Life Support and Habitation Systems: Crew Support and Protection for Human Exploration Missions Beyond Low Earth Orbit

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The National Aeronautics and Space Administration (NASA) has recently expanded its mission set for possible future human exploration missions. With multiple options there is interest in identifying technology needs across these missions to focus technology investments. In addition to the Moon and other destinations in cis-lunar space, other destinations including Near Earth Objects and Mars have been added for consideration. Recently, technology programs and projects have been re-organizing to better meet the Agency's strategic goals and address needs across these potential future missions. Life Support and Habitation Systems (LSHS) is one of 10 Foundational Domains as part of the National Aeronautics and Space Administration's Exploration Technology Development Program. The chief goal of LSHS is to develop and mature advanced technologies to sustain human life on missions beyond Low Earth Orbit (LEO) to increase reliability, reduce dependency on resupply and increase vehicle self-sufficiency. For long duration exploration missions, further closure of life support systems is of interest. Focus includes key technologies for atmosphere revitalization, water recovery, waste management, thermal control and crew accommodations. Other areas of focus include technologies for radiation protection, environmental monitoring and fire protection. The aim is to recover additional consumable mass, reduce requirements for power, volume, heat rejection, crew involvement, and meet exploration vehicle requirements. This paper provides a brief description of the LSHS Foundational Domain as defined for fiscal year 2011.

Nomenclature

CO_2 = Carbon Dioxide
O_2 = Oxygen

I. Introduction

IN 2010, the President and Congress unveiled an ambitious new direction for NASA, laying the groundwork for a more sustainable and affordable approach to exploration. This direction, including long-term strategic goals and outcomes, is outlined in the 2011 NASA Strategic Plan[1]. The plan responds to many of the concerns highlighted in the findings of the Review of U.S. Human Space Flight Plans Committee[2], chaired by Norman Augustine, which reviewed U.S. plans for human spaceflight and offered possible alternatives including more practicable strategies for exploration beyond low-Earth orbit. Advanced technology development and the architectures it supports must be affordable and sustainable over a long budget horizon. Technology investments are expected to lay the foundation for travel beyond low-Earth-orbit, including destinations such as the asteroids, the Lagrangian points, Mars' moons and Mars itself, as well as revisits to the Moon.

The President's Fiscal Year (FY) 2011 Budget request outlined an innovative new path for human space exploration to strengthen the capability to extend human presence throughout the solar system[3]. It proposed

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transforming NASA's technology programs, focusing on developing and demonstrating long-range, critical technologies to provide the foundation for a broad set of future human exploration capabilities. Technology projects within the Exploration Technology Development Program (ETDP) were re-evaluated, resulting in ten "Foundational Technology Domains" established to advance the state-of-the-art and knowledge base in key technical disciplines. Life Support and Habitation Systems (LSHS) is one of these Foundational Domains. It encompasses the technology development portfolio formerly under five ETDP projects, including Exploration Life Support[4], Thermal Control System Development for Exploration, Advanced Environmental Monitoring and Control, Fire Prevention, Detection and Suppression, and Radiation Protection. This paper will provide an overview of the LSHS Foundational Domain, its organization, technical content and mission factors that impact the selection of technologies in its portfolio.

II. Missions and the Requirements that Drive Technology Development

NASA's strategy for affordable and sustainable exploration has broadened the number of destination options for consideration for possible future human missions away from Earth. Consistent with the Augustine Committee's "flexible path", destination options include Low Earth Orbit (LEO) and the International Space Station (ISS), High Earth Orbit (HEO) and Geosynchronous Orbit (GEO), cis-lunar space (Lagrangian/Libration points, e.g. L1, L2), lunar orbit and the surface of the Moon, destinations beyond Earth's vicinity including Near-Earth Asteroids (NEAs) and other Near-Earth Objects (NEOs), and the moons of Mars (Phobos, Deimos), Mars orbit, and the surface of Mars. NASA chartered the Human Exploration Framework Team (HEFT)[5] in April 2010 to build a set of architectures or mission "frameworks" for these multiple destinations, to lay the groundwork and to define the knowledge, capabilities, and infrastructure necessary to successfully support human space exploration.

HEFT found that the most robust path for NASA in human space flight is a capability-driven approach where evolving capabilities would enable increasingly complex human exploration missions over time. A capability-driven framework also provides increased flexibility, greater cost effectiveness, and sustainability. Notional architectural

Table 1. Mission factors that impact Life Support and Habitation Systems

Mission Factors	SOA - LEO Space Station (ISS)	NEO Space	Moon & Mars (Space & Surface)
Mission Duration	Short to Long	Intermediate	Short or Long
Consumables	Progress, ATV, HTV	Transport or Recycle	Transport, Recycle, Pre-deploy, ISRU
Location Factors	Within Van Allen Belts Thermal – Cyclic Orbit Return on Demand	Radiation Protection & Warning Thermal – Deep Space Constrained Return Possible Interplanetary Dust	Radiation Protection & Warning Thermal – Deep Space & Cyclic Constrained Return Surface Dust
Autonomy, Constrained Return	Dependency on Earth (Resupply, Sample Analysis, Spares)	Autonomy with High Reliability No Resupply Certify Consumables in Place	Autonomy with High Reliability No Resupply or Pre-deploy Certify Consumables in Place
Human Spacecraft Requirements	Ambient Atmosphere Large Volume Simple Waste Streams Partly Closed ECLSS Consumables/ORUs	Reduced Pressure, Elevated O_2 Small to Intermediate Volume More Complex Waste Streams Partly Closed ECLSS Reduced Consumables/ORUs	Reduced Pressure, Elevated O_2 Small to Intermediate Volume More Complex Waste Streams More Fully Closed ECLSS Reduced Consumables/ORUs
Solid Waste Management	Limited Use Materials No Recovery Store & Jettison	Reduce/Extended Use Recover Water Compact, Stabilize & Return	Reduce/Reuse Recover Other Resources Process Waste & Return Residuals
Spacecraft and Mobility	Orion to ISS; EVA	Deep Space Habitat, Excursion Vehicle, suit port, new EVA suit	Deep Space & Surface Habitats, Excursion Vehicles, Landers, Rovers, suit port, & surface suit
Planetary Protection	Not applicable	Forward - Protection of Science	Mars: Forward & Backward – Life & Science Moon: Forward – Science

elements identified by HEFT applicable to LSHS include the Multi-purpose Crew Vehicle (MPCV), landers, Multi-Mission Space Exploration Vehicle (MMSEV) and Deep Space Habitat (DSH). The applicability of technology needs was assessed over all destinations. For destinations involving longer duration missions away from Earth, including lunar surface elements, NEA and the orbit, moons and surface of Mars, technologies considered "required" include fire prevention, detection and suppression for reduced cabin pressures, environmental monitoring and control, high reliability life support systems, space radiation protection and shielding, and thermal management. Space radiation protection and shielding were also found to be applicable for destinations closer to Earth, including LEO and cis-lunar space, especially with respect to Solar Particle Events (SPEs). Advances in environmental monitoring and fire protection may also be required for advanced LEO and cis-lunar destinations. Although a fully closed Environmental Control and Life Support Systems (ECLSS) would probably be required for these missions as well, improvements in reliability were judged more important except for Mars missions.

There are many mission factors across the destination options that will impact Life Support and Habitation Systems, identify technology needs and gaps and ultimately drive technology development. A summary of some of the most important of these relevant to LSHS are listed in Table 1. Probably the most well understood factor is mission duration and distance from Earth, which drives ECLS loop closure to minimize consumable mass and subsequent launch costs. A factor that also drives for increased ECLS loop closure but is less widely known is planetary protection. A spacecraft that recycles most of its consumables will not vent or leave behind wastes that could contaminate a planetary surface with signatures of life or interfere with science measurements. Without the benefit of resupply or down mass capability, the missions will need to be much more autonomous. There will need to be sufficient on-board environmental monitoring and laboratory capability to ensure recycled atmosphere and water are fit to breath and drink, and to resolve issues with environmental toxicology as they may arise. For example, if the mission includes an In Situ Resource Utilization (ISRU) plant to produce oxygen or water for use by the crew, it may be necessary to have sufficient instrumentation to certify the purity of these consumables, and have the necessary processors if further purification is required. For destinations far from Earth, including NEA and Mars, emergency quick return may not be feasible. Where return to Earth will be constrained, high reliability will be an absolutely essential parameter. In addition, the crew, vehicle and mission must be able to recover from events such as fire or impacts from micrometeoroids and orbital debris (MMOD). Space travel beyond protection of the Earth's geomagnetic field exposes the crew to increased doses of space radiation, necessitating an integrated approach to radiation protection and shielding. Lastly, vehicles, habitats and space suits must employ an integrated set of reduced pressure internal atmosphere capability, rather than a single design level for all elements, to mitigate risks of fire, decompression sickness and hypoxia[6].

Late in FY2010 NASA's Office of the Chief Technologist sponsored development of fourteen Space Technology Roadmaps (STRs). Three have applicability to LSHS: TA06 – Human Health, Life Support and Habitation Systems; TA07 – Human Exploration Destination Systems; and TA14 Thermal Management Systems. This set of draft products provides a critical snapshot of specific challenges and technologies, as well as how these technologies can support NASA's missions and contribute to significant national needs. These reports will be used as a strategic guide to inform the agency's budget formulation and prioritization process; organize the Office of Chief Technologist solicitations; and initiate an open process of community engagement through a National Research Council space technology evaluation and prioritization process.

III. Life Support and Habitation Systems Foundational Domain

The Life Support and Habitation Systems (LSHS) Foundational Domain develops and mature technologies to sustain life on long duration missions beyond LEO that are reliable, have minimal logistics supply and increase self-sufficiency. Focus is on key technologies that recover additional consumable mass, reduce requirements for power, volume, heat rejection, crew involvement, and which have increased reliability and capability to meet future mission requirements. Further closure of life support systems is over the state-of-the-art is of interest. Technical work is performed across seven NASA field centers: Johnson Space Center (JSC), Ames Research Center (ARC), Marshall Space Flight Center (MSFC), Kennedy Space Center (KSC), Glenn Research Center (GRC), Langley Research Center (LaRC), and the Jet Propulsion Laboratory (JPL).

The LSHS Foundational Domain consists of nine integrated technical elements, Atmosphere Revitalization, Water Recovery, Solid Waste Management, Crew Accommodations, Food Production, Thermal Control, Environmental Monitoring, Fire Protection and Radiation Protection, and three cross-cutting supportive elements, Project Analysis, Education and Outreach, and Technology Transfer. The Work Breakdown Structure (WBS) on which project organization is based is shown in Figure 1. The project plan and WBS follow NASA procedural and

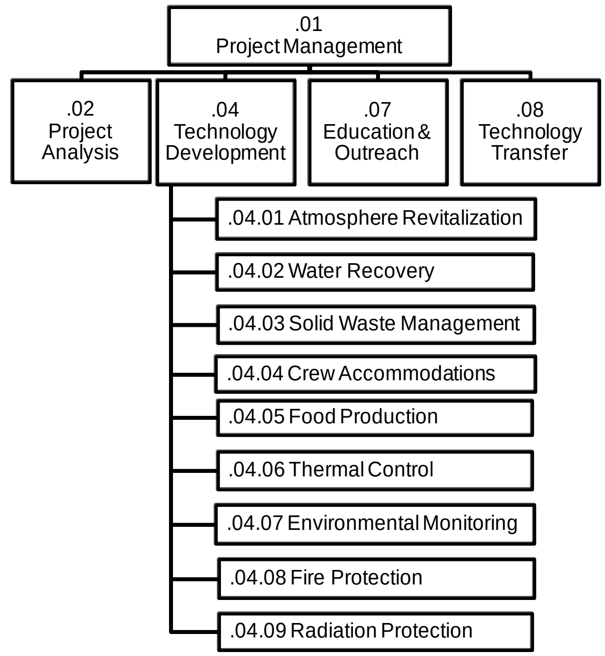

Figure 1. Life Support and Habitation Systems Work Breakdown Structure

approaches to waste management could result in production of plasticized bricks of compacted trash for use as radiation shielding.

Food Production Element: Full closure of life support systems will involve the in situ production of food. The level that this capability is manifested on a mission will depend on numerous factors. An initial implementation of food production technology will provide the capability to grow fresh vegetables and fruits to augment the crew's diet of packaged foods. These fresh foods will add texture, flavor, and variety to the diet and provide a source of bio-available nutrients, which can serve as a radiation countermeasure. Expanded food production systems for future missions will reduce the need for stowed foods and contribute to CO_2 removal/reduction, oxygen production and water recycling. A key component to any plant growth hardware will be its lighting subsystem. For electric lighting approaches the use of Light Emitting Diodes (LEDs) or other novel lighting technologies that can minimize power and volume requirements should be considered. In addition, collection of solar light from outside the habitat and delivering it to a plant growth chamber is of interest, since this has an even greater potential for reducing the power budgets for food production, especially for larger scale bioregenerative life support applications. Other areas of focus include crop selection, cultivation and horticulture, crop physiology, food safety and plant/human factors (benefit to crew mental and physiological well being).

Thermal Control Element: An effective thermal control system must provide three basic functions to a vehicle design: heat acquisition, heat transport, and heat rejection. The thermal control system for human-rated vehicles must reject heat from on-board equipment and maintain internal cabin temperature and humidity within the proper range to ensure crew comfort. Heat acquisition is the process of acquiring excess thermal energy from various heat dissipating components including electronics, avionics, computers, and, for a manned mission, the crewmembers' metabolic loads. Heat acquisition is typically accomplished using a myriad of hardware components including, but certainly not limited to, coldplates, air/liquid heat exchangers, and liquid/liquid heat exchangers. As the title implies, heat transport is the process of moving the now acquired energy to another location within the vehicle/system. Heat transport can be accomplished using active means such as a pumped fluid loop, but can also be performed using more passive methods such as a simple conductive path and/or heat pipes. The third, and final, thermal control system function is heat rejection which is the process of rejecting the thermal energy to the ambient environment. Heat rejection is performed using radiators, evaporators, and/or sublimators. The heat rejection function can also be supplemented with phase

Table 2. Fiscal Year 2011 Tasks Sponsored by the Life Support and Habitation Systems Foundational Domain *Estimates for current Technology Readiness Level (TRL) derived from a recent independent assessment by ETDP are provided where available.*

Milestone Title	TRL
Atmosphere Revitalization	
Carbon Dioxide Partial Pressure Control	
Low-Power CO2 Removal (LPCOR) System	4 to 4+
Engineered Structured Sorbent (ESS)	4
Open Loop Regenerable CO2 Removal System	4 to 4+
CAMRAS Evaluation	5+ to 6
Control Trace VOC Concentrations	
Advanced (alternative) Trace Contaminant Control (ATCC)	3
Photocatalytic System Development	3
Particulate Matter Removal	
Indexing Media Filter	3
FAST Multi-Stage Filtration System	3
Modeling of Cabin Particulate Environment	--
Test Contractor Filters	3
Resource Recovery and Recycling	
Closed Loop- Carbon Dioxide Reduction (CDRe)Technology	3
Co-Electrolysis	3
Gas Storage and Recycling	
Subcritical Liquid Storage	2 to 3
Scavenging of Oxygen from Gaseous Mixture	2 to 3
Water Recovery	
Wastewater Composition and Storage Systems	
Stabilization and Composition Assessment	3
Wastewater Storage	3
Primary Processing	
Osmotic Distillation (OD) System Development	4
Direct Osmotic Concentration (DOC) Evaluation	4
Cascade Distillation Subsystem (CDS) Development	5
Vapor Compression Distillation (VCD) Development	6
Post-processing, Disinfection & Potable Water Storage	
Biocide and Antimicrobial Technology	3 to 4
Thermal Catalyst Development	3
Processed Water Polishing	--
Water Recovery from Brine Systems	
Brine Membrane Enlcosure for Heat Melt Compactor	4
Brine Residual In-Containment (BRIC)	2
Water Recovery Systems	
Radiation Water Wall Concept	--
Waste Management	
Volume Reduction	
Mineralization	4
Heat Melt Compaction (HMC)	4
Waste Stabilization & Storage	
Microbial Characterization of Solid Wastes	--
Crew Accommodations	
Habitability Outfitting	
Habitability Outfitting Integration	2
Clothing Laundry	
Clothing Logistics Reduction Technology	2
Food Production	
Crop Production	
Crop Production Hardware and Concepts	3

change material heat sinks. The thermal control element seeks to use a rigorous technology development process to advance the state of the art in thermal control hardware by reducing hardware mass and improving hardware reliability, useful life, reducing volume, and improving thermal performance. Tasks for FY11 are summarized in Table 3.

The Environmental Monitoring Element seeks to develop a suite of technologies that address monitoring across target environments (air, water, surfaces) and across target chemicals and biologicals, leveraging the rapidly progressing technical community. The focus is on technologies which have potential for significant miniaturization without sacrificing performance or reliability, provide for measurement of a broad range of chemical species including specific potential contaminants of spacecraft air and water to ensure environmental standards and crew health and safety are achieved onboard space vehicles, and demonstrate technology where appropriate on testbeds such as the International Space Station (ISS). Tasks for FY11 include flight demonstration of the Vehicle Cabin Atmosphere Monitor (VCAM), development of monitors for microbial species, contaminants in water, and dust/ particulates in cabin air, and advancing Tunable Environmental Laser Spectroscopy (TELS) for target atmospheric contaminants.

The Fire Protection Element seeks to develop and mature technologies that will ensure crew health and safety on exploration missions by reducing the likelihood and severity of a fire or, if one does occur, minimizing the risk to the crew, mission, or system. An additional challenge for fire research is predicting flammability in low-pressure, partial-g environments, as materials can burn at lower oxygen concentrations than they do in normal gravity. Post-fire recovery, including the clean-up of the cabin atmosphere from any smoke or gaseous combustion products as well as clean-up of any fire suppression agent that was discharged, will be key for missions beyond Earth where rapid return of the crew may not be possible. The goals of Fire Protection are accomplished through the development of hardware, design rules and requirements, and procedures that enhance fire safety in exploration vehicles and habitats by addressing the areas of (1) fire prevention and material flammability, (2) fire signatures and detection, (3) fire detector development (both gaseous and particulate detectors), and (4) fire suppression and post-fire response. To achieve the objectives in these areas, the Fire Protection Element will draw on expertise in the disciplines of combustion science, fire safety engineering, risk assessment, failure analysis and systems engineering. Evaluations will take place in normal-gravity test facilities and, when necessary, ground-based microgravity facilities. Tasks for FY2011 are listed in Table 3.

Table 3. Fiscal Year 2011 Tasks Sponsored by the Life Support and Habitation Systems Foundational Domain *Estimates for current Technology Readiness Level (TRL) derived from a recent independent assessment by ETDP are provided where available.*

Milestone Title	TRL
Thermal Control	
Heat Transport	
Thermal Control System Fluids Life Test	--
Heat Rejection	
Radiator Dust Assessment and Mitigation	--
Integrated Radiator PCM Development	4 to 5
Variable Heat Rejection Radiator: Digital Radiator	4
Integrated Radiator Phase Change Material (PCM) Development	4 to 5
Transient Sublimator	3
Freezable Radiator	3
Electrochromic Radiator	3
Flow Through Phase Change Material (PCM) Module	3 to 4
Heat Acquisition	
Composite Heat Exchangers	4 to 5
Microchannel Heat Exchanger	5 to 6
Environmental Monitoring	
Atmosphere Monitoring	
Particulate Monitor - Optical Particle Counter (OPC)	2 to 3
Particulate Monitor - Charge-Based Detector (CBD)	2 to 3
Atmosphere Monitoring Technology Evaluation	--
TELS Technology Evaluation	3
Environmental Factors Air Contaminants Support	--
Water Monitoring	
Water Monitoring Technology Evaluation	--
Water Sample Input to Mass Spectrometer	--
Water Contaminants Support	--
Microbial Monitoring	
Microbial Monitoring	--
Microbial Monitoring Technology Assessment	--
Microbial Monitoring Technology Workshop	--
Fire Protection	
Material Flammability and Ignition	
Flammability Assessments in Spacecraft Atmosphere (UCB)	--
Modeling of NASA-STD-6001B Test 1 (CWRU)	--
Fire Safety Demo Formulation	--
Testing at White Sands Test Facility (WSTF)	--
Fire Detection	
Gaseous Detector Development	--
Particulate Detector Development	--
Fire Detector Testing	5
Fire Suppression	
Fire Suppression Technology Development	5
Post-Fire Recovery	
Post-fire Monitoring and Response	3
Post-fire Cleanup	--

The Radiation Protection Element addresses technical objectives including identifying, developing and demonstrating radiation protection technologies that further widen the envelope of space exploration capabilities. The content includes testing the feasibility of existing concepts, and also develops new concepts, to protect astronaut crews and hardware from the harmful effects of radiation, both in low Earth orbit and while conducting long-term missions away from Earth. Radiation monitoring technologies handed-off from the Human Research Program (HRP) will be matured for eventual demonstration on suitable platforms, including the ISS. Exposure to the space radiation environment poses both acute and chronic risks to crew health and safety that have clinically relevant implications for their lifetime, as well as risk to spaceflight instrumentation and hardware. Shielding from Solar Particle Events (SPEs) will be easier to solve than shielding from Galactic Cosmic Radiation (GCR). Protecting humans from SPEs may be accomplished through technology maturation of identified shielding solutions, spacecraft design and configuration, as well as operations, given investments in development of warning systems that forecast the occurrence and magnitude of SPEs. The major technical challenge for future human exploration is how to protect humans from the high-charge and high-energy galactic cosmic radiation (GCR) permeating interplanetary space. We must proactively provide mitigation technologies (such as shielding or biological countermeasures) for missions beyond LEO greater than ~90 to 100 days to remain below space radiation Permissible Exposure Limits (PELs)[9]. Tasks for FY2011 are listed in Table 4.

The Project Analysis Element performs analysis for trade studies, design, and test support. It assists technology developers and managers understand technology performance in an integrated system or mission application. It provides relevant mission frameworks for requirements, reference missions, and baseline assumptions. And it provides other systems engineering and integration support including analytical tool development, data management, reporting, and archiving. Task areas for FY2011 are listed in Table 4.

Table 4. Fiscal Year 2011 Tasks Sponsored by the Life Support and Habitation Systems Foundational Domain

Milestone Title
Radiation Protection
Radiation Shielding
Update of Material Database, Metric lists, and
Specimen Development, Fabrication and Testing
Instrumentation
Analysis
Dosimetry and Monitoring
Miniaturized Tissue Equivalent Monitors
Miniaturized Personal Monitor
Models & Tools
Development, validation and warning systems
Radiation Protection Systems
Model Integration
Project Analysis
Systems Engineering
Safety & Reliability Analysis of Life Support Systems
Metrics & Key Performance Parameters
Technology Readiness Level
Systems Analysis & Simulations
Analysis & Dynamic Simulation of Life Support Systems
Flagship & Mission Architecture Studies
Technology Analysis & Simulations
Systems Design & Technology Selection for Life Support
Closed Loop Water System Simulations
Closed Loop Air System Simulations
Technology Analytical Assessments
Reference Documents
New Mission Concepts Report
Customer Needs and Requirements Assessment

IV. Summary

The Life Support and Habitation Systems Project is one of 10 Foundational Domains under the Exploration Technology Development Program (ETDP) focused on developing long-range, critical technologies to provide the foundation for a broad set of future human exploration capabilities for such destinations as cis-lunar space, near-Earth asteroids, Mars and other celestial bodies. The ultimate goal of LSHS is to develop and demonstrate the capability to sustain humans indefinitely in space without reliance on Earth-based resources (Figure 2). Technology development is directed to meet challenges and fill gaps driven by mission factors such as the need for increased vehicle autonomy, higher systems reliability, ability to recover from anomalies, operate at reduced cabin pressures, protect the vehicle and crew from space radiation, reduce dependency on resupply, certify recycled consumables in place and process more complex waste streams. This will be accomplished through research and technology development, ground based integrated testing, utilization of flight experiments as warranted, and culminating in participation with mission customers in technology flight demonstrations.

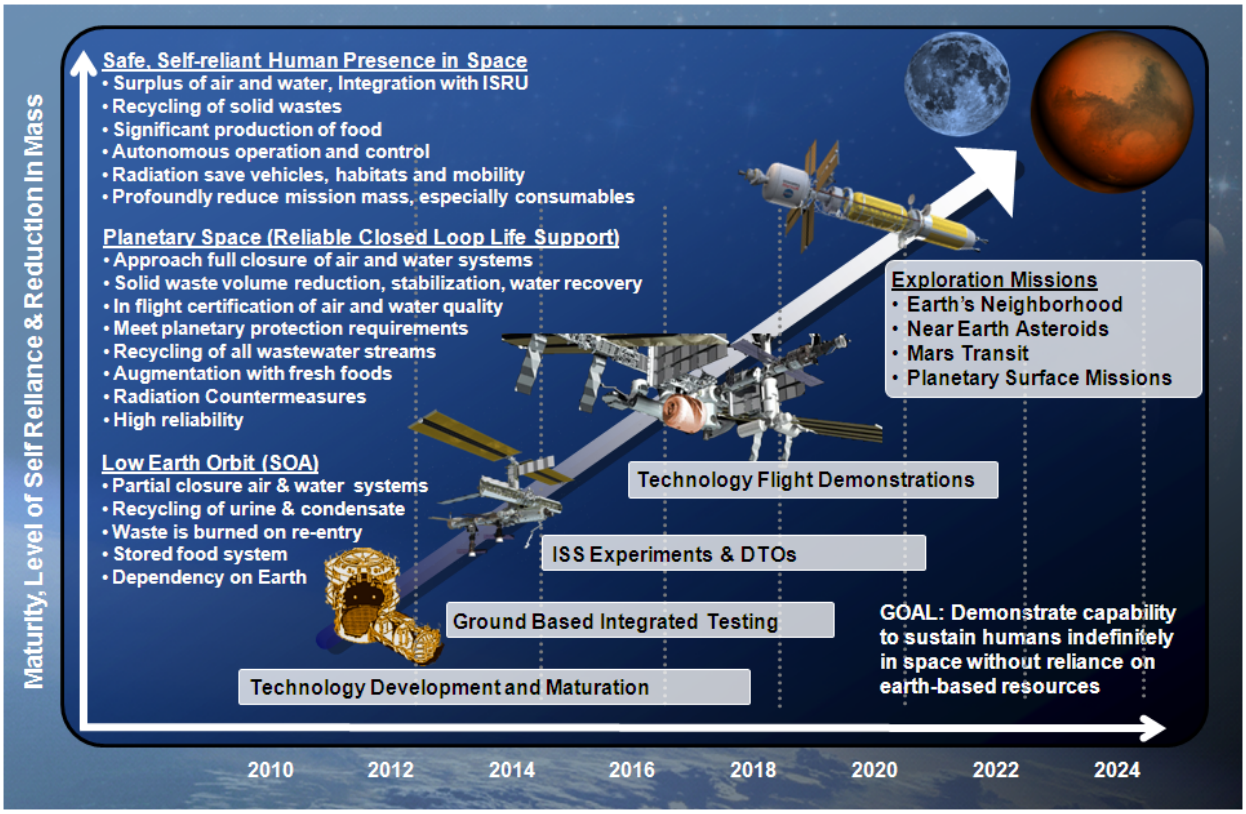

Figure 2. Top Level Life Support and Habitation Systems Roadmap

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