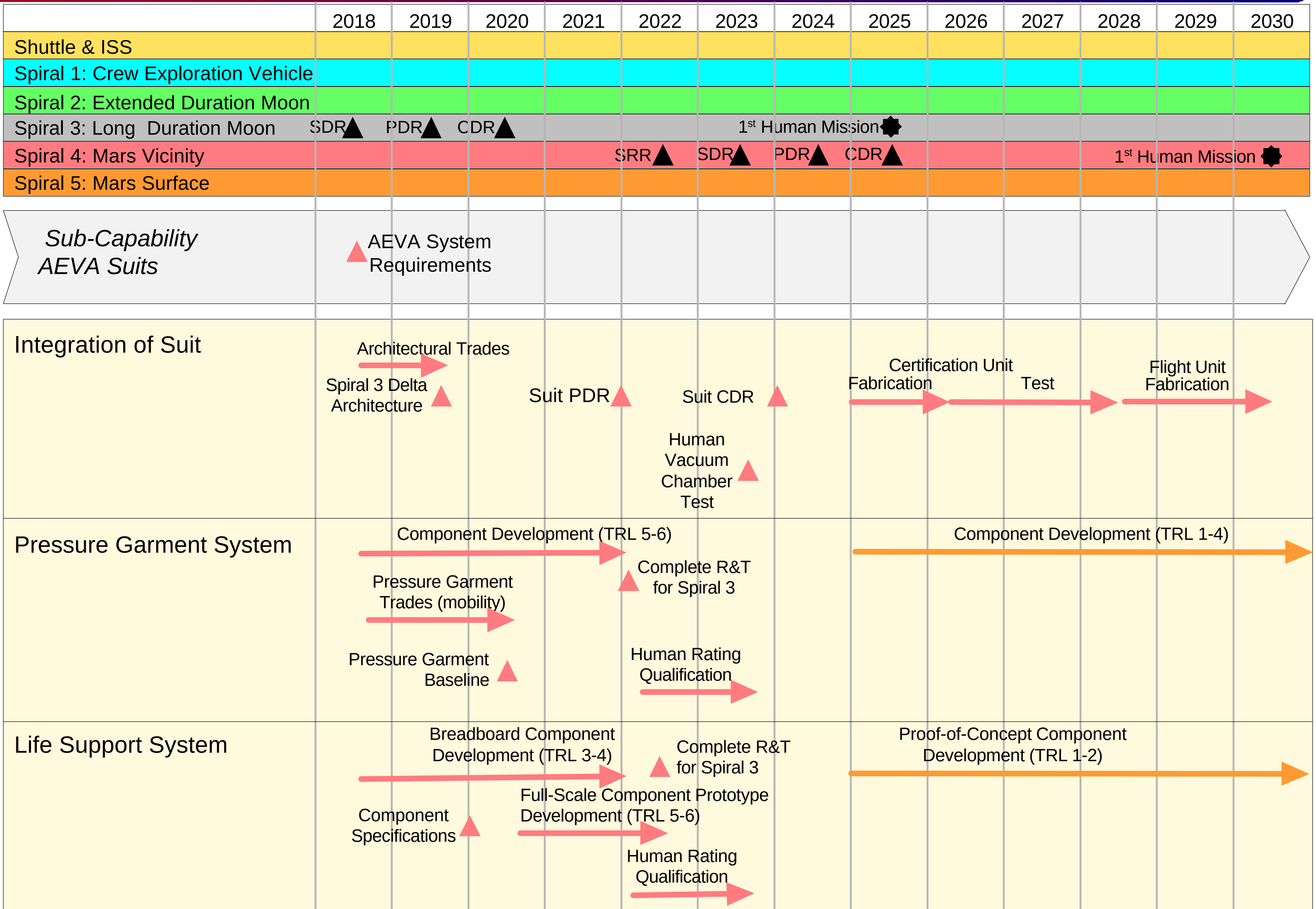
- **The current state-of-the-art for this capability is the Shuttle/ISS Extravehicular Mobility Unit (EMU) and the Russian Orlan**
  - The EMU is over is over 25 years old and is facing significant obsolescence issues. In addition, it is not compatible with the planetary environments of either the Moon 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



NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005 *NOTE: Milestone colors correspond to spiral color bars above*

Suits Roadmap



Maturity Level - Capabilities

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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 – Suits

Advanced Planning & Integration Office

Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6 (yrs)
Pressure Garments	• Shuttle Launch and Entry Suit (LES) • Sokol • Extravehicular Mobility Unit (EMU) • Orlan • Apollo Suit	• Launch, entry and abort pressure protection	• Vehicle Requirements Definition	• Modified LES,/ACES • Modified Sokol	6	0
		• In-space and surface pressure protection	• Lighter weight • Increased Mobility	• Modified LES/ACES for contingency EVA • Mark III, I-suit, D-suit	2	4-6
		• IVA comfort and mobility	• Vehicle Requirements Definition	• Modified LES,/ACES • Modified Sokol	6	0
		• In-space EVA mobility	• In-space EVA requirements	• Modified LES/ACES for contingency EVA • Mark III, I-suit, D-suit	2 5	2-4 1
		• Surface EVA mobility	• Increased Mobility • Low torque joints • Increased dexterity gloves/boots • Custom sizing manufacturing • Helmet/Visor technology	• Mark III, I-suit, D-suit	5	1

Technology Maturity Level – Suits

Advanced Planning & Integration Office

Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6 (yrs)
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 9 2 3 8 9	1 3 1 3-4 3-4 2-3 3-5 2

Technology Maturity Level – Suits

Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6 (yrs)
Ventilation (cont.)	• 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	<u>Containment vessels</u>		
				High Pressure	9	
				Low Pressure	9	1
				Nitrous Oxide	4	
				Chlorate Candles	7-8	
				Fullerene Storage	3	2
				Cryogenic Storage	3-4	2
				Potassium Super Oxide	2	2-3
				Emergency Oxygen		
				High Pressure	9	
				Low Pressure	9	
				Recirculation with Venting	3-5	1
				<u>Other Ventilation</u>		
				Traditional Fan	9	
				Air Bearing Fan	4	2
				Ejector/Transvector	2-4	2
				Regulators		
				Mechanical	9	
				Proportional Control	4	2
				Solenoid Valve		
				MEMS	1-2	3-5

Technology Maturity Level – Suits

Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6 (yrs)
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 9 3-4 4-5 4-5 3 3 3-4 4 4 4 2 1	2-3 2-3 1 1 2-3 2-3 1 1 1 1 3 5

Technology Maturity Level – Suits

Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6 (yrs)
Thermal (Cont.)	• 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	Radiator Convection Flow-through Variable Conductance Heat Pipe Control Valves Structure Coatings Auto cooling control	2-4 3 1 2-4 3 3 2-4 3	2 2 5 2 1 2-3 2-3 2
Power	• Batteries Silver Zinc Lithium Ion Nickel Metal Hydride	• Lightweight, high power • Standardized units	• High Energy Density • High Specific Energy • Long Shelf Life • High Cycle Life • Low Resupply Penalties • Increased component and system reliability • Lightweight • Regenerable	Batteries (increasing performance over current SOTA batts) Silver Zinc Lithium Ion Nickel Metal Hydride Super Capacitors Fuel cells PEM H2-O2 Methane CO-O2	 3 3 3 3-4 3-4 3-4 3-4 3-4	 1-5 1-5 1-5 2 2-3 2-3 2-3 2-3

Technology Maturity Level – Suits

Advanced Planning & Integration Office

Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6 (yrs)
Comm and informatics	• Paper cuff checklist • Single band Radio • IR CO2 sensor • Limited sensor data for suit performance monitoring	Wireless comm Integrated comm Maintenance and diagnostic trending	• Increased crew communication and data transfer • Lightweight informatics system • Higher crew efficiency for real-time data acquisition • Increased data insight for maintainability • High reliability sensors	• Wireless sensors and electronics • Heads up display • Ultra Wideband Communication • Solid state CO2 sensors • IR CO2 sensors • Voice Control • Maintainability systems • Diagnostics	3-4 2-3 3-4 2-3 5 2-3 2 2	1-2 2-3 2-3 2-3 1 2-3 2-3 2-3
Environ mental Protection	• EMU MLI • EMU Ortho fabric • Orlan	• In-space contingency EVA protection • Surface exploration protection	• Dust protection/resistant materials and bearings • Radiation protective materials • Lightweight • Flexible	• Micrometeoroid Protection • Dust mitigating material • Puncture resistant material • Radiation protective material • Biochemical protective material	8 1-5 2 2 2-4	 2-3 3-5 3-5 1-3

Metrics for Suits

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

EVA Tools and Mobility Aids

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- **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 Facilites
    - Simulators
    - Ground Processing Facilites

EVA Tools and Mobility Aids

Advanced Planning & Integration Office

- 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.

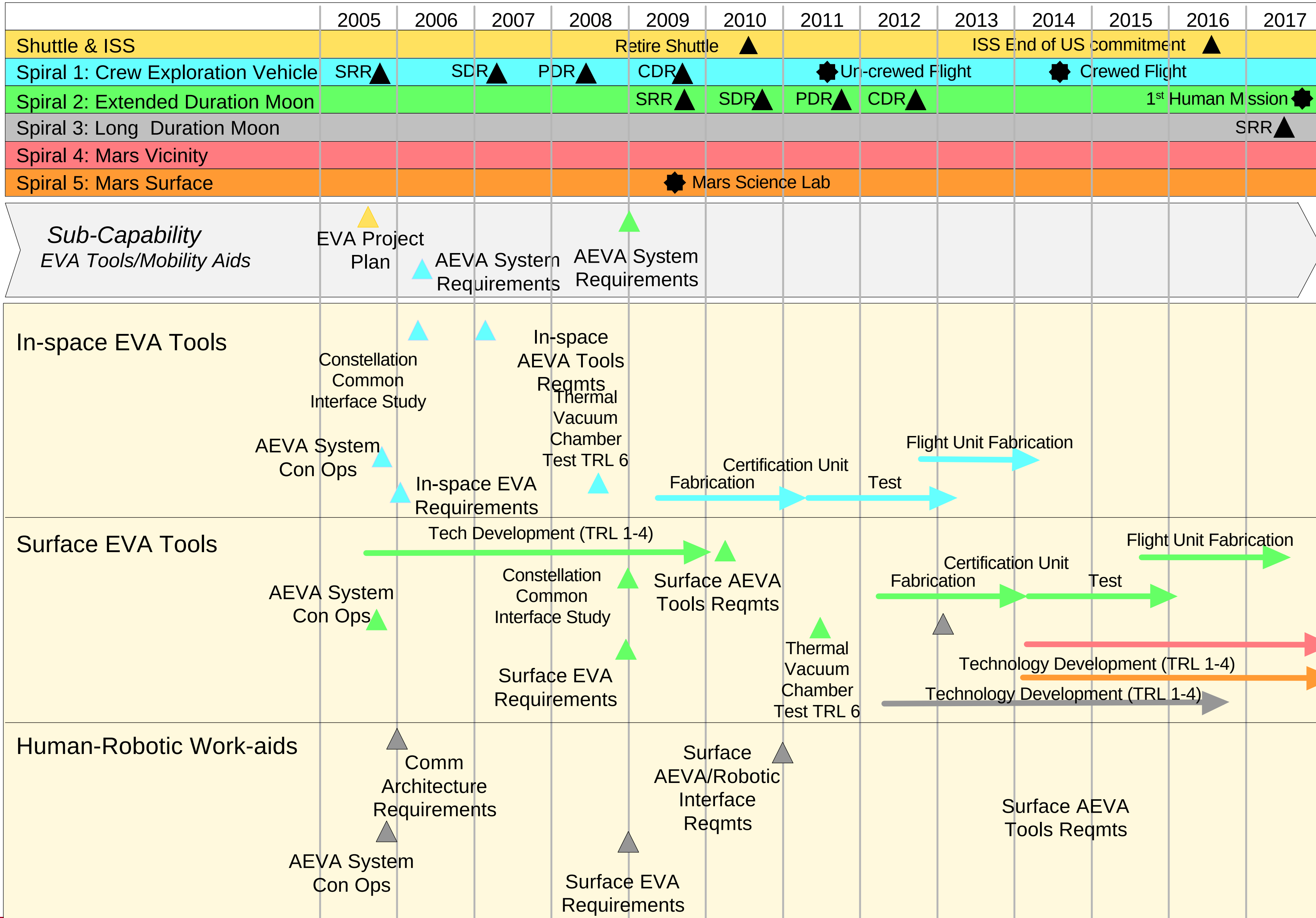
Benefits of the EVA Tools and Mobility Aids

- 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

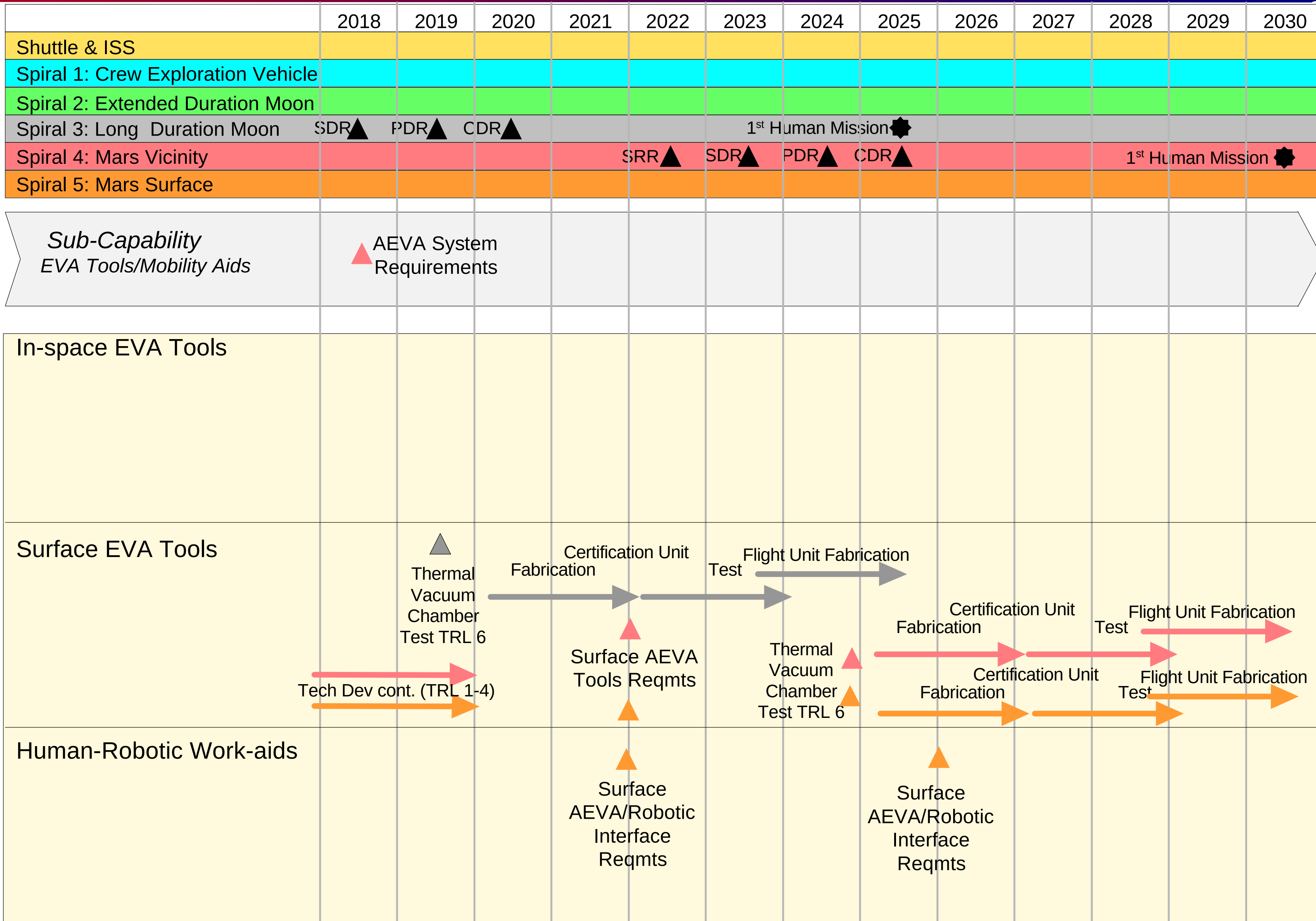
Current State-of-the-Art for EVA Tools and Mobility Aids

- 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



EVA Tools/Mobility Aids Roadmap



Maturity Level - Capabilities for EVA Tools and Mobility Aids

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 – Tools & Mobility Aids

Advanced Planning & Integration Office

Roadmap Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area/Candidates	TRL	Time to TRL =6

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
					
					3
					7
					2
					3
					1-2
						2
						
						6
						-
						
						8?

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 5	6-8 2

Metrics for EVA Tools and Mobility Aids

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

Advanced Planning & Integration Office

- 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.

Airlocks/Pressurized Volumes

- **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 Facilites
    - Simulators
    - Ground Processing Facilites

Benefits of the Airlocks/Pressurized Volumes

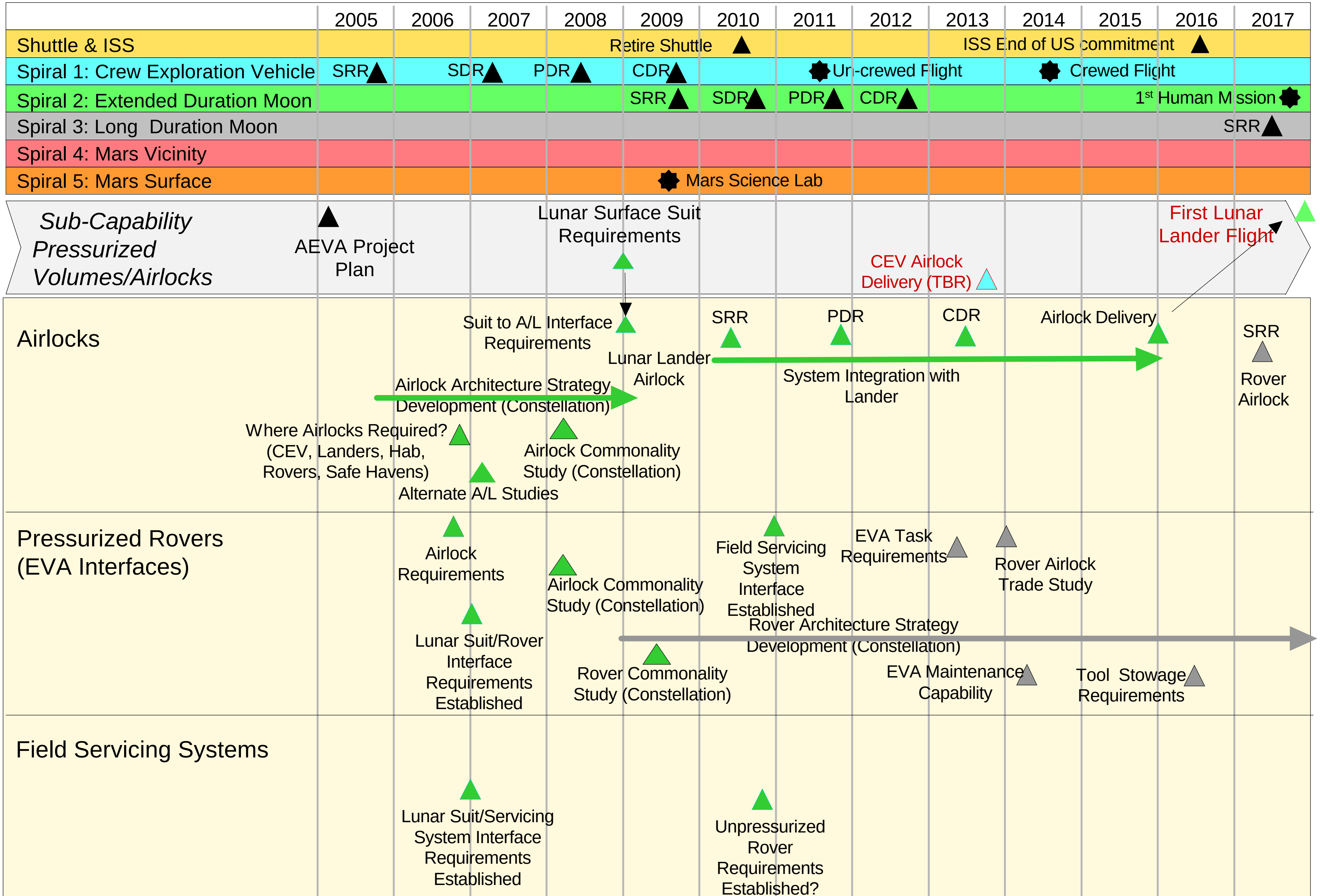
- **Airlocks provide external access without additional operational demands on pressurized cabins to tolerate routine depressurization cycles.**
- **Airlocks provide separable constrained volumes to deal with dust mitigation and other contamination issues from planetary surfaces**
- **Shirtsleeve microgravity 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

Advanced Planning & Integration Office

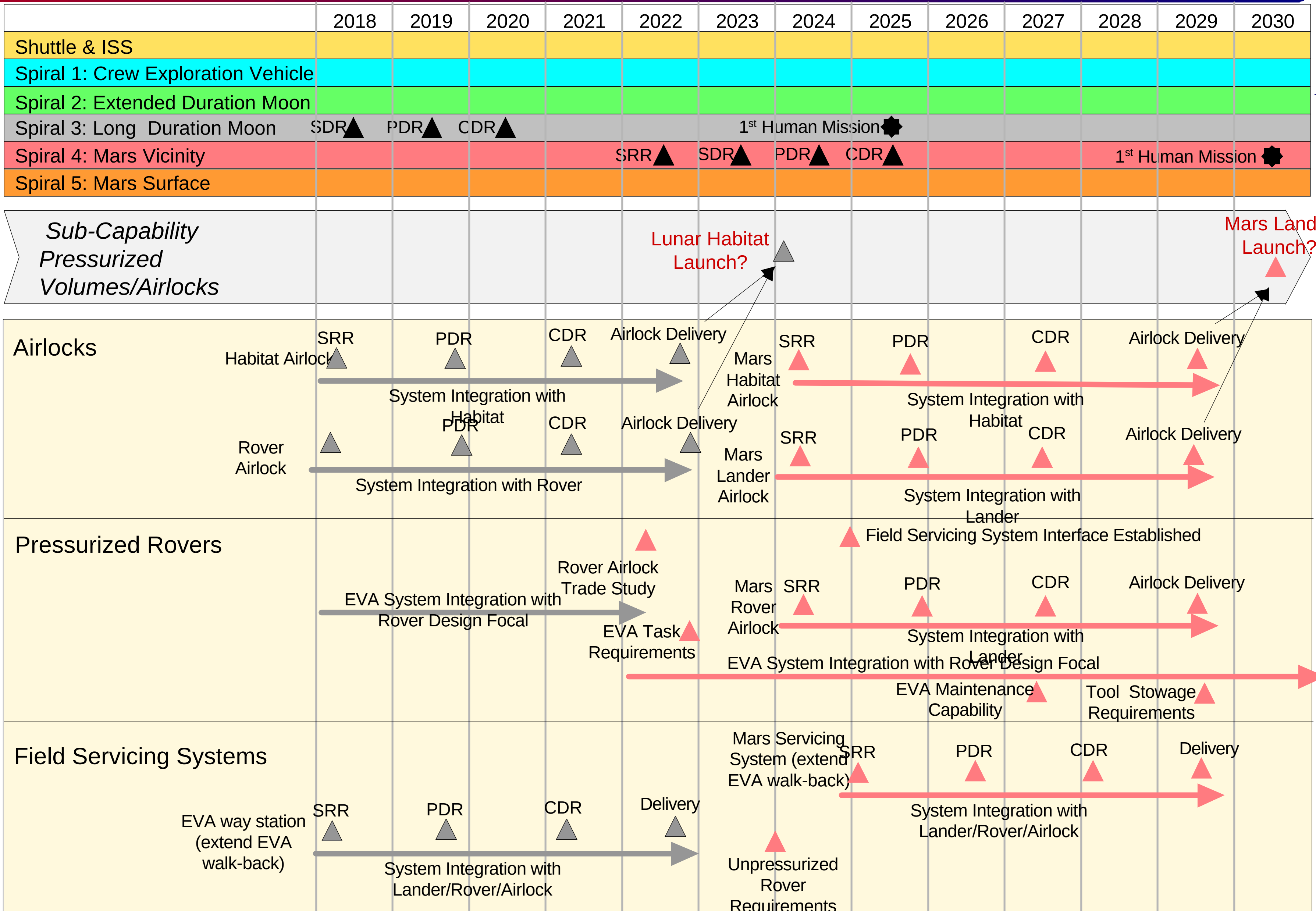
- Current airlock designs waste atmosphere and are not compatible with dust/biologic isolation.
- Dust contamination will be a significant issue on the surface of both the Moon and Mars. Dust mitigation and control must be considered in the design of planetary vehicles and EVA suit systems so that dust 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



NOTE: Milestone colors correspond to spiral color bars above

Pressurized Volumes/Airlocks Roadmap



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

NOTE: Milestone colors correspond to spiral color bars above

Maturity Level - Capabilities for Pressurized Volumes

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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 – Airlocks/ Pressurized Volumes

Roadmap Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area/ Candidates	TRL	Time to TRL= 6
Airlock	• Shuttle Airlock • Space Station Joint Airlock • Russian Space Station Airlock (DC-1) • Skylab Airlock	• Ingress/Egress • Suit Supportability	• Minimum consumable use (air and power) • Time efficiency • Dust Tolerance • Rapid Consumable Re-supply • Low Mass	• Lightweight Structure • Inflatable • Minimum Volume (Clamshell, suit ports) • Environmental Protection (e.g. Dust Mitigation) • Hatch Mechanisms • Rapid Suit Checkout & Recharge	3 3 3 2 5 3	6 6 6 8 2 6
Pressurized Rovers (EVA Interface)	• Lunar Rover	• Airlock • Suit Supportability • Tool Stowage • Commonality • EVA Maintainable	• See airlocks	• See airlocks • EVA Suit/rover consumable commonality • Simple external maintenance	3 2 3	6 8 6
EVA Field Service Stations	• NA	• Service Stations • Safe havens	• Rapid Recharge • Deployable (lightweight)	• Life Support Commonality • Communications • Suit Checkout and Recharge • Environmental protection	2 4 2 2	8 4 8 8

Metrics for Airlocks/Pressurized Volumes

- 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

EVA Ground Support System

- **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 Facilites
    - Simulators
    - Ground Processing Facilites

EVA Ground Support System

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- 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.

Current State-of-the-Art for EVA Ground Support System

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- 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

Advanced Planning & Integration Office

• 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 suited 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.

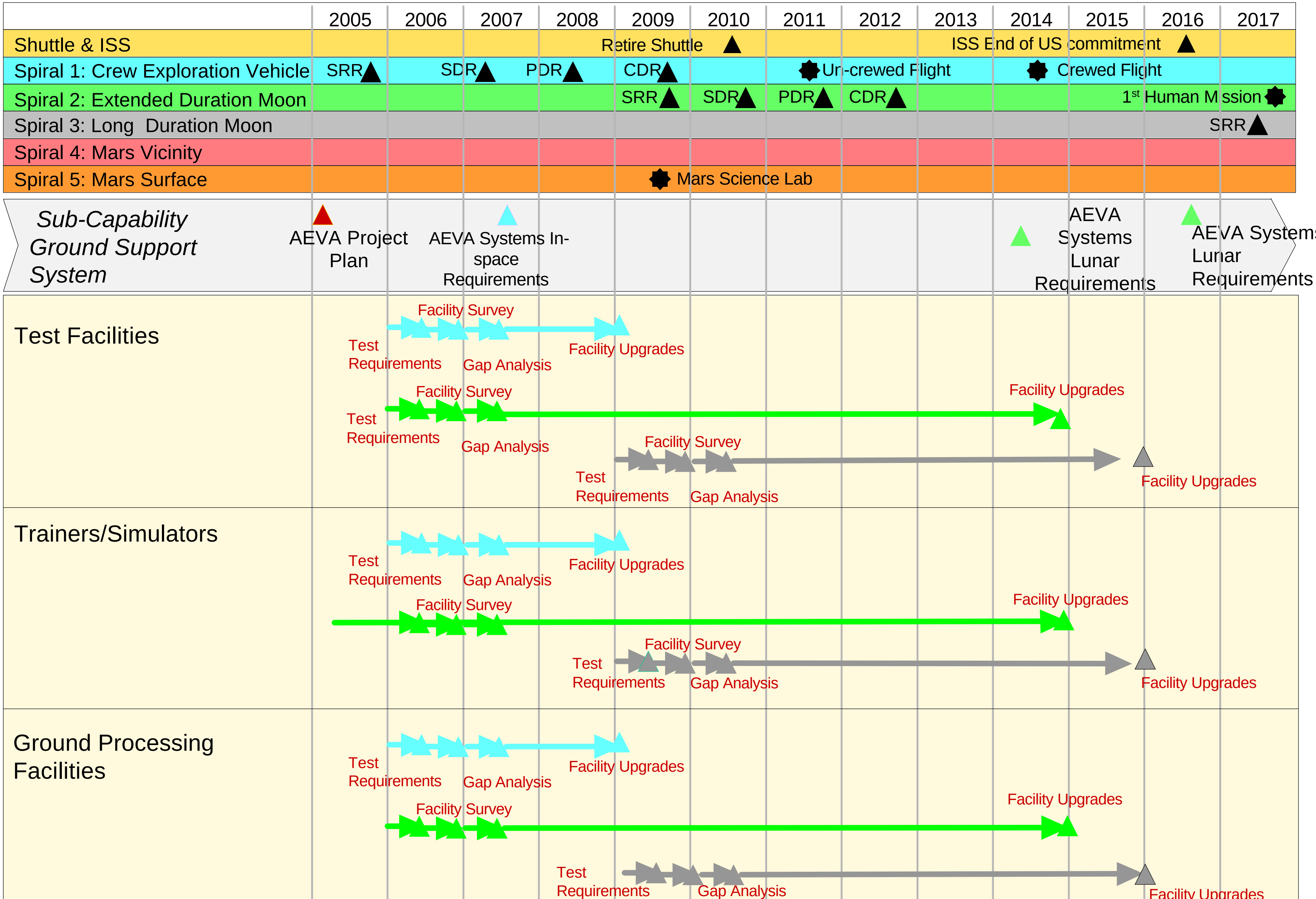
Chamber V Thermal-Vacuum

- 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.

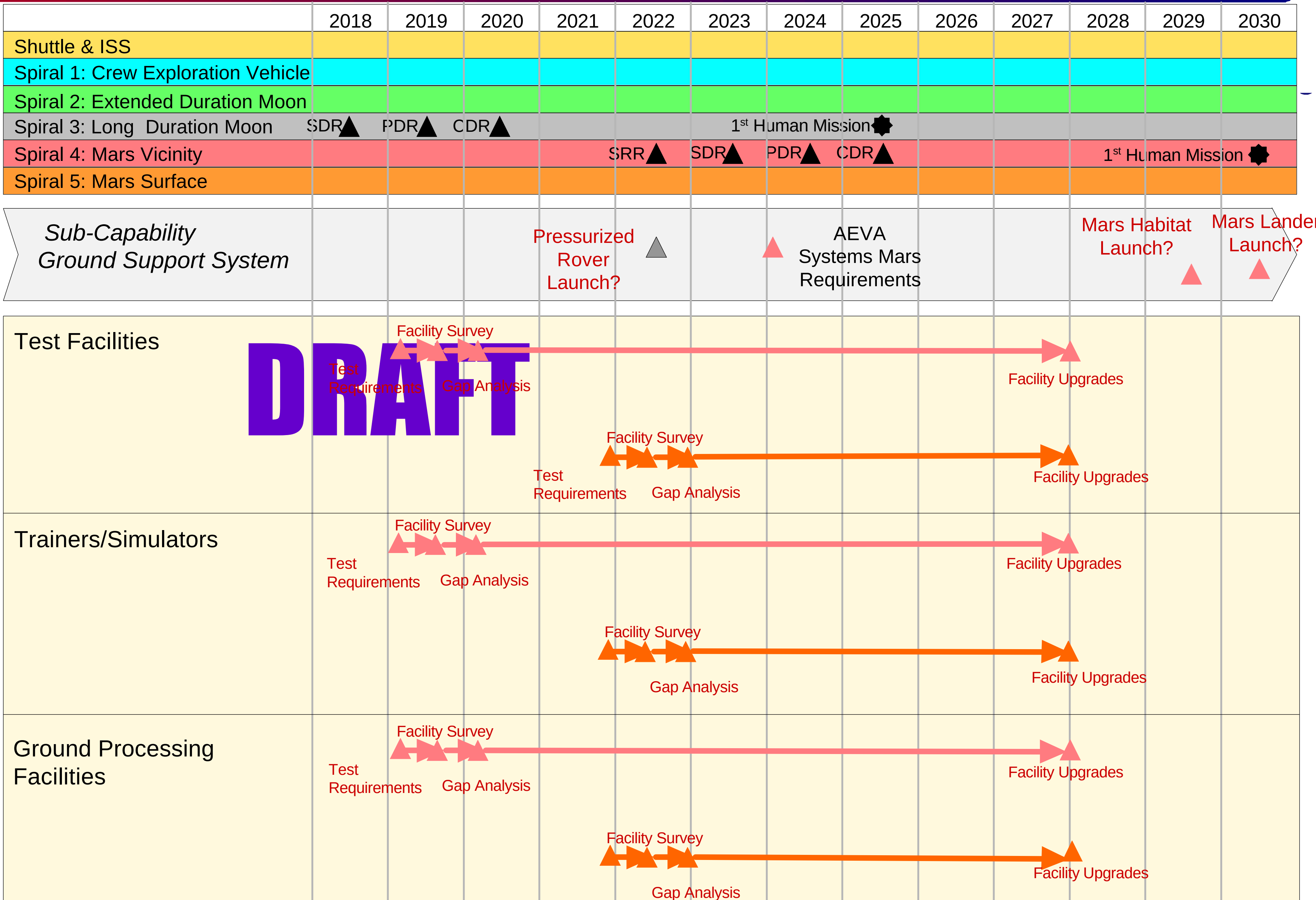
Building 32 Chambers

- 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.

Ground Support System Roadmap



Ground Support System Roadmap



Maturity Level - Capabilities for EVA Ground Support System

Advanced Planning & Integration Office

Advanced EVA Systems Capabilities (CRL 1:5)

Suits (CRL 1:5)

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

EVA Tools and Mobility Aids (CRL 1:5)

1. In-space EVA Tools (TRL 3 → 7)
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Airlocks/Pressurized Volumes (CRL 1:5)

1. Airlocks (TRL 2 → 5)
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Ground Support Systems (GSS) (CRL 1:5)

1. Test Facilities (TRL 3 → 9)
2. Trainers and Simulators (TRL 3 → 9)
3. 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

Roadmap Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6
Test Facilities	• Shuttle & Space Station Test Facilities	• Human Rated Vacuum Chambers • Systems Integration Lab • Simulated Surface Sites • 0G Environment • Partial Gravity Environment • Micrometeorite testing • Radiation testing • Dust effects testing	Updates/consolidation required ➢ Simulated integrated gravity, pressure, dust, radiation, atmosphere, micrometeoroid Martian Environment ➢ Simulated integrated gravity, dust, radiation, micrometeoroid Lunar Environment	• Lunar and Martian Simulants • Integrated Lunar and Martian environmental conditions • Software for Simulation Based Acquisition • Emission and leak testing • Boot and Glove Sizing • Advanced Processing for suit components • Advanced AEVA Life Support lab upgrades	NA	NA
Training Facilities	• Shuttle & Space Station Training Facilities	• NBL • Systems Integration Lab • Simulated Surface Sites • 0G Environment • Partial Gravity Environment	Updates/consolidation required ➢ Simulated integrated gravity, pressure, dust, radiation, atmosphere, micrometeoroid Martian Environment ➢ Simulated integrated gravity, dust, radiation, micrometeoroid Lunar Environment	• Lunar and Martian Simulants • Integrated Lunar and Martian environmental conditions	NA	NA

Ground Processing Facilities	• Shuttle & Space Station Ground Processing Facilities	• EVA Systems:
		  • Prep
		  • Storage
		  • Maintain
		  • Test
		  • Troubleshoot
			Updates/consolidation required
			➢ Needs Analysis
			➢ Gap Analysis
			➢ Facility Upgrades
				• Crew escape and EVA Integrated processing facility	3	NA

Metrics for EVA Ground Support System

Advanced Planning & Integration Office

- 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

Bioastronautics Roadmap

- 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.

Return

Advanced Planning & Integration Office

High Energy Power & Propulsion		Human Health & Support Systems	
Sub-Topic or Subsidiary Capability	Capability Flow & Criticality	Sub-Topic or Subsidiary Capability	Nature of Relationship
Nuclear Propulsion	⇔ (blue)	Human Health Performance	Reqmts for vehicle/ nuclear power separation is also beneficial for artificial gravity
Nuclear Propulsion	⇔ (red)	Human Health Countermeasures/ Radiation Protection	transit times/ exposure time
Nuclear Propulsion	⇔ (red)	EVA	Induced radiation/ thermal/ hazard environment relative to space craft
Power	⇔ (red)	Human Support Systems	Power reqmts/constraints affects technology
Red - Critical			
Blue - Moderate			

Return

CRM 3

Advanced Planning & Integration Office

In-Space transportation	Human Health & Support Systems			
Sub-Topic or Sub-sub-topic		Sub-Topic or Sub-sub-topic		Relationship
All of In-space transportation	⟺	Life Support/ Human Health & Performance/ EVA		Design of vehicle - reqmts/ trade-offs/ habitable volume/ heat rejection (mass rich or poor) Degree of in-space assy required
Red - Critical				
Blue - Moderate				

Return

CRM 4

Advanced Planning & Integration Office

Advanced Telescopes & Observatories	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
All	⟺ (Red)	EVA	Mission timing-Humans required to deploy? - concept of ops/ design compatibility contamination structural loads
All	⟺ (Red)	Advanced Life Support	contamination
Red - Critical			
Blue - Moderate			

Return

CRM 5

Communication & Navigation	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
All	←	Human Health/Radiation	Direct access to space weather systems for Mars
All	←	Human Health/Artificial Gravity	Antennae design & location
All	←	Human Health	Secure comm/ private conference/ psych consults Embedded human performance measures Bandwidth
	↔	EVA	Surface navigation/ information display Communication within & between EVA/ vehicle/ rover/ base
Red - Critical			
Blue - Moderate			

Return

CRM 6

Robotic Access to Planetary Surfaces	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
Entry, Descent, and Landing/ Observations	←	Human Health/Radiation	Rqmts for radiation definition on moon & Mars
Entry, Descent, and Landing/ Observations	←	Human Support	Rqmts for site characterization
Entry, Descent, and Landing/ Observations	←	Human Health/Life Support/EVA	environment characterization (dust, toxicity, radiation, etc.)
Red - Critical			
Blue - Moderate			

Return

CRM 7

Human planetary landing systems	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
All	⟷	Habitats	Architecture - integrated habitat? / Precision landing/ pressure
All	⟷	Human Health	human performance - g-load
	⟷	EVA	Routine access to planetary surface
Red - Critical			
Blue - Moderate			

Return

CRM 9

Human Exploration Systems & Mobility	**Capability Flow and Criticaltiy**	**Human Health & Support Systems**	**Nature of Relationship**
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
Rovers, in-space systems	↔	Human Health/Space Human Factors/EVA	Rover interface
Rovers	↔	Habitat	Rover interface
Rovers	←	Human Health/Radiation	Reqmts
Red - Critical			
Blue - Moderate			

Return

Advanced Planning & Integration Office

Autonomous systems & robotics	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
Human-Machine Interaction	⟷	Human Health/EVA	Robotic interface Application versus task functional allocation Robotic assistance for medical care?
Red - Critical			
Blue - Moderate			

Return

CRM 12

Advanced Planning & Integration Office

Scientific instruments and sensors	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
Surface Sample Acquisition & Analysis	← (red)	Human Support	Site selection reqmts
Red - Critical			
Blue - Moderate			

Return

CRM 13

Advanced Planning & Integration Office

In situ resource utilization	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
All	⟷	Human Support	reqmts for composition, quality, quantity
All	⟷	EVA	tools and functional reqmts
All	⟷	Radiation	potential shielding
All	⟷	Life Support	Water, oxygen production
Red - Critical			
Blue - Moderate			

Return

CRMs 14, 15, 16, & 11

Advanced modeling, simulation, analysis Systems engineering cost/risk analysis Nanotechnology/advanced technology concepts Transformation Spaceport/Range	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
All	Unknown	All	Unknown
Red - Critical			
Blue - Moderate			

Return

Capability Readiness Level 1

Advanced Planning & Integration Office

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.

Return

* Subcapabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Level 2

Advanced Planning & Integration Office

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.

Return

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

Capability Readiness Level 3

3 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

Return

* Subcapabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Level 4

Advanced Planning & Integration Office

4

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.

Return

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

Capability Readiness Level 5

Advanced Planning & Integration Office

5 **Integrated Capability Demonstrated in a Relevant Environment**

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

Return

* Subcapabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Level 6

Advanced Planning & Integration Office

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'

Return

* Subcapabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Level 7

Advanced Planning & Integration Office

7 Capability Operational Readiness

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…?)

Return

* Subcapabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)