Draft Technology Roadmap Overview
TA06 – Human Health, Life Support and Habitation Systems

Presentation to the National Research Council, Panel 4 Workshop
April 26, 2011

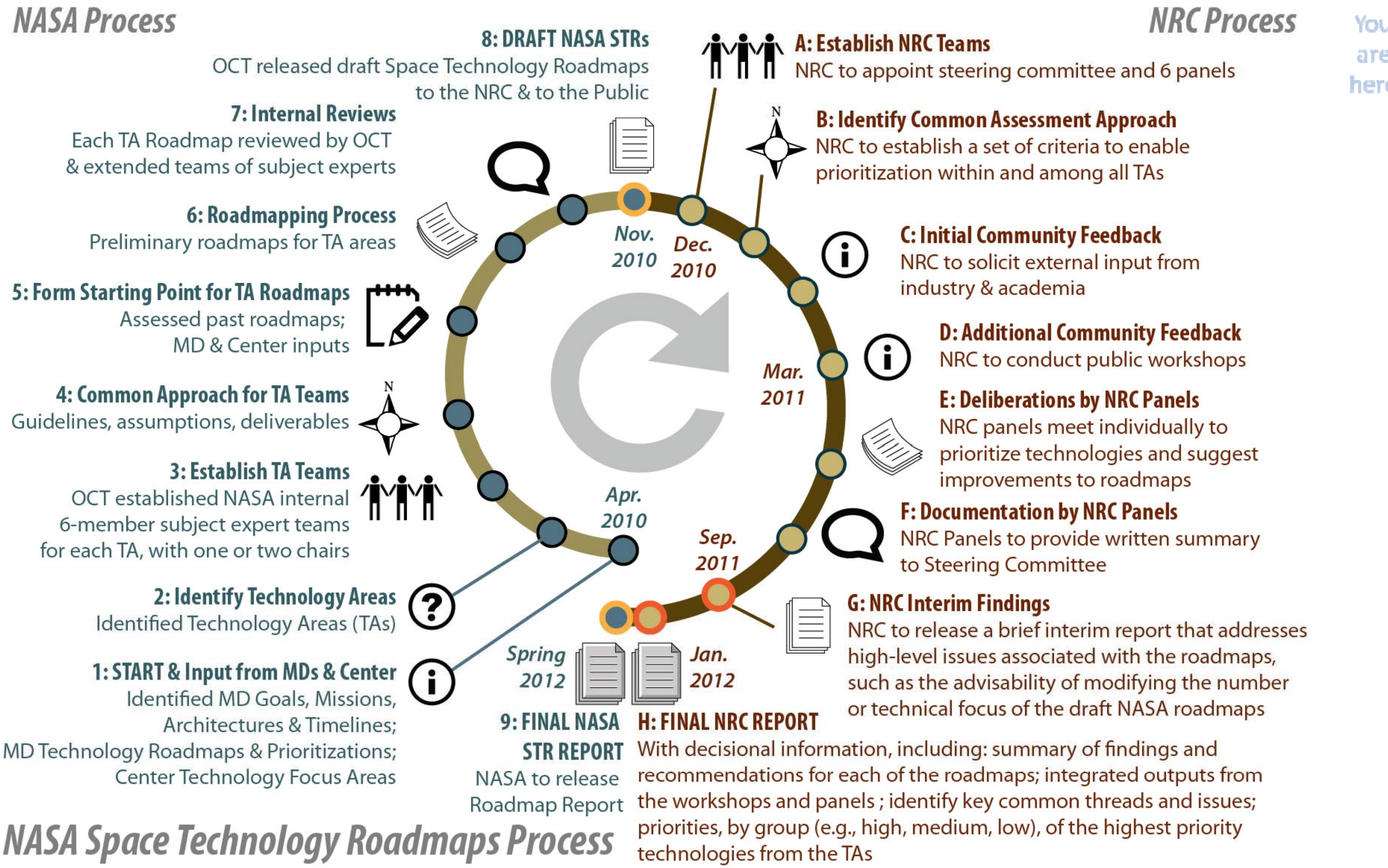
Overview

- Introduction of the TA06 Team
- Roadmapping Process
- Items of Interest
- TA06 Overview
- TA06 Breakdown Structure
- Detailed Portfolio Discussion
- NASA Defined Technology Readiness Levels
- Section 2 Overview/Highlights
  - Examples of Technologies with mid-TRL
- Summary
- Appendices
  - TA06 Roadmapping Process
  - Technology Area Strategic Roadmap (TASR)
  - Major Technical Challenges
  - Traceability to NASA Strategic Goals
  - Benefits of Investment in TA06 Technologies
  - Interdependency with Other TAs

Introduction to the TA06 Team

- Kathryn Hurlbert, *Chair*
- Bob Bagdigian
- Carol Carroll
- Antony Jeevarajan
- Mark Kliss
- Bhim Singh

Roadmapping Process

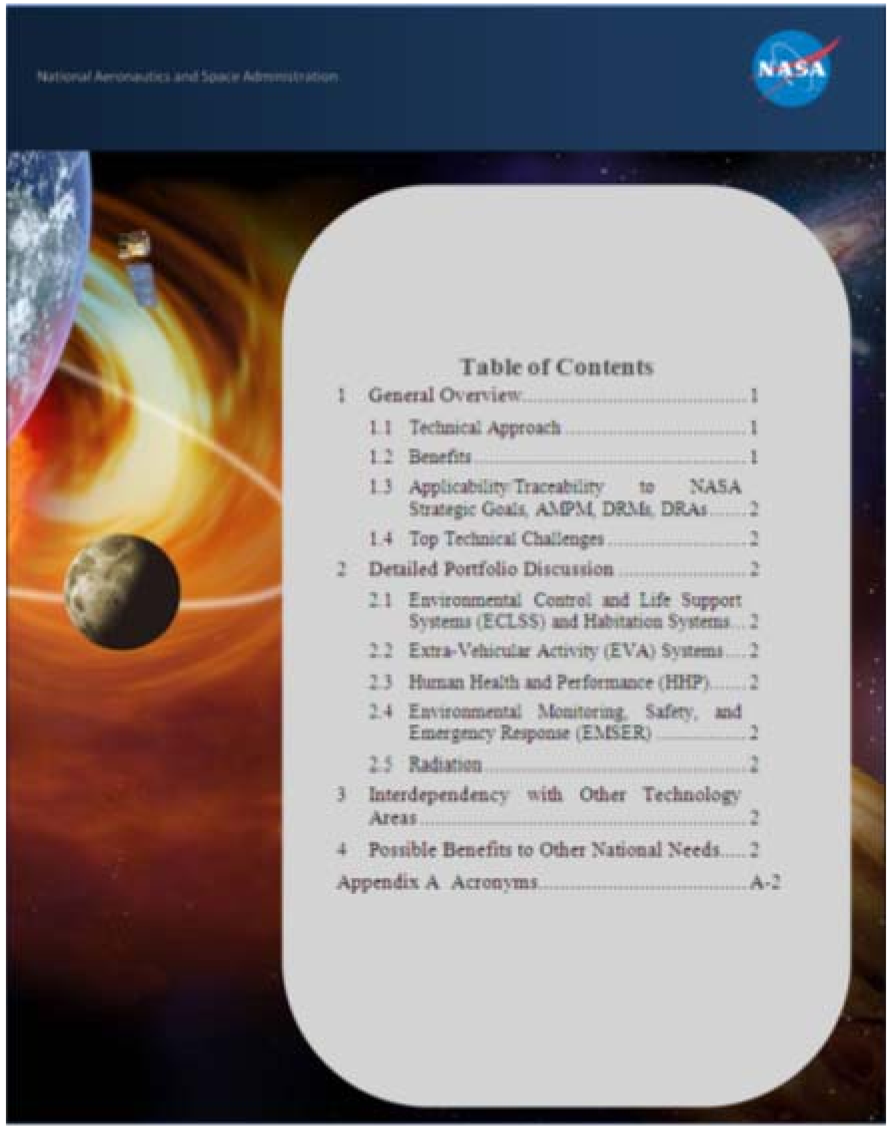


Items of Interest

6 person teams for each TA – all NASA and JPL (no contractors)

3 months from start to finish – very intensive effort

Everyone wore a NASA badge, not a Center badge



National Aeronautics and Space Administration

Table of Contents

30 page limit, including 3-page Executive Summary

20-year horizon for TA Strategic Roadmaps (TASRs)

Went beyond mission "pull" – big emphasis also on technology "push"

Technology Area Overview

Human Health, Life Support & Habitation Systems

Purpose: **to achieve the predicted national and agency goals** in space over the next few decades

- Includes **game-changing** and breakthrough capabilities
- Specifically for **crewed missions**

Sub-technology areas

- Environmental Control and Life Support Systems (ECLSS)
- Habitation Systems
- Extravehicular Activity (EVA) Systems
- Human Health and Performance
- Environmental Monitoring, Safety & Emergency Response (EMSER)
- Radiation

Technology Area Breakdown Structure

Human Health, Life Support & Habitation Systems

Chair:
Katy Hurlbert

- **Environmental Control & Life Support Systems & Habitation Systems**
  - Air Revitalization
  - Water Recovery & Management
  - Waste Management
  - Habitation
- **Extravehicular Activity Systems**
  - Pressure Garment
  - Portable Life Support System
  - Power, Avionics & Software
- **Human Health & Performance**
  - Medical Diagnosis/ Prognosis
  - Long-Duration Health
  - Behavioral Health & Performance
  - Human Factors & Performance
- **Environmental Monitoring, Safety & Emergency Response**
  - Sensors
    - Air
    - Water
    - Microbial, etc.
  - Fire
    - Detection
    - Suppression
  - Protective Clothing/ Breathing
  - Remediation
- **Radiation**
  - Risk Assessment Modeling
  - Radiation Mitigation
  - Protection Systems
  - Space Weather Prediction
  - Monitoring Technology

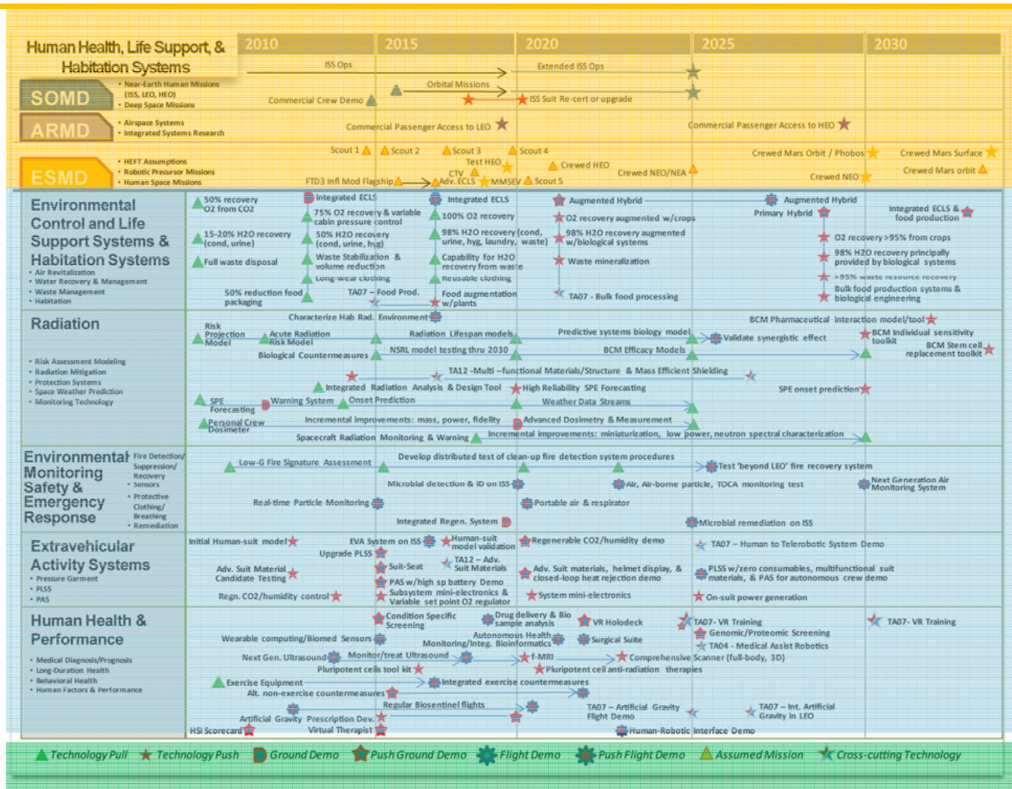
Team Leads

ECLS & Hab: Bob Bagdigian, Mark Kliss
EVA: Bhim Singh
HH&P: Antony Jeevaraian
EMS & ER: Carol Carroll
Radiation: Carol Carroll

Detailed Portfolio Discussion

Technology Area Strategic Roadmap Roll-up

Planned, predicted, and new proposed **missions and milestones** at the top



Technology milestones and activities for each of the sub-TAs

Icons distinguish between technology "pull" and "push", ground vs. flight demos, etc.

TASR milestones are aligned to

1) **Minimize the number of necessary flights** to progress the technologies; AND
2) **Maximize the use of integrated ground tests/demonstrations** for reduced risk

Detailed Portfolio Discussion

Technology Area Strategic Roadmap Document

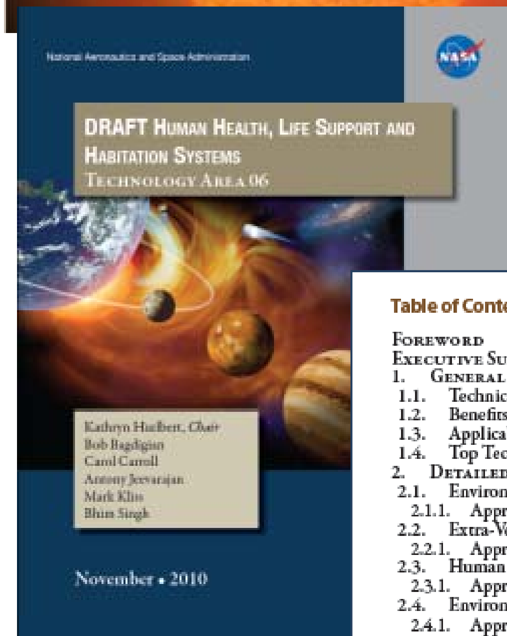


Table of Contents

Table 2. *ECLS and Habitation Technical Area Details*

Function	Current SOA/Practice	Major Challenges	Milestones/Activities to Advance to TRL-6 or beyond
Air Revitalization	[illegible]	Attain high reliability Reduce utilization of expendables Reduce power and equipment mass and volume [illegible]	2011-14: 75% O_2 recovery 2011-14: Variable cabin pressure control 2015-18: 100% O_2 recovery [illegible]

Table 1. *Major Technical Challenges*

Present – 2016
Integrate fundamental research results on radiation environment biological effects, and including other effects from space exposure, into dam[…] model(s) and consolidate and interpret databases of major signaling pathways causative of cancer from space exposure and other damage
Stabilize liquid and solid wastes to recover water and to control pathogens, biological growth and gas/odor production
Achieve high reliability and reduce dependence on expendables over existing SOA systems that recover O_2 from CO_2 and H_2O from humidity c[…] and urine
Develop advanced screening technologies, to detect and/or predict subclinical malignancies, subclinical cataracts, individual susceptibility lev[…] exposure (e.g., radiation) and carbon dioxide exposures, osteoporosis, oxidative stress, renal stone formation, anxiety, and depression
Demonstrate EVA technologies that could be used to extend EVA capability on ISS beyond 2020. These technologies include advances for on-b[…] able CO_2 and humidity control, advanced suit materials, and more capable avionics
Demonstrate real time airborne particle monitoring on the ISS

Section 2

- Detailed **explanation of each sub-TA**
- **Priority technologies and/or system functional areas**, which correlate with TASR content, and a **table** which lists:
  - Current State-of-the-Art (SOA)
  - Major challenges for advancement
  - Recommended milestones/activities to advance to a TRL-6 or beyond (i.e., demo in a relevant mission environment or simulation thereof)

NASA Defined Technology Readiness Levels

TRL 1 Basic principles observed and reported: Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.

TRL 2 Technology concept and/or application formulated: Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept: Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.

TRL 4 Component/subsystem validation in laboratory environment: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.

TRL 5 System/subsystem/component validation in relevant environment: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.

TRL 6 System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space): Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.

TRL 7 System prototyping demonstration in an operational environment (ground or space): System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.

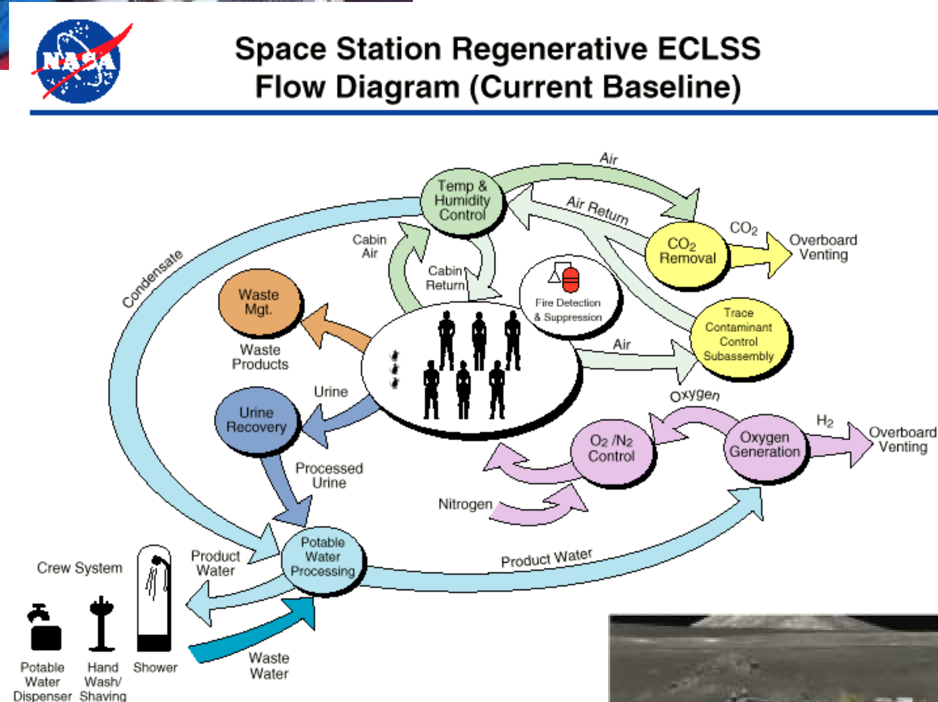
TRL 8 Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space): End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.

TRL 9 Actual system "mission proven" through successful mission operations (ground or space): Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

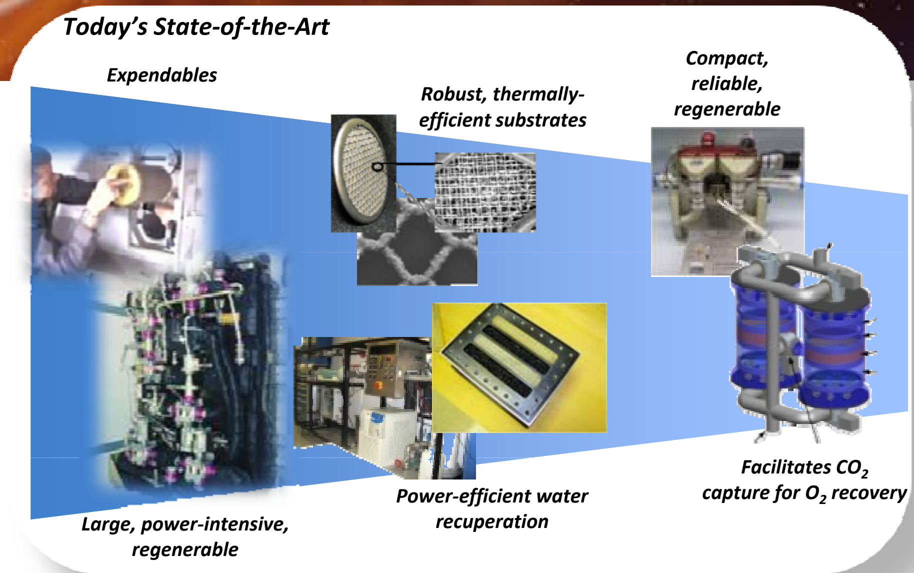
Section 2 Overview/Highlights

2.1 Environmental Control and Life Support Systems (ECLSS) and Habitation Systems

- Technologies/systems to **maintain an environment suitable for sustaining human life** throughout the duration of a mission
- Advancements are needed for future space missions
  - Human beings will spend **significantly longer periods of time farther from reliable logistics depots**, and
  - An **emergency quick-return option will not be feasible**
- Example game-changing capabilities
  - **Significant advancement in waste management**, including techniques to stabilize wastes, recover resources for re-use, and to control pathogens, biological growth and gas/odor production for crew safety
- Example enhancement of current capabilities
  - Mature technologies for **high reliability and increased recovery of O_2 from CO_2**



Removal of Carbon Dioxide from Spacecraft Cabins and Suit-Loops



Example Technology/Technical Solution:

Compact, reliable, energy-efficient regenerable materials to remove carbon dioxide from spacecraft cabins and EVA suit-loops.

Technology Description:

Stable, high-capacity sorbent systems that can be used to control carbon dioxide to safe levels under a variety of exploration mission conditions and human environments. Sustainable exploration can be enhanced by developing common technologies that can also be used in short-duration, open-loop missions and can also, without modification, be supplemented with additional water or carbon dioxide recovery capabilities to meet longer duration mission needs.

Critical Test Facilities

- Ground test stands for extended operational life and material stability tests
- Human-in-the-Loop (HITL) vacuum and/or variable pressure chambers and/or ground testbeds, with/without suit(s)
- ISS or commercial space platform for operational, micro-gravity testing and/or parabolic trajectory aircraft and/or suborbital test vehicles

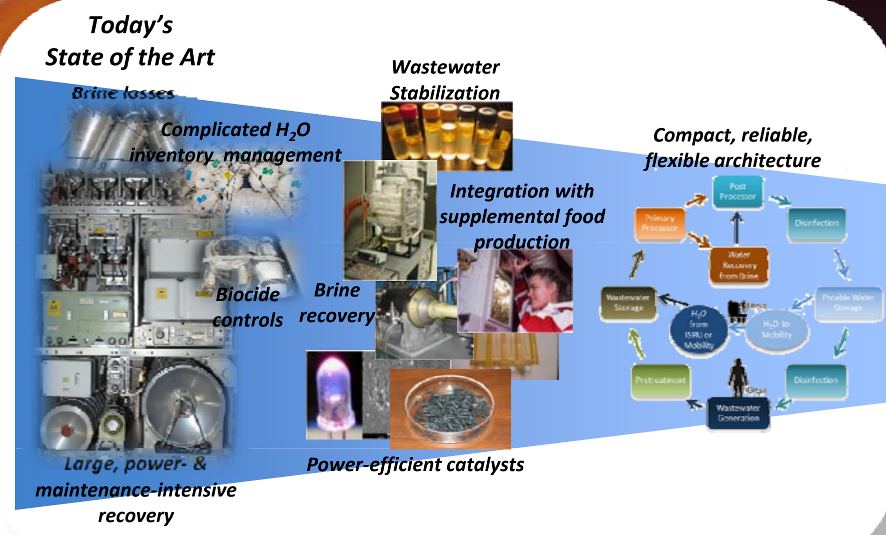
Current TRL: 4

Recommended Timeline to reach TRL 6: 2012 – 2016

Mission Applicability:

- Long Duration LEO
- Transit Beyond LEO
- Planetary

Recovery of Water from Wastewaters



Example Technology/Technical Solution:

Wastewater and product water stabilization, compact & reliable systems to provide flexible architecture to meet specific mission needs.

Technology Description:

Compact, reliable water recovery systems requiring minimum maintenance and contingency resources; expanded capability to recover water from a greater variety of wastewater sources (for example, laundry) to enable mission life cycle mass savings; recovery of re-useable water from concentrated wastes (brines); simple, reliable water inventory management. Long-term evolution to enable integration of supplemental food production with water recovery systems.

Critical Test Facilities

- Ground test stands for extended operational life and material stability tests
- Ground test stands for collection of representative human-derived wastewaters for subsystem and integrated testing
- Unique, large-scale, ground testbeds with/without test subjects for closed-loop extended duration ECLS testing
- ISS or commercial space platform for operational, micro-gravity testing

Current TRL: 2-4

Recommended Timeline to reach TRL 6: 2012 – 2028

Mission Applicability:

- Long Duration LEO
- Transit Beyond LEO
- Planetary

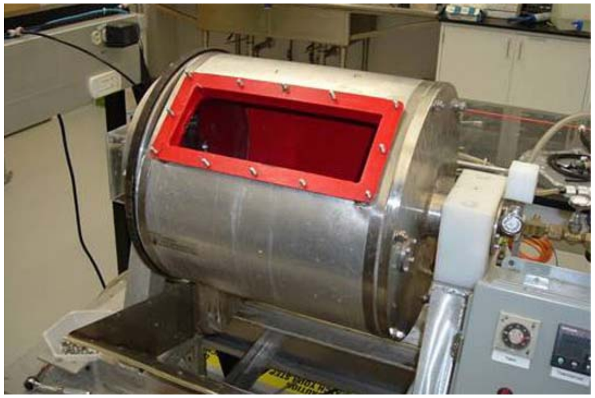
Waste Collection & Stabilization

Example Technology/Technical Solution:
Denitrification Composter

Technology Description:
Treatment of space-mission solid wastes, or trash, is a critical issue for mid to long duration space habitation or transportation. Composting is a process of accelerated biological decomposition of organic materials in a predominantly aerobic environment.

Critical Test Facilities

- Ground test stands for extended operational life and material stability tests
- Unique, large-scale, ground testbeds with/without test subjects for closed-loop extended duration ECLS testing
- ISS or commercial space platform for operational, micro-gravity testing and/or parabolic trajectory aircraft and/or suborbital test vehicles



Denitrifying Anaerobic Microbial Space Operations Bioconverter

Current TRL: 2

Recommended Timeline to reach TRL 6: 2015 – 2026

Mission Applicability:

- Long Duration LEO
- Transit Beyond LEO
- Planetary

Habitation

JAXA astronaut Koichi Wakata will be testing the clothes shown on the space station.

Example Technology/Technical Solution:

Lightweight Long-Wear Crew Clothing

Technology Description:

Development of crew clothing using modern, advanced light weight fabrics, with antimicrobial resistance, for long-term missions with minimal cleaning requirements. These clothes can be worn extensively before they become unpleasant in appearance, touch, and odor.

Critical Test Facilities

- Ground test stands for extended operational life and material stability tests
- Testing combined with other ground test - beds , with/without test subjects
- ISS or commercial space platform and space vehicles for long-duration, beyond LEO missions for operational, micro-gravity performance testing

Current TRL: 2

Recommended Timeline to reach TRL 6: 2012 – 2028

Mission Applicability:

- Long Duration LEO
- Transit Beyond LEO
- Planetary

Section 2
Overview/Highlights

2.2 Extra-Vehicular Activity (EVA) Systems

- **Technologies/systems for humans to perform EVAs** in space and on planetary surfaces
  - **Includes Launch, Entry, and Abort (LEA) suit systems** to protect the crew during launch, landing, and cabin contamination / depressurization events
- Advancements are needed for future space missions
  - Need to provide for **crew safety**,
  - Systems must be developed and provided **affordably**, and
  - Require **sustainability** in extreme environment(s) and for remote locations.
- Example game-changing technologies
  - **New suit materials** to perform multiple functions (e.g., integrated power generation, injury protection, radiation protection), and lead to **game-changing suit configurations and architectures** with decreased mass, improved mobility, self-sizing capabilities, and/or increased life
- Example enhancement of current capabilities
  - Technologies for improved **suit-seat interface design for crew protection** during nominal and off-nominal mission events

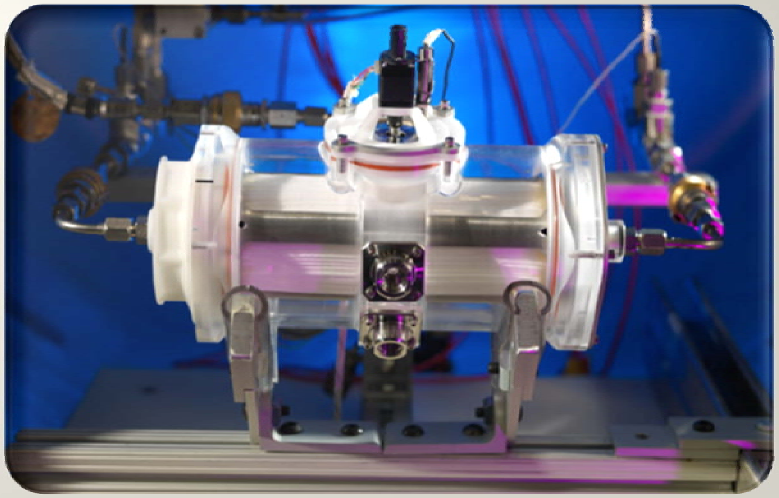
Spacesuit Thermal Control

Example Technology/Technical Solution:
Suit Water Membrane Evaporator (SWME)

Technology Description:
The SWME provides cooling to the spacesuit water loop by evaporating some of the water across a membrane into the vacuum of space.

The sheet membrane SWME uses six concentric cylindrical membranes to create water passages separated by a vented space. A back pressure control valve is used to control the pressure within the evaporator assembly, which controls the amount of water that is evaporated.

Critical Test Facilities
- Human-Rated Vacuum chamber(s)
- Space Suit Systems Lab
- Portable Life Support System (PLSS) Ventilation Lab



Sheet membrane suit water membrane evaporator

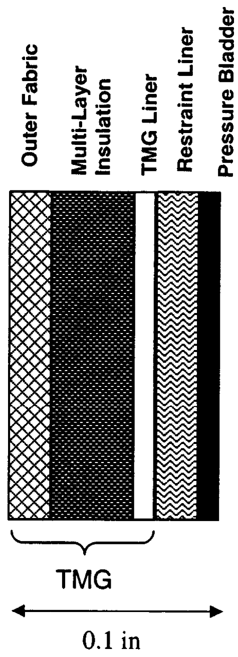
Current TRL: 2

Recommended Timeline to reach TRL 6: 2012 – 2025

Mission Applicability:
- Short Duration LEO
- Long Duration LEO
- Transit Beyond LEO
- Planetary

Spacesuit Materials

Dust Chamber



Layered Spacesuit Fabric

Example Technology/Technical Solution:
Advanced Multi-Functional Materials

Technology Description:
In addition to materials designed for radiation protection, micrometeoroid protection, self-healing, wear resistance, etc., alternatives to woven fabrics or applying surface coatings to keep particles from entering and penetrating the fabric weave can control dust contamination.

Critical Test Facilities
- Advanced Suit Lab
- Space Softgoods Lab
- Specialized Chambers for Planetary Dust Testing

Current TRL: 2

Recommended Timeline to reach TRL 6: 2012 – 2021

Mission Applicability:
- Short Duration LEO
- Long Duration LEO
- Transit Beyond LEO
- Planetary

Section 2
Overview/Highlights

2.4 Environmental Monitoring, Safety, and Emergency Response (EMSER)

- **Technologies to ensure crew health and safety** by protecting against spacecraft hazards, and for effective response should an accident occur
- Advancements are needed for future space missions
  - Provide essential **monitoring, prevention and safety systems for critical hazards** (e.g., fire, contamination)
  - Accommodate **remediation should a hazardous event occur** to support the crew and overall mission completion, especially in remote and extreme environments
  - Example game-changing technologies
    - Multi-analyte technology for **stand-alone water quality measurements and total organic carbon (TOC) monitoring**
  - Example enhancement of current capabilities
    - **Post-fire remediation recovery technologies** that are portable, regenerable, and are stand-alone from the critical ECLSS, to safely remove combustion products and fire extinguishing material(s)

National Aeronautics and Space Administration

Sensors for autonomous, real time air and water monitoring

Example Technology/Technical Solution:

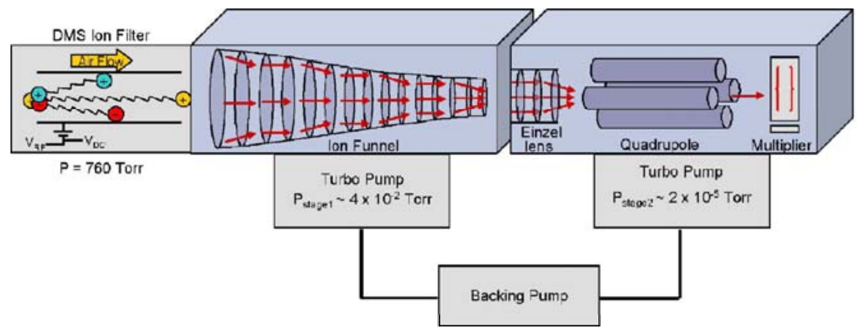
Differential mobility/mass spectrometry device(s)

Technology Description:

Instrument(s) that separate ions using differential mobility, which is based on the charge-, mass-, and structure-dependent movement of ions through a high electric field region. The separated compounds will be identified and quantified using mass spectrometry, which provides the capability of identifying unknown contaminants. Samples can be ionized using nickel-63, electrospray ionization, or pyrolysis. Multiple inlet sources provide the flexibility to monitor breath and body fluids for biomarker analysis.

Critical Test Facilities

- ISS or commercial space platform needed for crewed, long duration testing



Schematic design of DMS/MS system

Current TRL: 3

Recommended Timeline to reach TRL 6: 2012 – 2016

Mission Applicability:

- Long Duration LEO
- Transit Beyond LEO
- Planetary

Techniques for fire suppression systems

Unique Test Vehicles

Ground-Based CO_2 Fire Suppression System

Example Technology/Technical Solution:
Gaseous Fire Suppression System(s)

Technology Description:

Carbon dioxide based suppression system carbon dioxide or nitrogen, with single and multiple injection points and direct or distributed agent deployment

Critical Test Facilities

- Parabolic trajectory aircraft and/or suborbital test vehicles (note: recommendation to strongly consider suborbital options) for zero-g and partial-g evaluation
- ISS or commercial space station test beds
- Development of an unique, large scale test platform (e.g., re-entering ISS cargo vessel)

Current TRL: 2

Recommended Timeline to reach TRL 6: 2015 – 2026

Mission Applicability:

- Transit to/from LEO
- Short Duration LEO
- Long Duration LEO
- Transit Beyond LEO
- Planetary

Section 2
Overview/Highlights

2.3 Human Health and Performance (HHP)

- **Technologies to maintain the health of the crew and support optimal and sustained performance** throughout the duration of a mission
- Advancements are needed for future space missions
  - **Significant new challenges to crew health**, such as astronauts' psychological health in extreme and remote environments, hazards created by traversing the terrain of planetary surfaces during exploration, and the physiological effects of exposure to variable gravity environments
  - More remote missions with **limited communications** to obtain support from ground-based personnel for diagnosis and consultation of **medical events**
  - Ensure safety and success before, during, and after proposed flights, including those with **no option for emergency quick-return**
  - Example game-changing technologies
  - Use **virtual reality** for training and psychological benefits
  - Example enhancement of current capabilities
    - **Advanced human screening technologies** for early detection/prediction of critical medical conditions such as dental emergencies, subclinical medical conditions including malignancies, cataracts, individual susceptibility levels to radiation and carbon dioxide exposures, osteoporosis, oxidative stress and renal stone formation, sleep disorder, anxiety and depression

Mapping of HRP/NSBRI/SBIR Funded Technologies against OCT Roadmap

6.3.2.6	In-flight medical diagnosis	
		Non-Invasive Intracranial Pressure Device (Funded by HRP) NRA - TRL-6 at FY-2011
		Monitoring of Bone Loss Bio-Markers in Human Sweat (Funded by HRP) NRA TRL-6 at FY-2012
		Re-usable handheld lab technology proof-of-concept prototype hardware (Funded by SBIR) TRL-6 at FY-2011
		Test-strips for use in the rHealth sensor for diagnostic testing (Funded by SBIR) TRL-6 at FY-2012
		In-flight blood analysis system prototype (Funded by NSBRI) - TRL-6 at FY-2012
		In-flight banalysis of body fluid and resusable (Funded by HRP)
		Integration of i-revive with lightweight Trauma Module (Funded by NSBRI) TRL-6 at FY-2011
		Light-weight Trauma Module (Funded by HRP)
6.3.3.1	Crew monitoring and evaluation	
		Tools for Physiological Markers of Stress (Non-invasive Technology) - Funded by HRP - Directed Study
		Autonomous Monitoring Technology (Funded by SBIR)
		NIN (Near-Infrared Neuroimaging) Depression Detection Tool (Funded by NSBRI)
		OCR (Optical computer Recognition) of Stress (Funded by NSBRI
		Cognitive Perfoormance Monitoring Tech (Funded by SBIR)
		Behavior Tracking Software (Solicited by SBIR)
		Developing, Maintaining and Restoring Team Cohesion (Funded by HRP/NRA)
6.3.4.1	Human/system displays and interfaces, and HIS	
		Automation Interface Design Tools Development (AIDT) (Funded by HRP)
		Displays and Controls Interfaces (Human-Computer/Vehicle) (Funded by HRP)
		Lunar Lnader, Human-Automation Interactions (Funded by NSBRI)
		Computer-based Tool for Assessment of Mission Function Allocation Strategies (Funded by SBIR)
		Evaluation Toolkits and Methods for Assessing Human-Robot Teams (Funded by HRP)
		Tool for reporting Human Factors Incidents to eliminate errors in recall-by-memory (Funded by SBIR)

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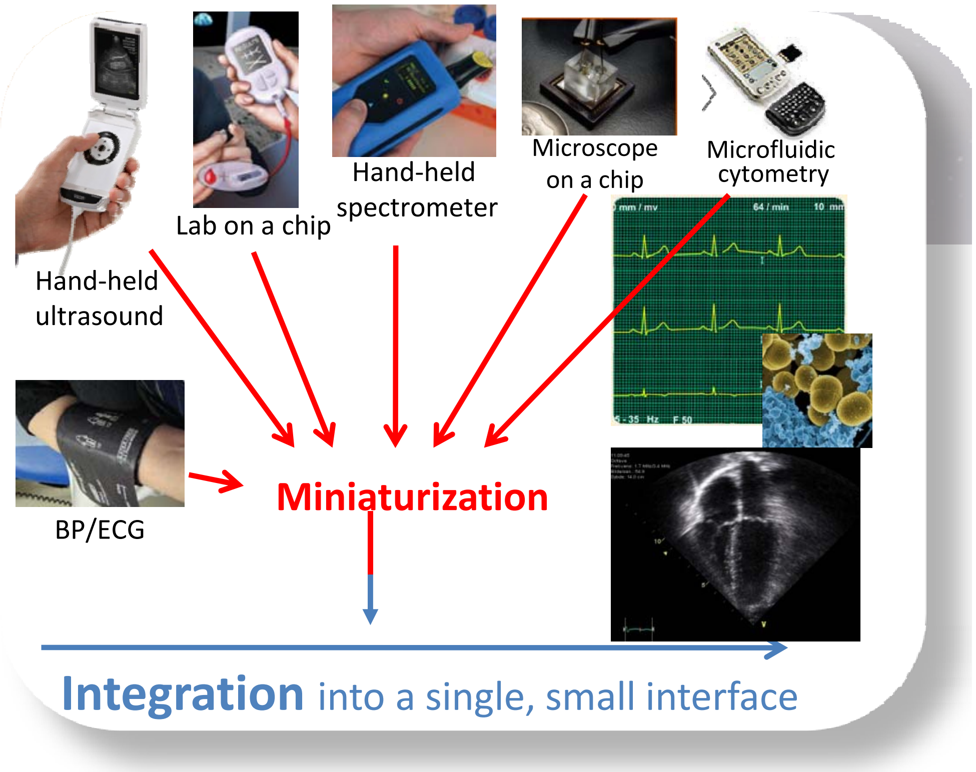
In-flight Medical Diagnosis



Example Technology/Technical Solution:

Hand-held diagnostic Suite

Technology Description:

Technologies under consideration include (but not limited to) ultrasound imaging, Blood pressure, ECG monitoring, micro-digital microscope, microfluidic cytometry, spectrometry and a diagnostic laboratory-on-a-chip. These technologies will be further miniaturized and integrated into a single unit that will function as a portable computer interface similar to the picture shown

Critical Test Facilities

- ISS or commercial space platform needed for crewed, long duration testing

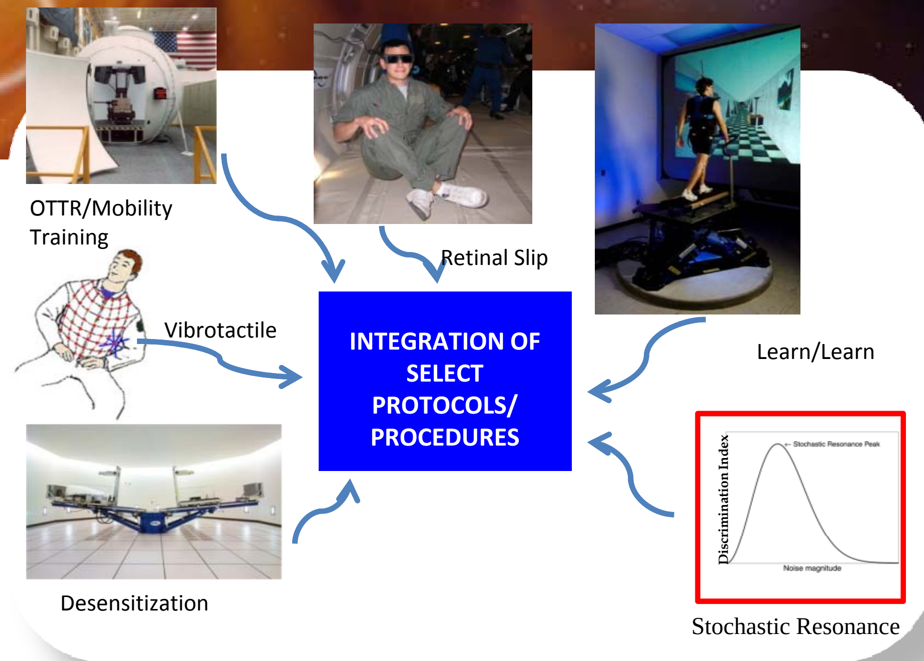
Current TRL: 2-3

Recommended Timeline to reach TRL 6: 2012 – 2017

Mission Applicability:

- Long Duration LEO
- GEO
- NEO
- Lunar
- Mars

Non-pharmacological Treatment for Sensorimotor Flight Disorders



Example Technology/Technical Solution:

Suite of Protocols/Procedures for Neurosensory Disorders

Technology Description:

Technologies under consideration include (but not limited to) vibrotactile feedback for spatial orientation, stochastic noise to provide low level brainstem input, stroboscopic illumination to prevent retinal slip, desensitization protocols, pre and in-flight training protocols and learning to learn strategy protocols

Critical Test Facilities

- Short-arm Centrifuge
- OTTR
- ISS as a platform to test operational implementation

Current TRL: 1-2

Recommended Timeline to reach TRL 6: 2012 – 2017

Mission Applicability:

- Long Duration LEO
- GEO
- NEO
- Lunar
- Mars

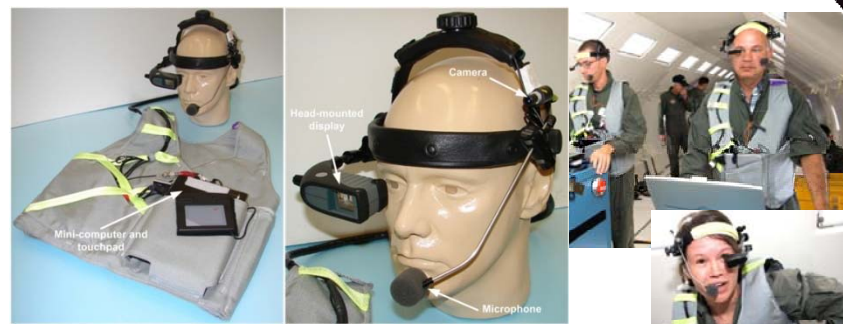
Advanced Displays & Controls

Example Technology/Technical Solution:
Wearable, modular computing

Technology Description:
Advancements in D&C, cameras, and communication technologies, an "all-in-one" human interface system can be developed and integrated to provide display of information, crew-to-crew/ crew-to-ground communications and crew situational awareness capability for future, autonomous human mission operations. Development includes ground assessments, integrated testing of prototype hardware.

Critical Test Facilities

- Parabolic trajectory aircraft for zero-g and partial-g evaluation
- ISS or commercial space station test beds for crewed and long duration testing
- Other analog environments such as NEEMO, D-RATS



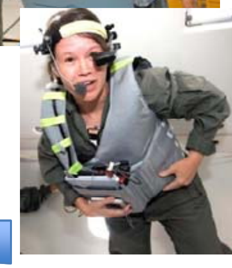


Figure 1. **Components of the current prototype system.**

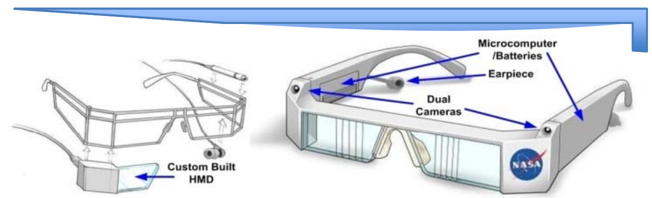


Figure 2. **A concept for the future wearable computing system.**

Current TRL: 3

Recommended Timeline to reach TRL 6/7: 2012 – 2016

Mission Applicability:

- Transit to/from LEO
- Short Duration LEO
- Long Duration LEO
- Transit Beyond LEO
- Planetary
- Ground operations

Biosentinels

Example Technology/Technical Solution:

Suite of Nanosatellite platforms to carry out space environment effects on Cells, microbes, plants and multicellular organism

Technology Description:

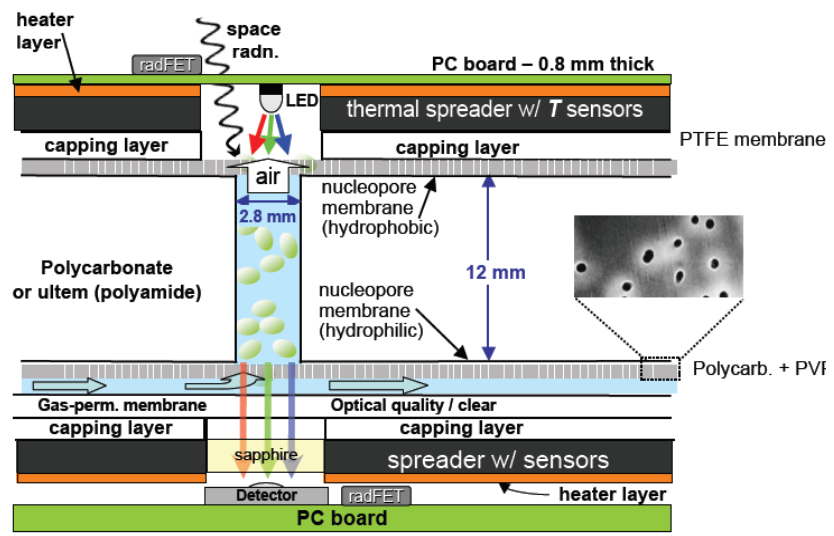
Technologies under consideration include (but not limited to) Drug dose dependence alteration in high dose radiation and microgravity, grow/analyze microorganisms in space environments and follow organism viability, chemical stability, drug efficacy and gene expression

Critical Test Facilities

- Nanosatellite platforms
- ISS as a platform to test operational implementation

SESLO (bio) Fluidic/Thermal/Optical Architecture

Fluidic / optical / thermal cross-section



Current TRL: 3-4

Recommended Timeline to reach TRL 6: 2012 – 2016

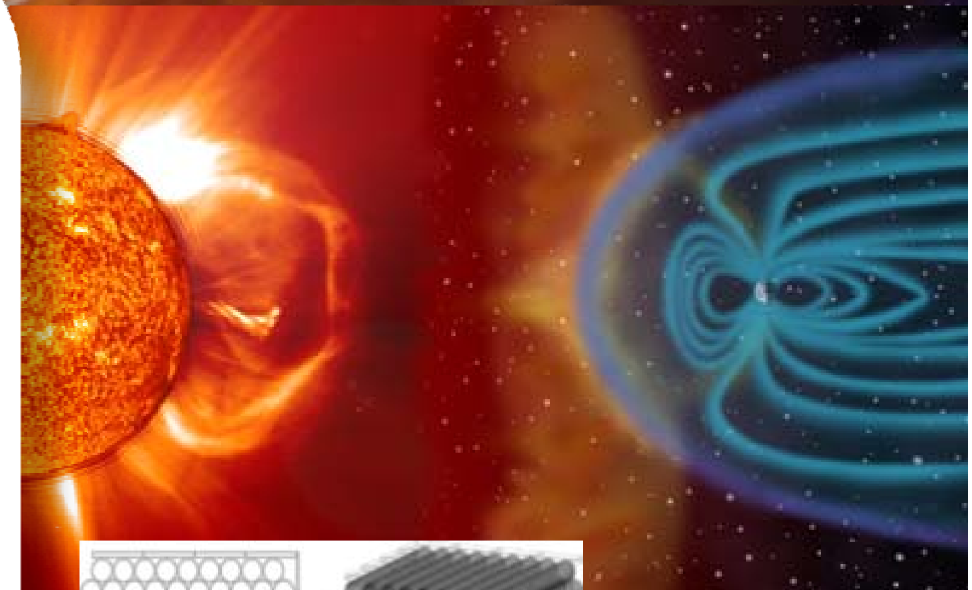
Mission Applicability:

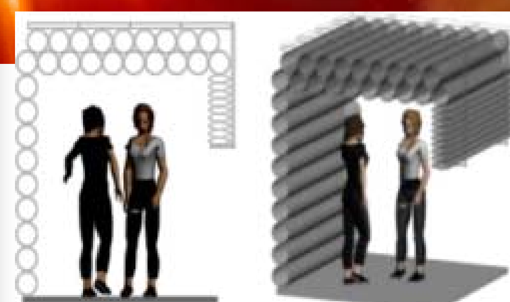
- Long Duration LEO
- GEO
- NEO
- Lunar
- Mars

Section 2
Overview/Highlights

2.5 Radiation

- **Technologies and** the development of **a knowledge base** to understand and **quantify radiation health and performance risks, for monitoring space radiation and crew exposure, to develop mitigation countermeasures, and to minimize exposures** through the use of material shielding systems and/or combination strategies
- Advancements are needed for future space missions
  - Sufficient **ground and flight data on living systems exposed to the relevant space environment** to support models to accurately predict radiation risks, identify genetic selection factors, and develop mitigation measures for remaining risks
  - Develop **effective design(s) of integrated radiation protection systems**
- Example game-changing technologies
  - **Radiation mitigation/biological countermeasures** for chronic galactic cosmic radiation (GCR) or intermediate solar particle event (SPE) dose rates
- Example enhancement of current capabilities
  - **Space weather** prediction to include **real-time monitoring and forecasting model(s)**, and prediction of onset and evolution of SPE as well as all-clear periods





Medipix small active radiation dosimeter

Medipix prototype without casing

Example Technology/Technical Solution:
Active Dosimeter for crew and area monitoring

Technology Description:
Miniaturized, radiation-hard pixel-based technology to provide fully active personal radiation monitoring including EVA. Replaces "dosimetry" with a full personal spectral field measurement.

Critical Test Facilities
- ISS or commercial space platform needed for crewed, long duration testing

Current TRL: 5

Recommended Timeline to reach TRL 6: 2012 – 2014

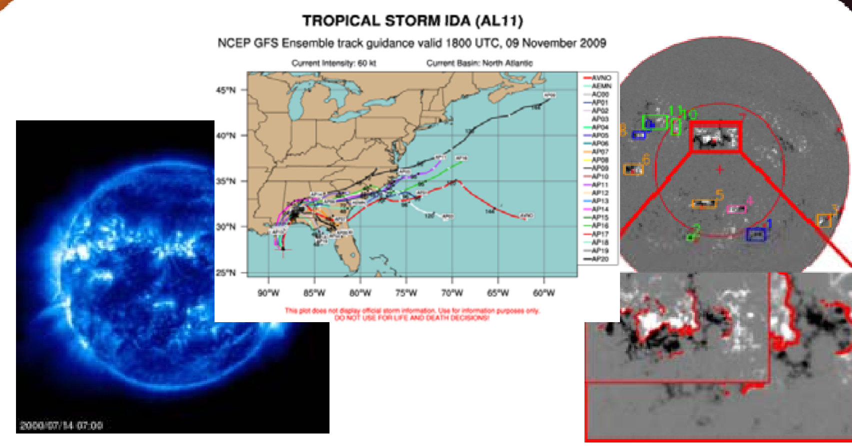
Mission Applicability:
- Long Duration LEO
- Transit Beyond LEO
- Planetary

Ensemble Forecasting for Space Weather Risk Mitigation

Example Technology/Technical Solution:
Ensemble forecasting of hurricane tracks in terrestrial weather

Technology Description:
Ensemble techniques are the state-of-the-art in terrestrial weather forecasting for decreasing uncertainty in individual forecast models. Current space weather forecasting models identified as reaching sufficient maturity will be transitioned to operations using an ensemble approach. Much enhanced forecast fidelity could be obtained with this approach. Tests would be conducted in real-time during the next solar max to assess overall forecast skill and false alarm rate. Ensemble techniques provide for inclusion of additional models into the suite of tools as models mature.

Critical Test Facilities
- Computational platform for testing ensemble models
- Infrastructure for testing operational utilization concepts
- Possible use of ISS as a platform to test operational implementation



Translation of ensemble techniques for mitigating Solar Proton Events

Current TRL: 1

Recommended Timeline to reach TRL 6: 2013 – 2017

Mission Applicability:
- Long Duration LEO
- GEO
- NEO
- Lunar
- Mars

Summary

- The development of this roadmap showed that technology investments in the Human Health, Life Support, and Habitation Systems TA will help enable human space missions to Low Earth Orbit (LEO) and well beyond, and provide significant benefit to national needs.

Acknowledgements

- Our great support team of Audrey Burge, Jeannie Corte, Karen Spears, and Rilla Wolf, who provided administration, graphic artistry, technical editing and many other things …
- The wide array of technical experts and contributors supporting our efforts, including Dr. Howard Ross

Appendices

- TA06 Roadmapping Process
- Technology Area Strategic Roadmap (TASR)
- Major Technical Challenges
- Traceability to NASA Strategic Goals
- Benefits of Investment in TA06 Technologies
- Interdependency with Other TAs

TA06 Document Development Process Overview

In parallel to OCT expert review, our team did a review with selected topical experts, including a NASA Engineering and Safety Center (NESC) Fellow

Updated draft 10/2010

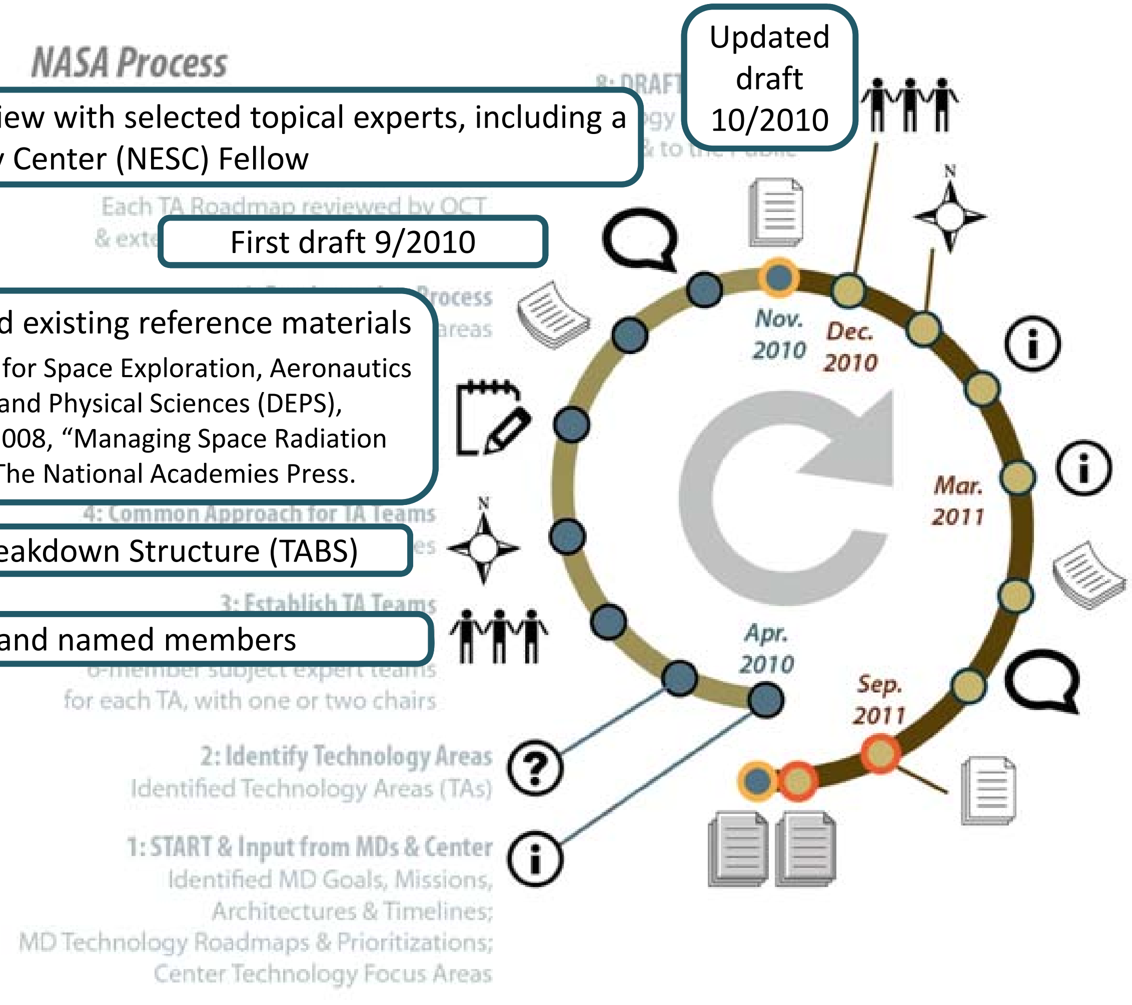
First draft 9/2010

Solicited inputs from recognized experts and acquired existing reference materials

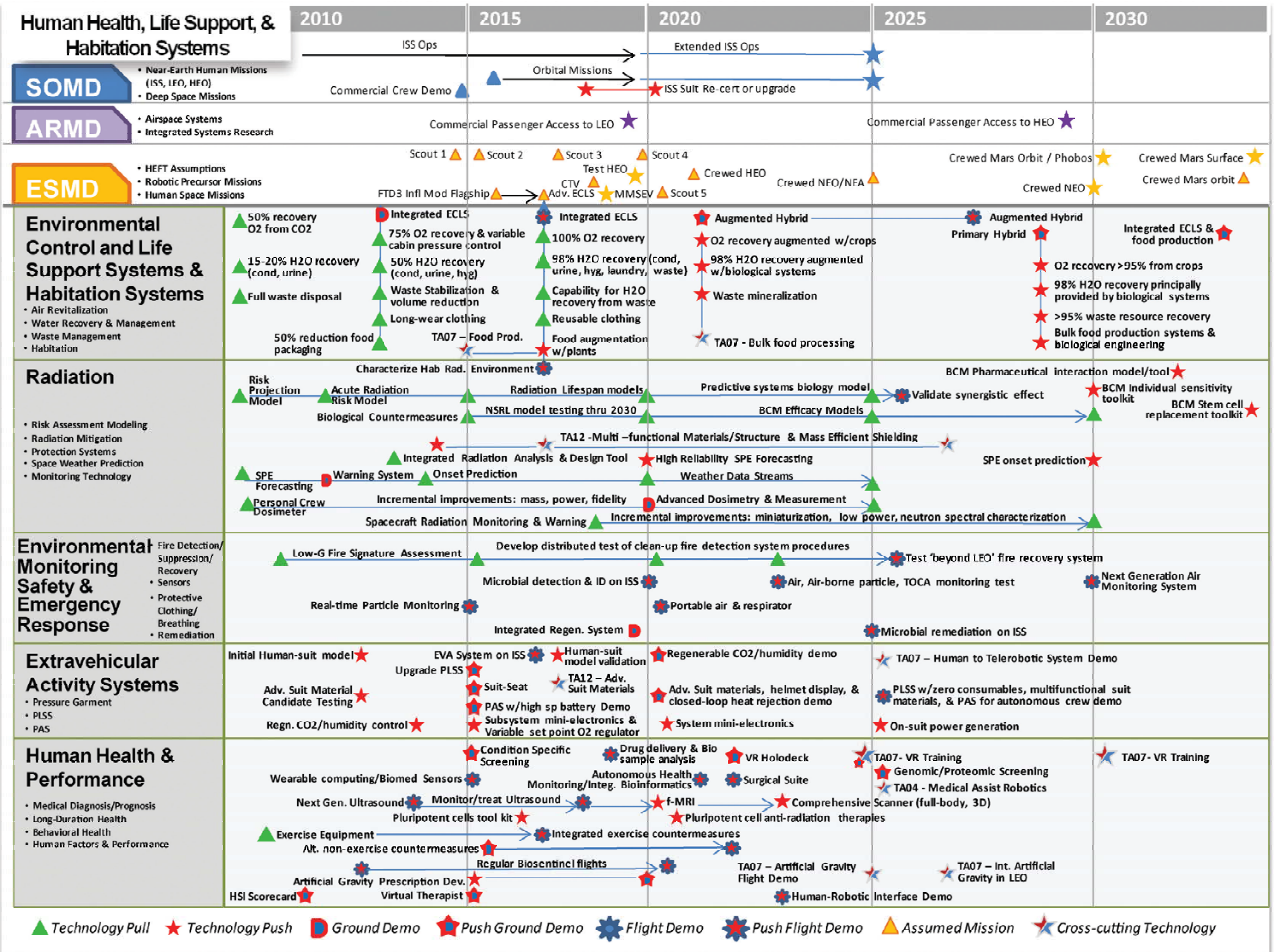
Example: Committee on the Evaluation of Radiation Shielding for Space Exploration, Aeronautics and Space Engineering Board (ASEB), Division on Engineering and Physical Sciences (DEPS), National Research Council of the National Academies (NRC), 2008, "Managing Space Radiation Risk in the New Era of Space Exploration," Washington, D.C.: The National Academies Press.

Our team developed a Technical Area Breakdown Structure (TABS)

OCT formed TA teams and named members



NASA Space Technology Roadmaps Process



Human Health, Life Support, & Habitation Systems
2010
2015
2020
2025
2030
SOMD
• Near-Earth Human Missions (ISS, LEO, HEO)
• Deep Space Missions
ISS Ops
Extended ISS Ops
Orbital Missions
Commercial Crew Demo
ISS Suit Re-cert or upgrade
ARMD
• Airspace Systems
• Integrated Systems Research
Commercial Passenger Access to LEO
Commercial Passenger Access to HEO
ESMD
• HEFT Assumptions
• Robotic Precursor Missions
• Human Space Missions
Scout 1
Scout 2
Scout 3
Scout 4
Test HEO
Crewed HEO
CTV
FTD3 Infl Mod Flagship
Adv. ECLS
MMSEV
Scout 5
Crewed NEO/NEA
Crewed Mars Orbit / Phobos
Crewed Mars Surface
Crewed NEO
Crewed Mars orbit
Environmental Control and Life Support Systems & Habitation Systems
• Air Revitalization
• Water Recovery & Management
• Waste Management
• Habitation
50% recovery O2 from CO2
15-20% H2O recovery (cond, urine)
Full waste disposal
50% reduction food packaging
Integrated ECLS
75% O2 recovery & variable cabin pressure control
50% H2O recovery (cond, urine, hyg)
Waste Stabilization & volume reduction
Long-wear clothing
TA07 – Food Prod.
Integrated ECLS
100% O2 recovery
98% H2O recovery (cond, urine, hyg, laundry, waste)
Capability for H2O recovery from waste
Reusable clothing
Food augmentation w/plants
Augmented Hybrid
O2 recovery augmented w/crops
98% H2O recovery augmented w/biological systems
Waste mineralization
TA07 - Bulk food processing
Augmented Hybrid
Primary Hybrid
Integrated ECLS & food production
O2 recovery >95% from crops
98% H2O recovery principally provided by biological systems
>95% waste resource recovery
Bulk food production systems & biological engineering
Radiation
• Risk Assessment Modeling
• Radiation Mitigation
• Protection Systems
• Space Weather Prediction
• Monitoring Technology
Risk Projection Model
Acute Radiation Risk Model
Characterize Hab Rad. Environment
Radiation Lifespan models
Biological Countermeasures
NSRL model testing thru 2030
Predictive systems biology model
BCM Efficacy Models
Validate synergistic effect
BCM Pharmaceutical interaction model/tool
BCM Individual sensitivity toolkit
BCM Stem cell replacement toolkit
TA12 - Multi –functional Materials/Structure & Mass Efficient Shielding
Integrated Radiation Analysis & Design Tool
High Reliability SPE Forecasting
SPE onset prediction
SPE Forecasting
Warning System
Onset Prediction
Weather Data Streams
Personal Crew Dosimeter
Incremental improvements: mass, power, fidelity
Advanced Dosimetry & Measurement
Spacecraft Radiation Monitoring & Warning
Incremental improvements: miniaturization, low power, neutron spectral characterization
Environmental Monitoring Safety & Emergency Response
Fire Detection/ Suppression/ Recovery
• Sensors
• Protective Clothing/ Breathing
• Remediation
Low-G Fire Signature Assessment
Develop distributed test of clean-up fire detection system procedures
Test 'beyond LEO' fire recovery system
Microbial detection & ID on ISS
Air, Air-borne particle, TOCA monitoring test
Next Generation Air Monitoring System
Real-time Particle Monitoring
Portable air & respirator
Integrated Regen. System
Microbial remediation on ISS
Extravehicular Activity Systems
• Pressure Garment
• PLSS
• PAS
Initial Human-suit model
EVA System on ISS
Human-suit model validation
Regenerable CO2/humidity demo
TA07 – Human to Telerobotic System Demo
Upgrade PLSS
TA12 – Adv. Suit Materials
Adv. Suit Material Candidate Testing
Suit-Seat
Adv. Suit materials, helmet display, & closed-loop heat rejection demo
PLSS w/zero consumables, multifunctional suit materials, & PAS for autonomous crew demo
PAS w/high sp battery Demo
Regn. CO2/humidity control
Subsystem mini-electronics & Variable set point O2 regulator
System mini-electronics
On-suit power generation
Human Health & Performance
• Medical Diagnosis/Prognosis
• Long-Duration Health
• Behavioral Health
• Human Factors & Performance
Condition Specific Screening
Drug delivery & Bio sample analysis
VR Holodeck
TA07- VR Training
TA07- VR Training
Wearable computing/Biomed Sensors
Autonomous Health Monitoring/Integ. Bioinformatics
Surgical Suite
Genomic/Proteomic Screening
TA04 - Medical Assist Robotics
Next Gen. Ultrasound
Monitor/treat Ultrasound
f-MRI
Comprehensive Scanner (full-body, 3D)
Pluripotent cells tool kit
Pluripotent cell anti-radiation therapies
Exercise Equipment
Integrated exercise countermeasures
Alt. non-exercise countermeasures
Regular Biosentinel flights
TA07 – Artificial Gravity Flight Demo
TA07 – Int. Artificial Gravity in LEO
Artificial Gravity Prescription Dev.
HSI Scorecard
Virtual Therapist
Human-Robotic Interface Demo
Technology Pull
Technology Push
Ground Demo
Push Ground Demo
Flight Demo
Push Flight Demo
Assumed Mission
Cross-cutting Technology

Major Technical Challenges

- Determined by **reviewing the recommended content for each sub-TA for the time period** specified, and selecting **one or two technologies** and/or priority system functions within that domain for a **balanced representation** of HLHS
- The selected technologies include those that:
  - Are a **low TRL** and require extended development time to be ready for future missions
  - May **significantly impact mission implementation** (e.g., high reliability, reduced logistics, decreased mass, high efficiency power systems, etc.)
  - Are **critical to human safety and well-being**

Major Technical Challenges

Period	Challenges
Present – 2016	• **Integrate fundamental research results on radiation environment biological effects**, and including other effects from space exposure, into damage/risk model(s) and consolidate and interpret databases of major signaling pathways causative of cancer from space exposure and other damage • **Stabilize liquid and solid wastes** to recover water and to control pathogens, biological growth and gas/odor production • **Achieve high reliability and reduce dependence on expendables** over existing SOA systems that recover O_2 from CO_2 and H_2O from humidity condensate and urine • **Develop advanced screening technologies**, to detect and/or predict subclinical malignancies, subclinical cataracts, individual susceptibility levels to space exposure (e.g., radiation) and carbon dioxide exposures, osteoporosis, oxidative stress, renal stone formation, anxiety, and depression • Demonstrate EVA **technologies** that could be used **to extend EVA capability on ISS beyond 2020**. These technologies include advances for on-back regenerable CO_2 and humidity control, advanced suit materials, and more capable avionics • **Demonstrate real time airborne particle monitoring** on the ISS
2017 – 2022	• **Develop radiation risk model(s)** as a predictive systems biology model approach for space radiation, including development of experimental methods/ techniques and models to verify integrated risk and understand synergistic effects of other spaceflight stressors (microgravity, reduced immune system response, etc.) combined with radiation • **Validate physiological and psychological countermeasures** for long-duration missions, which can include any combination of exercise, non-exercise (e.g., pharmacological) and/or advanced techniques (e.g., Virtual Reality technologies such as a "Holodeck", artificial gravity) • **Close high-reliability ECLSS more fully**, with >95% O_2 and H_2O recovery from an integrated mission perspective • Implement **bulk food processing in-flight and augmentation of food supply** with plants • **Advanced EVA technologies to enable missions to NEOs**, which includes suits that incorporate advanced materials and component demonstrations of life support technologies that reduce consumables • Complete **development of a distributed hybrid fire-detection system** for space missions

Major Technical Challenges

2023 – 2028

- **Demonstrate hybrid physical/chemical and biological ECLSS** with >95% recovery of O_2 and H_2O **with bulk food production**
- **Develop and validate a non-ionizing, full body, dynamic, 3-D imager** with in-situ diagnosis and treatment capabilities (e.g., renal stone ablation)
- **Validate real-time monitoring and forecasting space weather model(s)**, to include prediction of onset and evolution of Solar Particle Events (SPEs) as well as all clear periods
- **Flight demonstration of an advanced EVA system**, including suits that utilize multifunctional materials, a portable life-support system (PLSS) with no consumables, on-suit power generation, and avionics that enable the crew to operate autonomously
- Complete integrated **system testing of portable, non-solvent-based microbial remediation** on ISS

Traceability to NASA Strategic Goals

- **Technology Area Strategic Roadmap (TASR) development process**
  - Used our interpretation of the **overall agency goals, outcomes and objectives** as "pull" for the technology content and milestones
  - **Incorporated the NASA Mission Directorates and NASA Centers needs and focus** into the sub-Technical Areas (sub-TAs)
- **Major missions and milestones were derived from multiple sources**
  - **Drafted FY11 Agency Mission Planning Manifest** (AMPM)
  - **Design Reference Missions** (DRMs) were assumed based on **Design Reference Architectures** (DRAs) being evaluated as a part of the **Human Exploration Framework Team** (HEFT) activity
  - Attempt made to include **items on the TA07, Human Exploration and Development of Space, roadmap**, as considerable overlap potential exists with this technology area
  - **"Push" missions and milestones that are recommended for consideration**, with the an example being the **extension of ISS operations beyond 2020**
    - It should be noted that alternative platforms might serve this purpose as well

Traceability to NASA Strategic Goals

The drafted roadmap does not fully link all items directly to a specific agency mission or milestone at this time, but rather provides time phasing that would allow infusion of technologies or capabilities to support appropriate future agency missions and/or milestones

Benefits of Investment in TA06 Technologies

The **primary benefit** of significant technology development for the Human Health, Life Support and Habitation Systems (HLHS) domain is the **ability to successfully achieve human space missions to Low Earth Orbit (LEO) and well beyond**

- **Continuing operation and missions of the International Space Station (ISS)**
  - **Recommend consideration for extending operations there, or that an alternative permanent or semi-permanent in-space facility** be identified to allow for continued and sustained research/testing and associated advancements related to the effects of living and working in space
- **Proposed bold space missions currently under consideration, like to a Near Earth Object (NEO)**
- **Proposed roadmap also includes suggested in-flight and ground test activities for pre-flight evaluation and augmented research/testing**, which will regularly and efficiently provide advancements

Benefits to Other National Needs

Many of the **proposed technologies identified** in the roadmap **can lead to improvements in the quality of life here on Earth, creating benefits of national and global interest**

Life Support and Habitation

- Potential for complete wastewater recovery to potable standards for **military, remote and water-scarce regions, and disaster relief emergency response**
- Efficient methods for CO_2 capture, conversion, sequestration, and advanced contaminant removal/destruction, and particulate management for **climate change mitigation, mine safety, enclosed spaces, military applications, and synthetic fuel production**
- Light-weight, deployable, inflatable, interior structures provide **rapid shelter construction for military deployments, disaster response**, etc.....

Space Suit Technologies

- Previous and recent **space suit technologies** have provided materials and manufacturing techniques that have led to significant improvements in **commercial products**, like athletic shoes, **and specialized items** that benefit many, like **efficient manufacture of pharmaceuticals**
  - **Therapeutic suits for people with medical needs**
  - **Protective suits** like those for race car drivers and firefighters
  - **Life-saving gas and chemical masks**, etc....

Benefits to Other National Needs

Human Health & Performance

- Technologies may lead to smaller portable analysis and imaging units that could be used in **austere/harsh environments, or even in rural settings without access to large medical facilities**
  - Countermeasures developed for space are likely to **impact clinical practice by providing a better understanding of how the body works**
  - **New tools to influence both wellness, and treatment of diseases**
  - Technologies for enhanced crew interfaces and autonomy will have the **potential for use in extreme environments**, etc….

EMS & ER and Radiation

- Biological innovations or breakthroughs would also be of **interest to the National Institutes of Health**, and have the potential to significantly improve life on Earth
  - Technologies for radiation may **help cancer patients suffering from radiation treatments, increase understanding of early onset of diseases of old age, and provide preventive measures to delay or block their appearance**
  - Innovations for **homeland security for detection of hazardous aerosols**
  - Development of microbial and chemical sensors can easily translate to multiple applications, such as **analysis of water sources in remote locations**, etc….

Interdependency with Other TAs

The listing below identifies technologies where overlaps are likely to exist and/or key technologies that may be of joint benefit. Further discussion and/or collaboration in these areas is recommended.

Technology Area	Overlapping Technology Descriptions
TA02: In-Space Propulsion Systems	Tanks for high pressure gas storage and/or cryogenics; if tanks are "shared" then purity is an issue for ECLSS use
	For cryogenics, issues include zero-g or low-g management/boil-off control (*also overlap with TA03 and TA14)
TA03: Space Power and Energy Storage Systems	Tanks for high pressure gas storage and/or cryogenics; see description under TA2 (*also overlap with TA14)
	Low mass, high efficiency, long life, high reliability, etc. batteries for EVA/suits and/or human habitat/vehicle power systems
	High efficiency electrolyzers for production of O_2 and/or potable water
TA04: Robotics, Tele-robotics and Autonomous Systems	Human factors (e.g., immersive visualization) and human/robot interaction and automation systems (e.g., human-robot interfaces for remote operations)
	Medical-assist robotics
	Human safety enhancement (e.g., robotic surveying and remote operations)
TA5: Communication and Navigation Systems	Very high bandwidth communication systems (e.g., telemedicine, software uploads)
TA07: Human Exploration Destination Systems (HEDS)	Manufacture of components, tools, soft goods (e.g., o-rings, seals) etc/3D model Printing; see description under TA12
	Research grade water production/recycle/reuse for research platforms/needs
	Integrated Habitat Systems (e.g., lighting, acoustics, advanced habitat materials)
	EVA mobility (e.g., rovers), interfaces (e.g., suitport/lock), and tools
	Virtual reality/Holodeck (e.g. STAR TREK) technologies for training, etc.
	Radiation protection materials and/or structures/architecture using in-situ resources (*also overlap with TA12)
	Contamination control and housekeeping (e.g., dust)
	Artificial gravity devices/architecture (e.g., rotating vehicle, centrifuge chair)
	In- situ or remote food production and processing

Interdependency with Other TAs

Technology Area	Overlapping Technology Descriptions
TA10: Nanotechnology	Nano-systems/sensors for non-invasive physiological monitoring of crew and/or medical treatment Advanced batteries for EVA suits (*also overlap with TA3) Nanoporous and/or other advanced nano-engineered materials/structures for ECLSS and/or other human-related applications (e.g., CO2 removal, water filtration, radiation protection, environmental and/or constituent sensors)
TA11: Modeling, Simulation, Information Technology and Processing	Human, environmental, subsystem and overall vehicle monitoring and data management systems Models and simulations/simulators for human and systems performance
TA12: Materials, Structural and Mechanical Systems, and Manufacturing	Materials compatible with future ECLS environment of 8 psi (reduced pressure) and 32% O_2 (enriched oxygen) Multifunctional materials and/or structures, including combined structural and radiation protection, microbial control (e.g., materials and/or coatings), and other examples: • The "water wall" concept envisions incorporating water required for life support into the vehicle structure to eliminate the extra mass of water tanks and provide additional radiation shielding in specific locations (e.g., crew quarters, storm shelter) • The idea is to build spacecraft internal structures (struts, secondary structure, avionics boxes, seat cushions, etc) out of materials that can, for example, absorb CO_2. If enough of the materials could be incorporated into the spacecraft and preserved throughout ground processing (or "regenerate" its capacity prior to launch), then for short missions the spacecraft structures could absorb all the CO_2 from the atmosphere Manufacture of components, tools, soft goods (e.g., o-rings, seals) etc./3D model printing; in space for increased reliability, to reduce spares, etc., similar to a STAR TREK replicator (*also overlap with TA7) Materials Flammability associated with advanced materials testing, and update(s) to MSFC-HDBK-527, Materials Selection List for Space Hardware Systems
TA14: Thermal Management Systems	High-efficiency, non-degradable condensing heat exchangers and lightweight radiators Non-venting, closed heat rejection system with no consumables for EVA/suits Tanks for high pressure consumables and/or cryogenics, including issues include zero-g or low-g management/ boil-off control (*also overlap with TA02 and TA03)