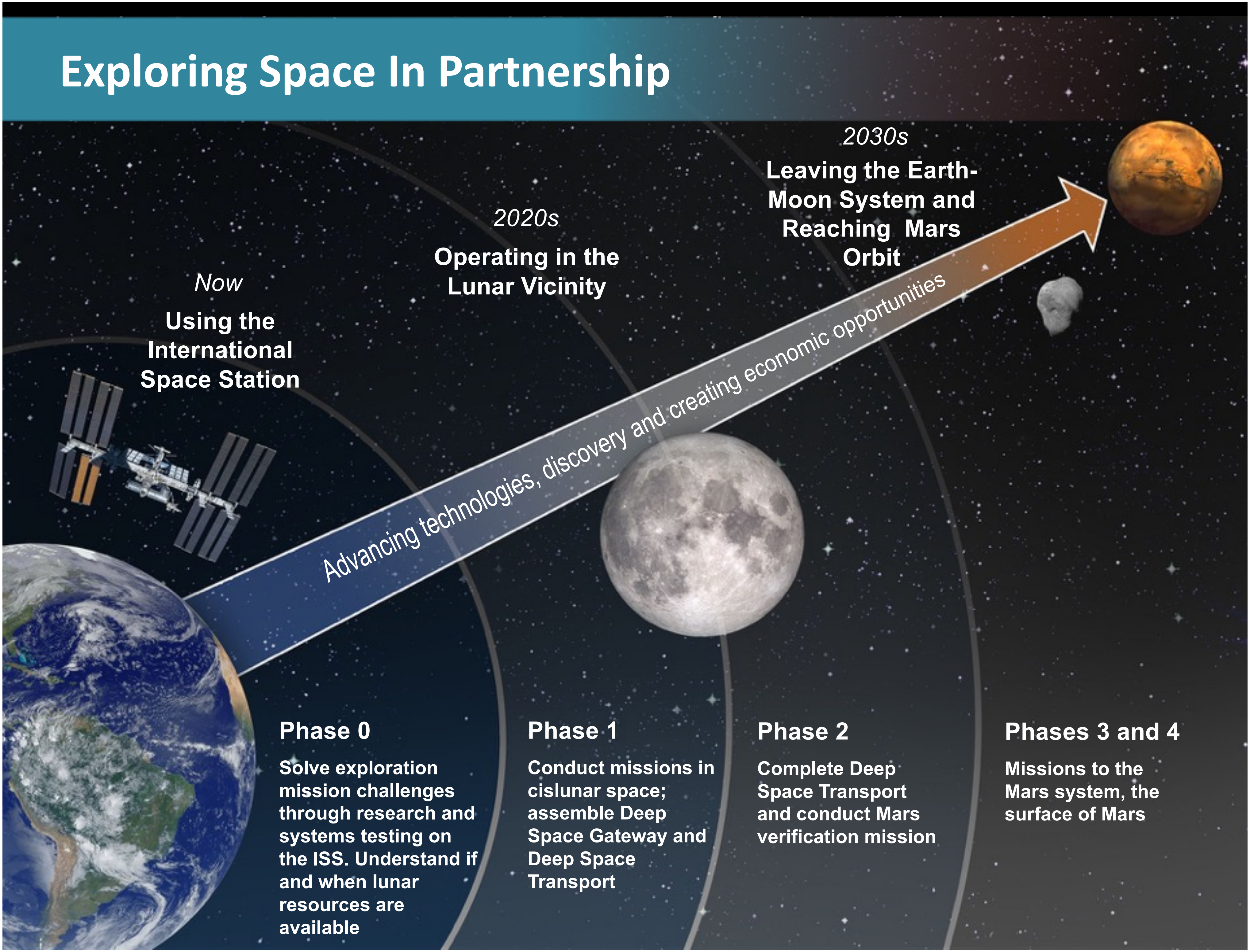
Cislunar Habitation & Environmental Control & Life Support Systems

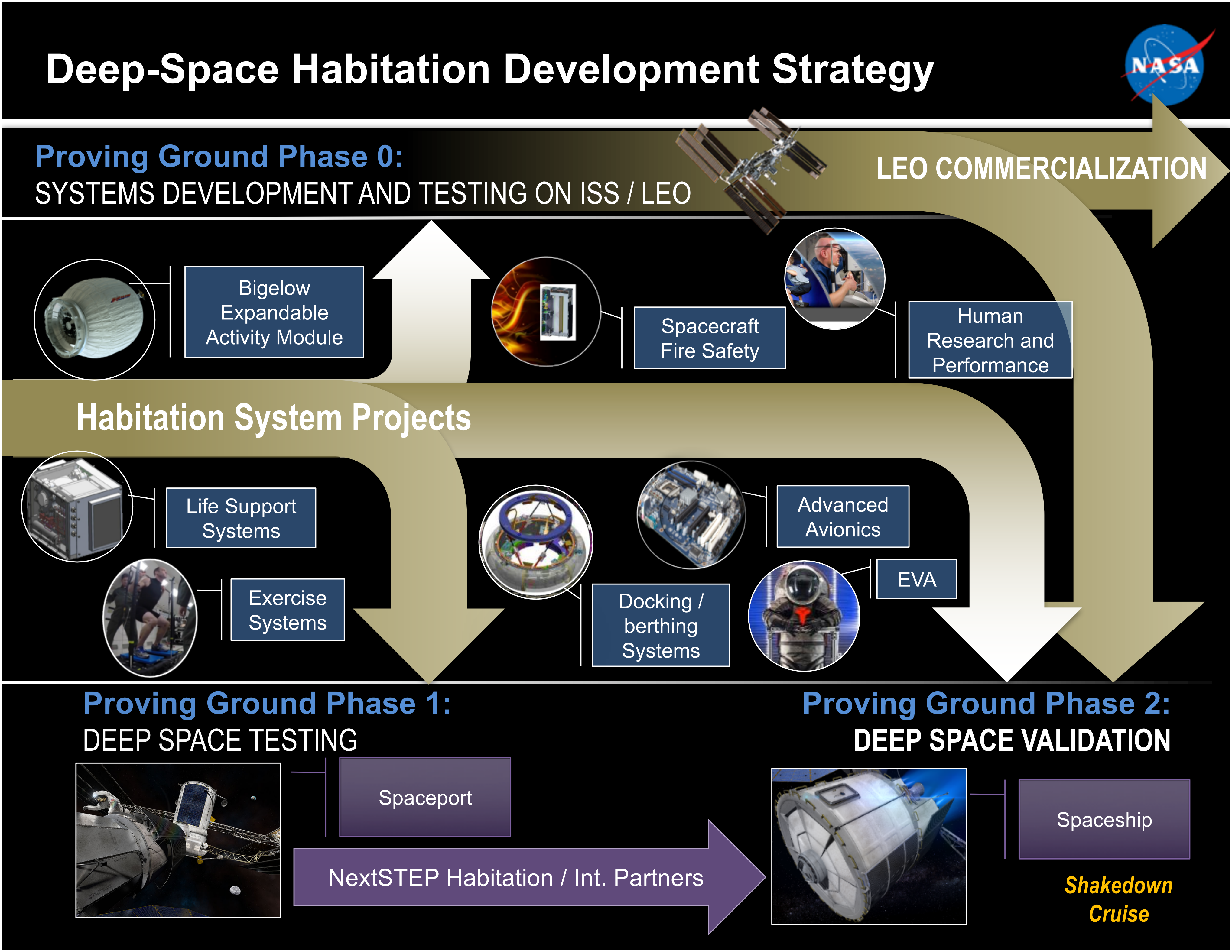
NASA Advisory Council
Human Exploration & Operations Committee
29 March 2017

Jason Crusan, Director, Advanced Exploration Systems Division
Robyn Gatens, Deputy Director, International Space Station


Exploring Space In Partnership
Now
Using the International Space Station
2020s
Operating in the Lunar Vicinity
2030s
Leaving the Earth-Moon System and Reaching Mars Orbit
Advancing technologies, discovery and creating economic opportunities
Phase 0
Solve exploration mission challenges through research and systems testing on the ISS. Understand if and when lunar resources are available
Phase 1
Conduct missions in cislunar space; assemble Deep Space Gateway and Deep Space Transport
Phase 2
Complete Deep Space Transport and conduct Mars verification mission
Phases 3 and 4
Missions to the Mars system, the surface of Mars

HABITATION CAPABILITY

Systems to enabling the crew to live and work safely in deep space. Capabilities and systems for use in conjunction with Orion and SLS on exploration missions in the Proving Ground and beyond.


Deep-Space Habitation Development Strategy
Proving Ground Phase 0:
SYSTEMS DEVELOPMENT AND TESTING ON ISS / LEO
LEO COMMERCIALIZATION
Bigelow Expandable Activity Module
Spacecraft Fire Safety
Human Research and Performance
Habitation System Projects
Life Support Systems
Exercise Systems
Docking / berthing Systems
Advanced Avionics
EVA
Proving Ground Phase 1:
DEEP SPACE TESTING
Spaceport
NextSTEP Habitation / Int. Partners
Proving Ground Phase 2:
DEEP SPACE VALIDATION
Spaceship
Shakedown Cruise

Habitation Development Approach

Hab Development Phase 1

- Obtain Innovative Cislunar Habitation Concepts that leverage Commercialization Plans for LEO (NextSTEP Phase 1)
- Developed required deliverables including Concept Description with concept of operations, Phase 2 proposal and SOW
- Initial discussions with international partner contributions

2015-2016

Ends with Industry Developed Concepts – Decision on contract(s) continuation

Hab Development Phase 2

Continue concept refinement and development of domestic ground prototype module(s) and lead the development of standards and common interfaces (US/International)

- **Contractor (NextSTEP Phase 2)**: Concept description with concept of operations, provide Phase 3 proposal and SOW, delivery of ground prototype module(s)
- **NASA**: Define reference habitat architecture based on contractor and international concepts and identified GFE in preparation for Phase 3

2016 - 2018

Ends with: 1) Domestic Developed Ground Prototype Modules performing integrated tests, 2) identified standards and common interfaces, 3) identification of NASA provided GFE- Decision point on contract continuation and focus, and 4) Understanding of International Contribution potential

Hab Development Phase 3

- Determine acquisition approach including domestic and international partnerships
- Development of Deep Space Habitat for Proving Ground Phase 1 Objectives
- Deliverables include Flight Unit(s) (note may be multiple modules integrated via common interfaces and standards)

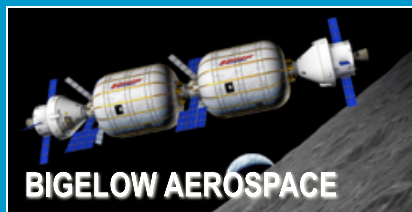
2018+

Ends with Deployment and Operational Status of Deep Space Habitation and Habitation Systems

NextSTEP Habitation Overview

NextSTEP Phase 1: 2015-2016

Cislunar habitation concepts that leverage commercialization plans for LEO

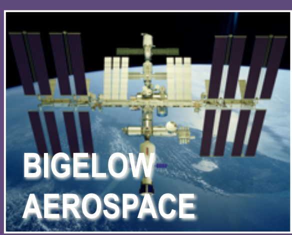


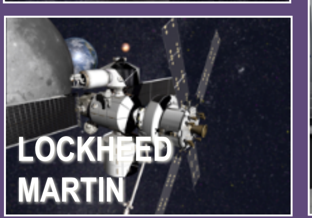
FOUR SIGNIFICANTLY DIFFERENT CONCEPTS RECEIVED

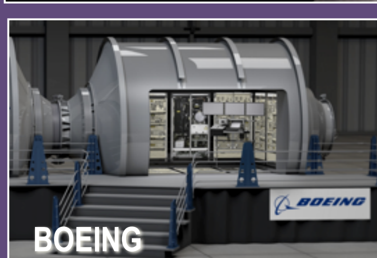
Partners develop required deliverables, including concept descriptions with concept of operations, NextSTEP Phase 2 proposals, and statements of work.

NextSTEP Phase 2: 2016-2018

FIVE GROUND PROTOTYPES BY 2018

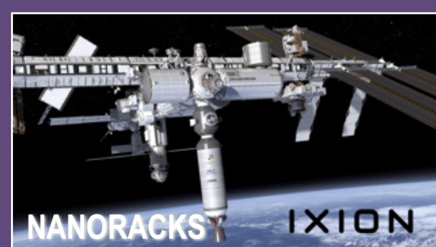






- Partners refine concepts and develop ground prototypes.
- NASA leads standards and common interfaces development.

ONE CONCEPT STUDY



Initial discussions with international partners

Define reference habitat architecture in preparation for Phase 3.

Phase 3: 2018+

- Partnership and Acquisition approach, leveraging domestic and international capabilities
- Development of deep space habitation capabilities
- Deliverables: flight unit(s)

Standards Development Approach

- Standards development approach is acquisition strategy neutral
- An iterative process to develop a set of standards that will include external feedback from industry and the International Partners
- Established a Habitation Capability Standards Working Group (WG) led by the International Space Station (ISS) and Advanced Exploration Systems (AES) Divisions with support from the Technical Authorities (TA) to define a suite of standards
- Technical Authority Standards: Used HEOMD-CSD-10001 standards as guide, taking into account aspects of deep space mission to assess applicability
- High Priority Interoperability Standards: Future Capabilities Team continuing work with International Partners
- The Associate Administrator for HEOMD will be the approving authority for the standards

NextSTEP BAA Habitation GFE Areas

- **In Line GFE – Contractor Specific**

- **Cross Cutting GFE**
  - ECLSS
  - Avionics
  - Softgoods Testing
  - Window Material Database
  - Radiation Analyses
  - Exercise Equipment
  - Ground Testing

NextSTEP Phase 2 Habitation Capability - Goal

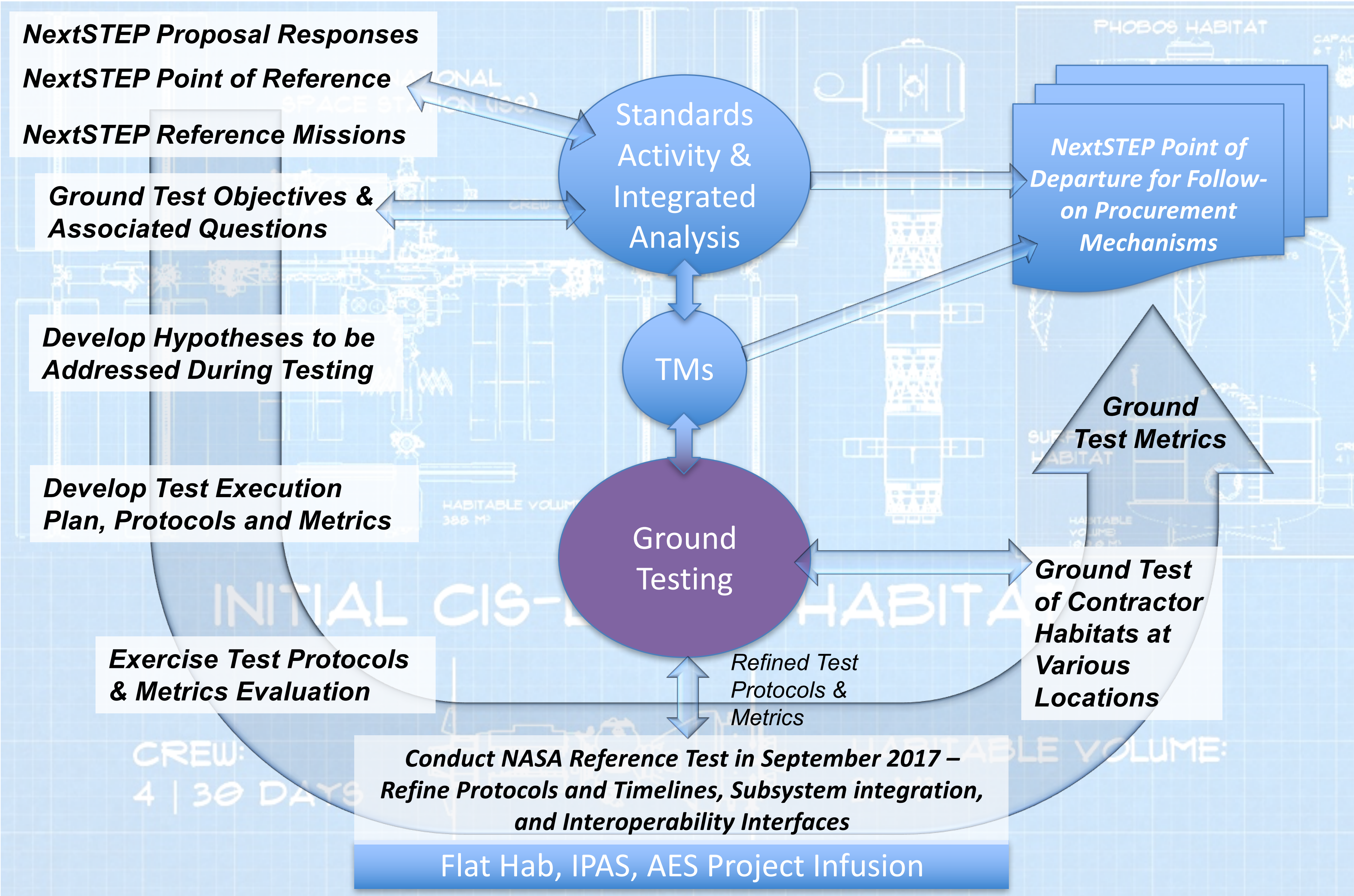
Develop a deep space habitat for ground-based testing by 2018, while simultaneously stimulating commercial habitat development in LEO

- Develop long-duration deep-space habitation capabilities that lead towards a deep-space transit habitat and can be flown on SLS flight(s) (or alternative launch vehicles) starting by the early to Mid 2020s.
- Advance the long duration deep space habitation capability concepts and mature the design and development of the integrated system(s) to achieve a high level of fidelity.
  - Developing prototype deep space habitation capability options to test a full size ground prototype unit(s) by the end of Phase 2 in 2018 to support first flight opportunities in Early to Mid 2020s
- Potential for different capabilities from domestic and international suppliers will require standards and common interfaces for aggregation. NASA led standards working group will be implemented during Phase 2.

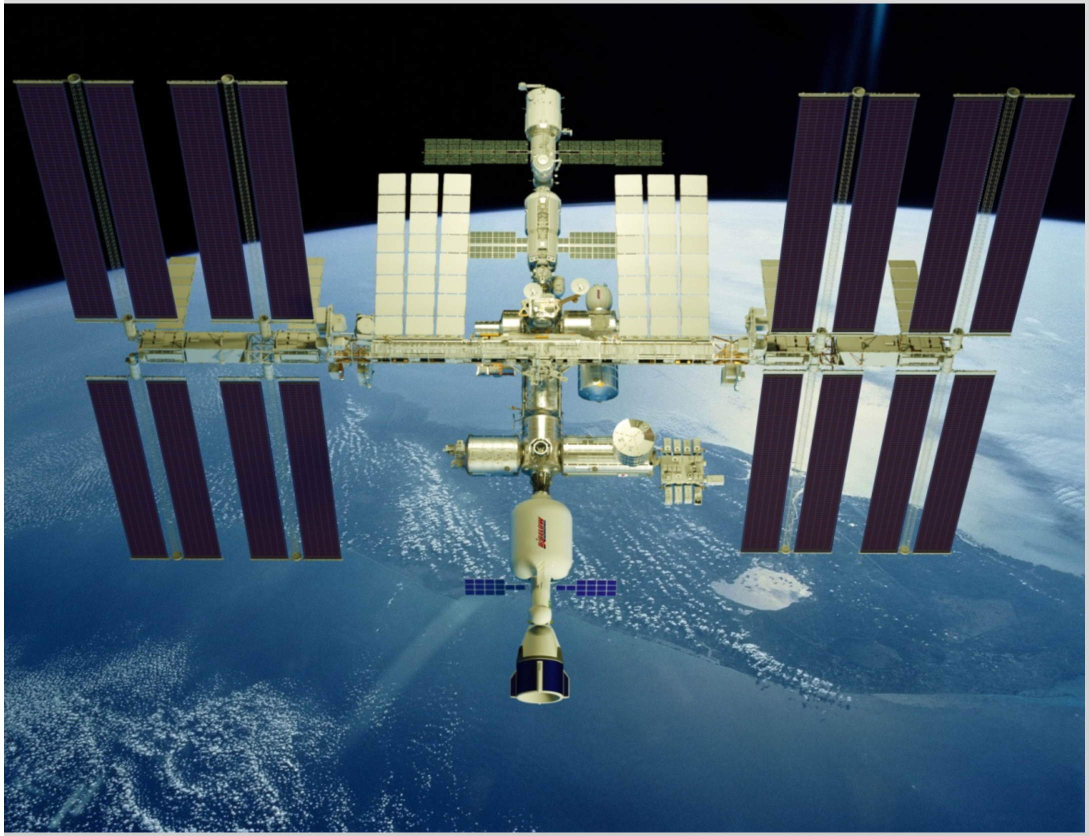
Ground Prototype units delivered to NASA for testing and integration of NASA developed habitation systems

- Testing includes form, fit, volumetric, subsystem integration, and interface standards
- May use NASA-developed node/airlock and hab mockups for integration testing with contractor modules
- Ensures consistent test and interface verification approach, allows us to incorporate and test other AES subsystems, facilitates crew training and feedback on human factors, shows stakeholders progress

Ground Testing Execution Plan



NextSTEP Phase II
Bigelow Aerospace B330 / XBASE



OBJECTIVES & TECHNICAL APPROACH

- 330 m^3 habitat that will attach to the ISS as a testing platform for deep space exploration technologies and procedures.
- Technical approach includes refinement of the concept of operations, a series of tests including structural tests and ECLSS prototype tests, full scale prototype development activities, and integration studies in Virtual Reality.
- Phase II will involve active support from Bigelow Aerospace for standards and common interfaces working groups.

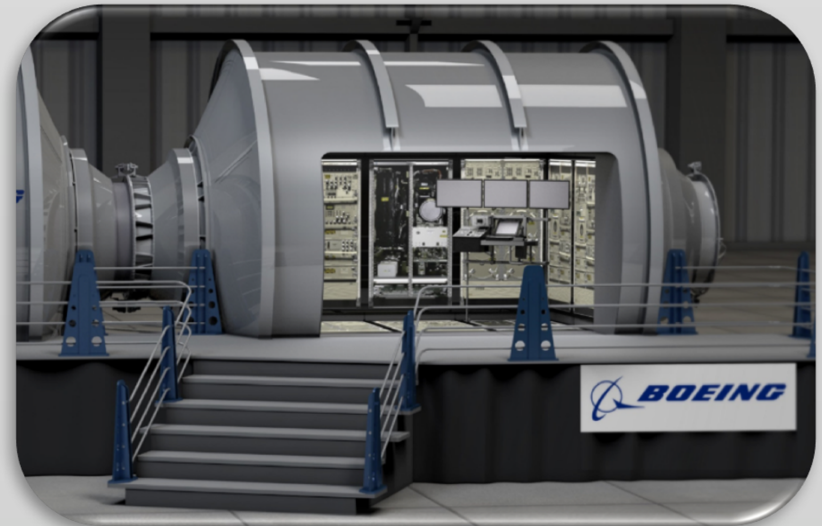
TEAM

- **Robert Bigelow:** President of Bigelow Aerospace / Program Manager
- **Colm Kelleher, PhD:** Deputy Program Manager and Chief Scientist ECLSS
- **Lisa Thomas:** Deputy Program Manager
- **Uy Duong:** Deputy Program Manager – Structures

KEY ATTRIBUTES

- Provides opportunity to develop and test an inflatable-based integrated deep-space Spaceship that incorporates new structures and exploration capabilities (e.g. Liquid Processing System, CO2 Removal systems)
- Supports both LEO Commercialization and future human exploration mission objectives
  - Provides opportunity to test NASA exploration class ECLSS and other exploration systems while docked to ISS
  - Once exploration systems validated, the module could then be detached from ISS and become a LEO free flyer and continue to test exploration systems while supporting commercial needs
  - Second copy of module could be developed as the Spaceship Habitat and flown to Spaceport for assembly and outfitting
- 2018 Ground Test to be performed at BA facilities

NextSTEP Phase II
The Boeing Company



OBJECTIVES

Develop input to NASA's reference architecture for long duration, deep space human spaceflight exploration missions and develop habitation element concepts for cislunar space

- Build a full scale ground demonstrator prototype habitat
- Define standards and common interfaces
- Describe intersections between the NextSTEP-2 partnership and industry interest in commercial activities in LEO

TEAM

- Boeing leads a global team of companies, each contributing valuable habitat systems experience, subject matter expertise, and services
- The Boeing NextSTEP-2 team includes support from NASA centers, including JPL, JSC, KSC, and MSFC
- Boeing has engaged industry and university partners focused on advanced concepts and exploration technologies for joint study and collaboration

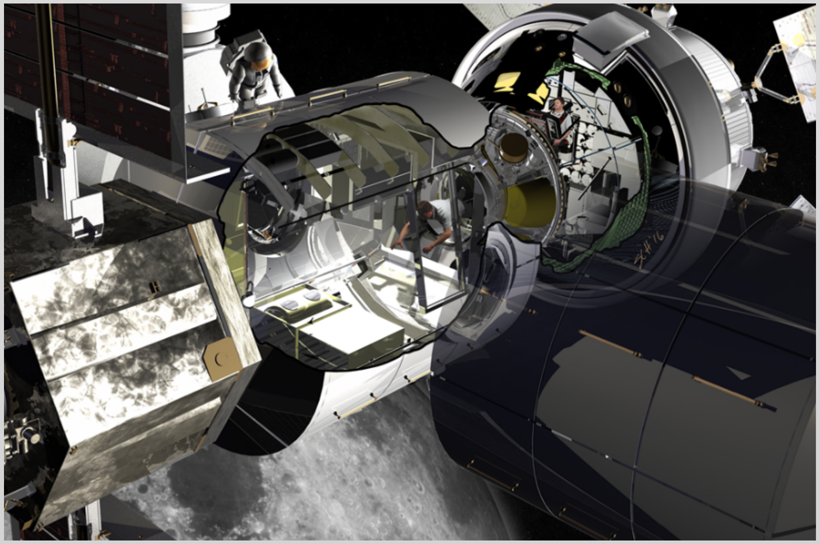
TECHNICAL APPROACH

- Design and analyze modular habitation system concepts and assess requirements relative to NASA's exploration architecture
- Validate designs and interface standards
- Test habitat functionality in Boeing's full scale ground prototype demonstrator

KEY ATTRIBUTES

- Concept uses existing technology
  - Already developed ISS assets
  - Boeing's commercial GEO satellite bus for power/propulsion module
- Provides innovative modular approach for subsystem integration into habitat module
- Performs long duration missions in cislunar space when fully assembled
- Good leverage of NASA workforce
- 2018 Ground Test to be performed at MSFC facilities

NextSTEP Phase II
Lockheed Martin



OBJECTIVES

- Refine design concept over three design and analysis cycles. Utilize virtual prototyping in order to rapidly iterate on core design. Incorporate lessons learned from IWG and prototype builds. Identify LEO and cislunar commercialization intersections.
- Work with NASA to define common interface standards.
- Refurbish NASA provided MPLM as a full-scale habitat module prototype, with integrated avionics and ECLSS, to provide risk reduction and form/fit testing.
- Prove out command and data handling between HSV and Orion. Demonstrate crew interface commonality between DSTH and Orion.
- Build and test a high-fidelity prototype to demonstrate the integrated habitat and Orion operations and to characterize subsystem performance, interactions, and behaviors when the modules share a common atmosphere.

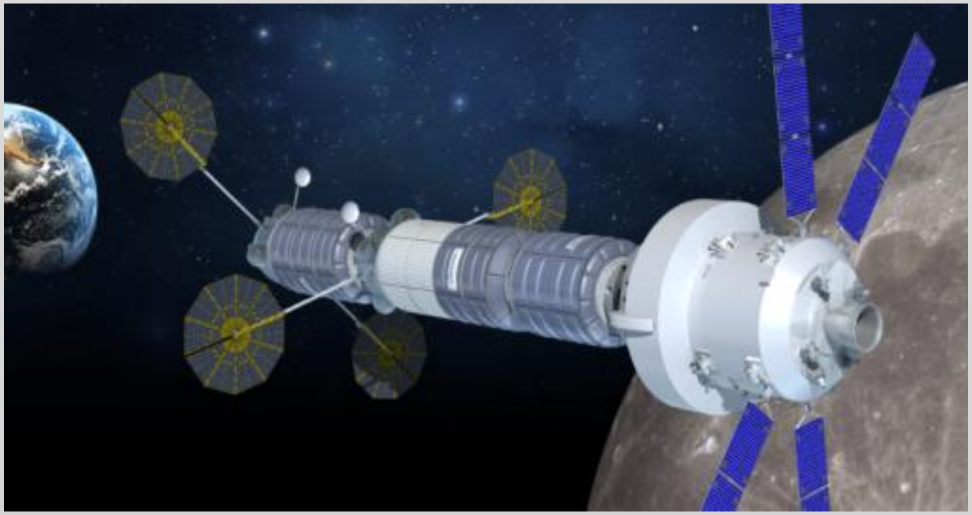
KEY ATTRIBUTES

- Provides a concept using existing technology
  - Use existing ISS assets (e.g., MPLM) for the primary module concept
  - Leverages LM's commercial and deep space bus heritage for power/propulsion module
  - Uses Orion command and control capability to leverage NASA investment
- Concept provides innovative approach for EVA module and airlock functions
- Once fully assembled, can perform long duration missions in cislunar space, serving as a lunar space portal and construction platform for Mars elements (flexible design)
- Provides good leverage of NASA workforce
- 2018 Ground Test to be performed at KSC facilities
  - Leverages ISS Donatello MPLM as prototype module

TEAM

- **Lockheed Martin:** Prime contractor responsible for entire system concept and prototypes
- **Thales Alenia Space – Italy:** Habitat module primary and secondary structure
- **ILC Dover:** ECLSS engineering services, EVA, inflatable technologies integration
- **Thin Red Line Aerospace:** Inflatable Technologies
- **Airbus Defense & Space:** Habitat science integration lunar surface exploration, advanced habitation systems integration
- **Made in Space:** in-space material recycling
- **MDA:** Habitat robotic systems
- **NASA JSC:** ECLSS, EVA, power avionics and software, crew displays and controls
- **NASA LaRC:** Radiation mitigation and inflatable technologies

NextSTEP Phase II
Orbital ATK



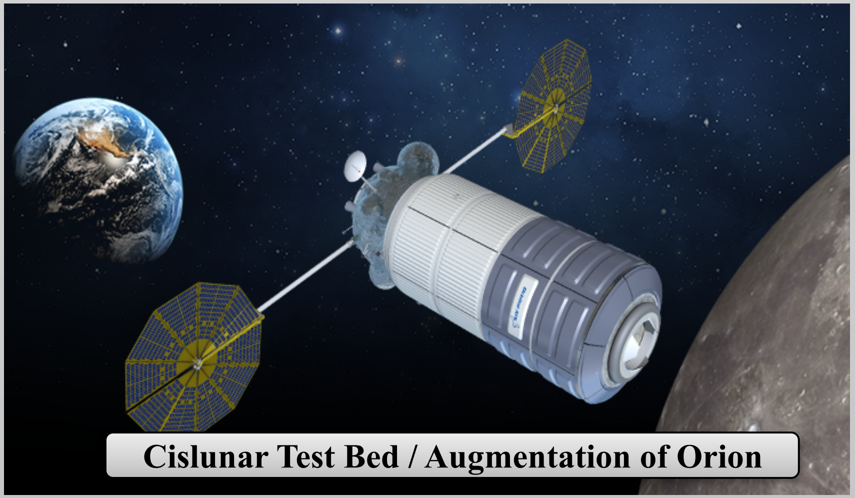
OBJECTIVES

Develop long-duration deep space habitation capabilities that enable the deployment of a deep space transit habitat in the early 2020s

- Advance the long duration deep space habitation system concepts and mature the design and development of the integrated system(s)
- Apply standards and common interfaces defined by the NASA-led standards working group during Phase 2
- Develop high fidelity ground prototype units and deliver to NASA for additional testing and integration
- Further define and develop deep space habitation and logistics capabilities that can be flown as co-manifested payloads on SLS Block 1 B or on other independent launch vehicles
- Identify options to maximize NASA and commercial LEO opportunities such as demonstration missions at the ISS or in cislunar space

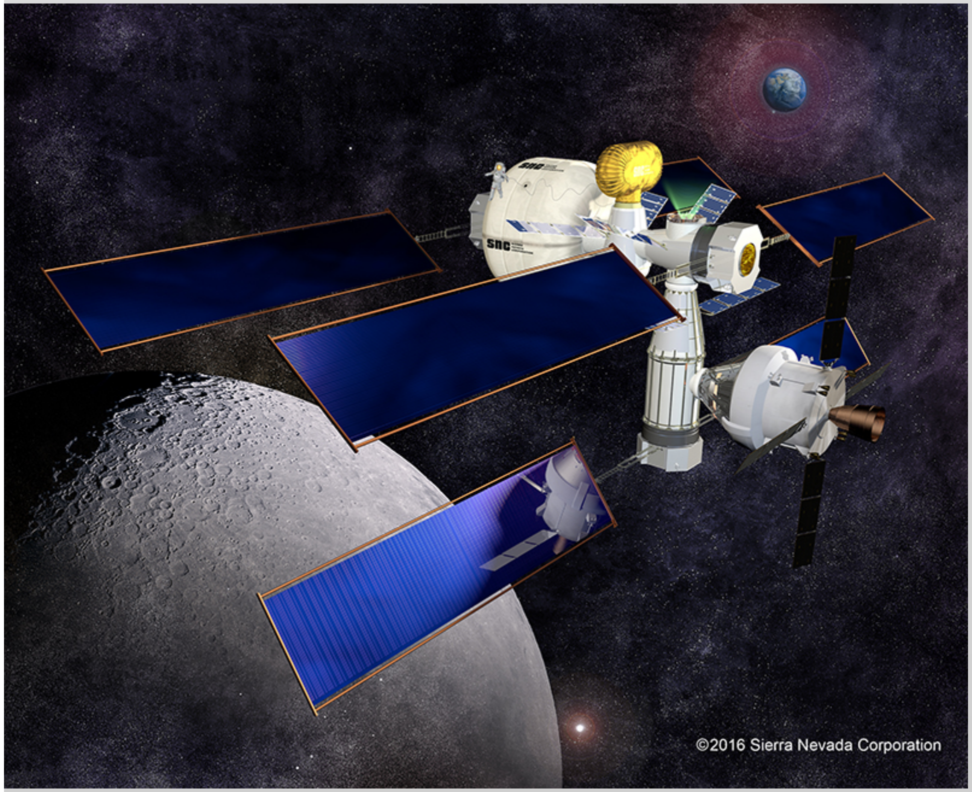
KEY ATTRIBUTES

- Designed to perform long duration missions in cislunar space
- Utilizes existing technology in vehicle design
- Leverages Orbital ATK's human-rated and operational commercial cargo spacecraft
- Provides innovative approach for EVA module and airlock functions
- Supports 2018 Ground Test to be performed at NASA facilities
- Evolvable to support future Exploration needs



Cislunar Test Bed / Augmentation of Orion

NextSTEP Phase II
Sierra Nevada Corporation



KEY ATTRIBUTES

- New to NextSTEP Hab activity – will have to accelerate concept refinement to meet milestones
- Provides innovative solution for deep space habitation
  - Leverages off of SNC's cargo resupply development activities
  - Uses advanced inflatable materials for habitat
  - Flies initial habitat to ISS for assembly and check-out and then meets up with remaining elements in LEO and is then sent to cislunar space
- 2018 Ground Test to be performed at JSC facilities

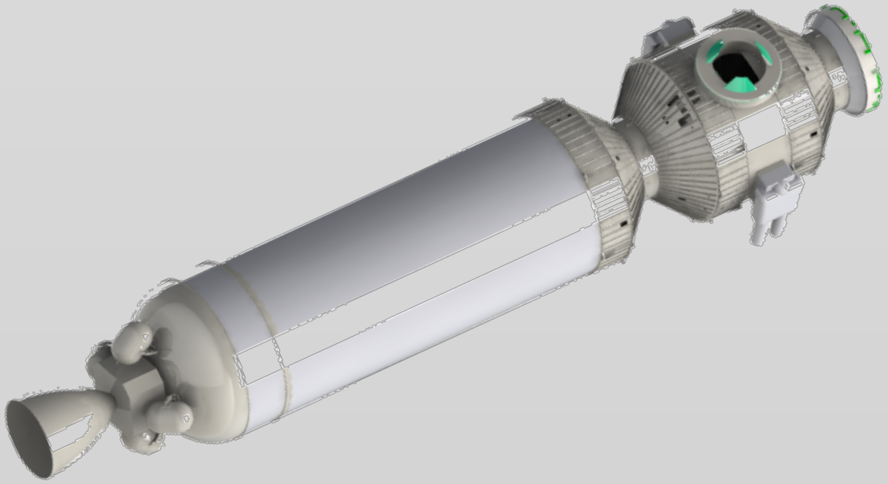
OBJECTIVES & TECHNICAL APPROACH

- Matures and refines SNC's deep space habitat concept through system trades and full-scale ground prototyping and testing
- Leverages a modular and flexible architecture that builds on NextSTEP-1, CRS2 and cooperative commercial investments.
- Requires four launches to complete the mission; able to co-manifest with SLS/CRS2 or utilize commercial launch vehicles to provide NASA flexibility in assembling habitat that supports Orion mission timelines
- Uses mature system building blocks and evolving capabilities to achieve long-duration mission objectives
- Includes ongoing technology evaluation to further LEO and deep space commercialization

TEAM

- **SNC** – CCDev, CCiCap, and CRS2 contracts with NASA to deliver a human-rated flight systems for LEO
- **ORBITEC** – SNC business unit, provides ECLSS subsystem for CRS2 contract, and also awarded NextSTEP-1 contract to develop a habitat plant growth system.
- **Aerojet Rocketdyne** – Awarded NextSTEP-1 contract to advance electric propulsion capabilities through EP thruster development
- **ILC Dover** – Applies TransHab, Lunar Habitat Study and Resilient Tunnel Plug technology to develop inflatable habitat for SNC's concept
- **NASA LaRC** – Considerate experience with inflatables and long-duration radiation mitigation.

NextSTEP Phase II NanoRacks



OBJECTIVES

- Leverage proven, affordable, and safe flight hardware by converting a Centaur and other rocket stage into a habitat;
- Perform feasibility assessment of habitat outfitting via robotics;
- Transform the LEO commercial marketplace by combining Nanoracks and SSL's unique private sector experience and customer base for next-generation orbital satellite manufacturing, assembly, and deployment; space tourism; media activities; and orbital experiments.
- Explore cost/benefit analysis in differing space regimes of this proposed approach in comparison to other current approaches/technologies

KEY ATTRIBUTES

- Provides study to look at feasibility of converting spent upper-stages into habitats while in space
- Uses advances in robotics to perform the upper-stage safing and outfitting
- Leverages partners' extensive knowledge in robotics, launch vehicle upper-stages, and commercial use of low-earth-orbit
- Concept provides innovative approach for development of future large habitats at a potentially great cost savings
- Study will finish in four months, contractor to continue afterwards to support interface and standards working group
- Activity will not result in development of a ground prototype unit

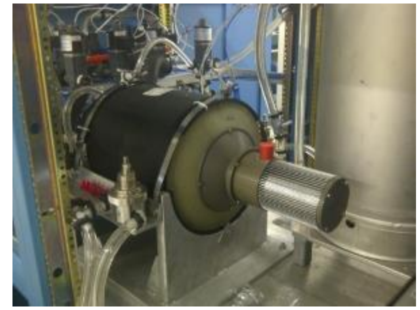
TEAM

- **NanoRacks, LLC**
  - Prime contractor, habitat systems design, LEO commercial operations
- **Space Systems Loral**
  - Robotics, Solar Electric Propulsion, LEO/GEO commercial satellite manufacturing
- **United Launch Alliance**
  - Centaur tank, launch services, and mission design

Deep Space Habitation Systems

Bigelow Expandable Activity Module (BEAM): Test of inflatable module structures on ISS (JSC).

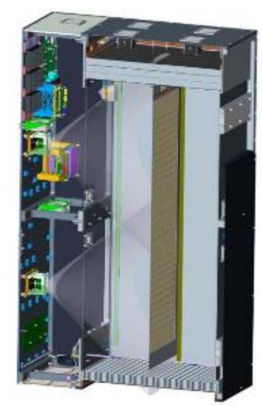
Atmosphere Resource Recovery & Environmental Monitoring: Integrated ground testing of ISS-derived life support system components (MSFC).



Water Recovery: Development of processes and systems for recycling wastewater (JSC).

Radiation Protection: Development and testing of radiation sensors and shielding (JSC).

Logistics Reduction: Waste processing to reduce logistics mass (JSC).



Spacecraft Fire Safety: Flight experiment on Cygnus to investigate how large-scale fires propagate in microgravity (GRC).

Bigelow Expandable Activity Module – 2 Year Demonstration
Launched April 2016 • Installed May 2016

- **Module is performing as expected**
  - Maintaining pressure
  - Radiation readings indicate Galactic Cosmic Ray exposure is same as other space station modules
- **Thermal analysis shows module is slightly warmer than predicted, but does not pose any risk to crew or station.**


NASA astronaut Peggy Whitson (left) and ESA astronaut Thomas Pesquet are photographed inside the Bigelow Expandable Activity Module, February 2017.

- **Eight ingresses as of March 2017. Astronauts conduct modal tests, take microbial samples, and inspect structural stability.**
- **Ground stations regularly receive data, which is analyzed by the NASA and Bigelow Aerospace teams.**
- **Forward focus is on continued radiation exposure analysis and orbital debris data.**

Life Support Systems

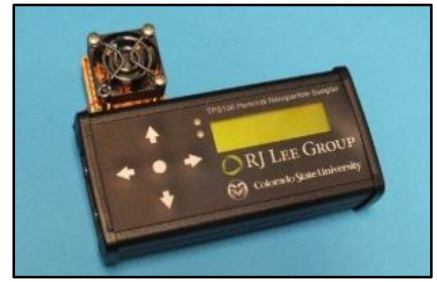
Currently in Development for Demonstration on ISS

- **Aerosol Sampler:** Demonstration of modified COTS Aerosol Sampler on ISS to gather quantitative data on ambient air quality (launched Oct. 2016). Collected samples will be returned on SpaceX-10.

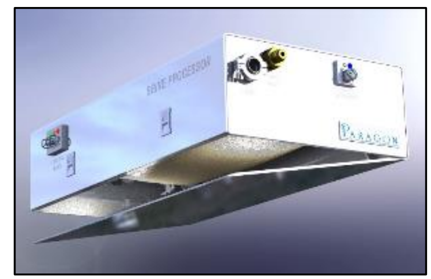
- **Brine Processor:** Demonstration of Ionomer Membrane Water Processor to purify and recover 98% of the available water from brine (Aug. 2018).
  - $5.1M Phase 3 SBIR contract awarded to Paragon (Jun. 2016).
  - Completed System Design Review (Oct. 2016).

- **Spacecraft Atmosphere Monitor:** Demonstration of miniature mass spectrometer for detecting trace gas contaminants in ISS air (Jun. 2018).
  - Completed System Design Review (Apr. 2016)
  - Next milestone: Complete development model (Feb. 2017)

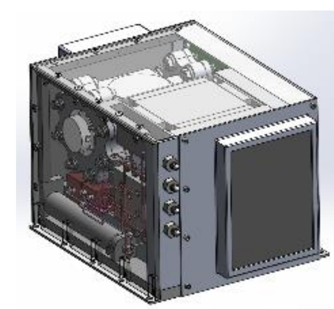
- **Demonstrator for Ionized Inert Gas**: Investigate the effects of microgravity on an inert gas plasma. This information will be used to design a plasma pyrolysis reactor that will recover hydrogen from methane (Oct. 2018).



Aerosol Sampler

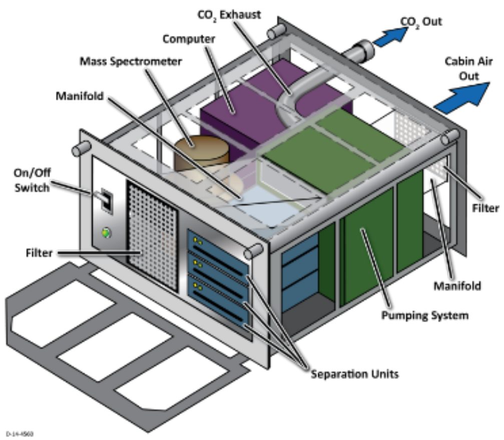


Brine Processor



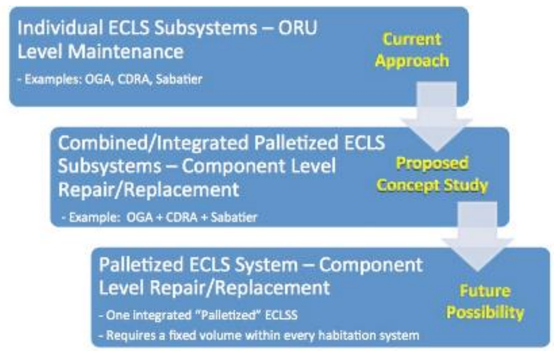
Spacecraft Atmosphere Monitor

NextSTEP Life Support Systems



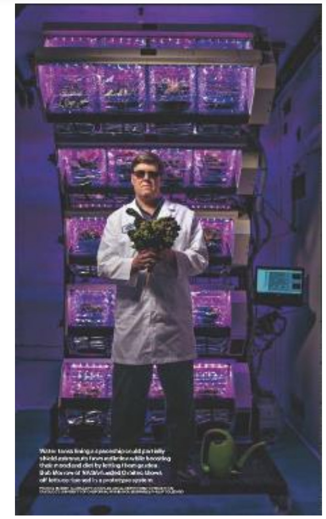
Dynetics:

- Miniature atmospheric scrubbing system to remove CO_2.
- Fabricated separation units for laboratory test bed.
- Planning ISS demo.
- FY17 Milestone: Complete fifth generation design for CO_2 separation.



UTC Aerospace Systems:

- Study of modular life support system concepts.
- Planning to incorporate AES-developed life support system into modular pallet design.
- FY17 Milestone: Deliver mockup pallet for verifying interfaces with prototype habitats.



Orbitec:

- Hybrid life support system using plant growth modules in habitat wall.
- Completed prototype "Greenwall" plant growth module.
- Featured in Nov. issue of *National Geographic*.
- FY17 Milestone: Identify flight equivalent materials.

Expect to award Phase 2 contracts for all three projects in March.

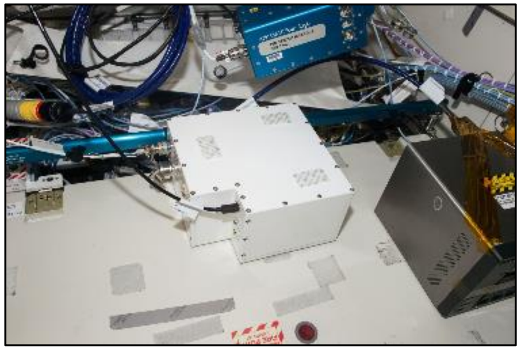
Radiation Sensors (RadWorks)

- Launched Fast Neutron Spectrometer (FNS) on OA-5 mission and activated on ISS. FNS will measure the energy of secondary neutrons generated when galactic cosmic rays interact with the spacecraft structure.

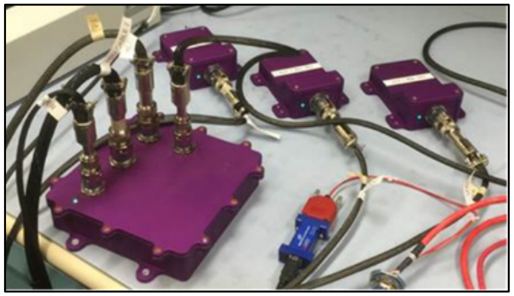
- Completed validation testing of Hybrid Electronic Radiation Assessor (HERA) being developed for EM-1 and EM-2. Sensors were exposed to helium, carbon, and proton beams at NASA Space Radiation Lab.

- RadWorks will provide radiation transport modeling and analysis support to NextSTEP-2 contractors developing prototype cislunar habitats.

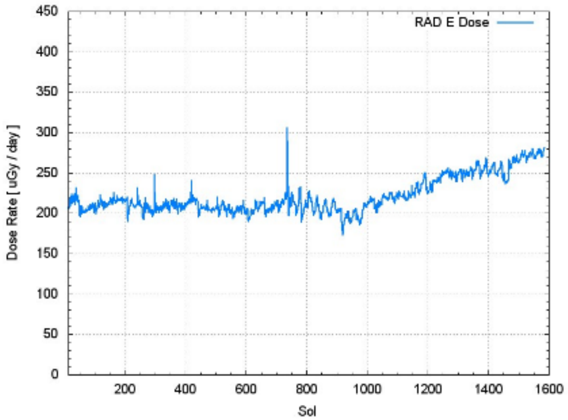
- The Radiation Assessment Detector (RAD) has operated for 1585 sols on Mars. The radiation dose rate has increased 35% since the summer of 2015 due to decrease in the solar cycle.



Fast Neutron Spectrometer



Hybrid Electronic Radiation Assessor (HERA)

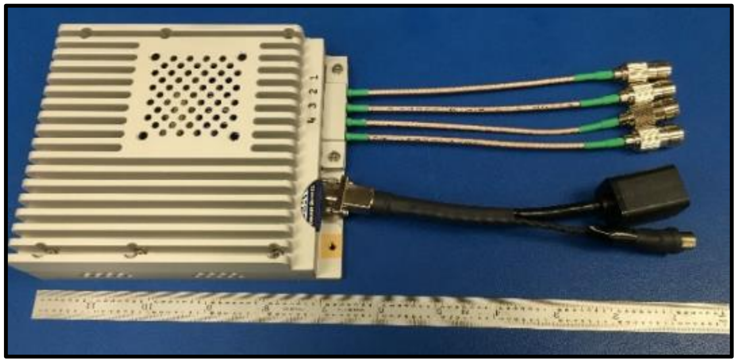


RAD Dose Rate

Logistics Reduction

- The Radio Frequency Identification Enabled Autonomous Logistics Management (REALM-1) will be used to track inventory and locate missing items quickly.
  - REALM-1 hardware (RFID hatch readers, antennas, and cables) was launched to ISS on Dec. 9. and installed in late Jan.

- The Universal Waste Management System (UWMS) is a compact toilet being developed for ISS, Orion, and deep space habitats.



REALM-1 flight reader (1 of 6)

UWMS ground prototype

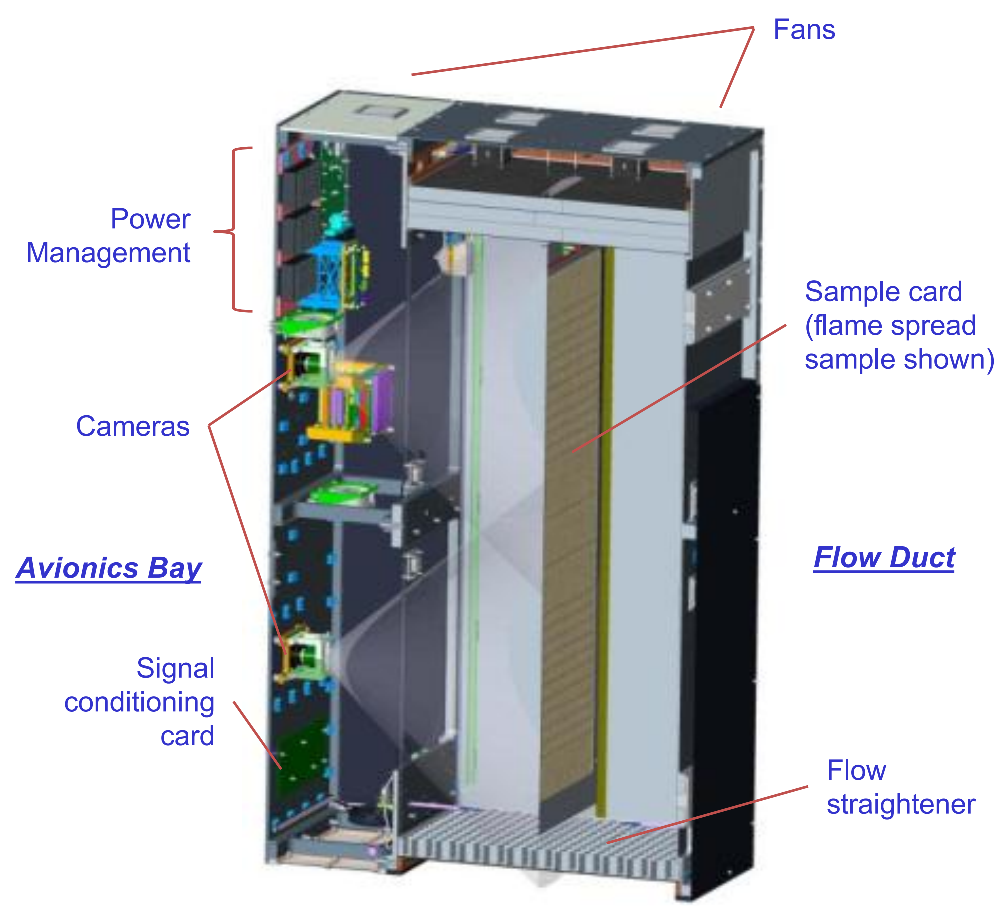
Saffire-I, II, and III Overview

Needs:

- ♦ *Low-g flammability limits for spacecraft materials*
- ♦ *Definition of realistic fires for exploration vehicles*
  - – *Fate of a large-scale spacecraft fire*

Objectives:

- ✓ *Saffire-I*: Assess flame spread of large-scale microgravity fire (spread rate, mass consumption, heat release)
- ✓ *Saffire-II*: Verify oxygen flammability limits in low gravity
- ♦ *Saffire-III*: Same as Saffire-I but at different flow conditions.



- *Data obtained from the experiment will be used to validate modeling of spacecraft fire response scenarios*
- *Evaluate NASA's normal-gravity material flammability screening test for low-gravity conditions.*

Saffire module consists of a flow duct containing the sample card and an avionics bay. *All power, computer, and data acquisition modules are contained in the bay. Dimensions are approximately 53- by 90- by 133-cm*

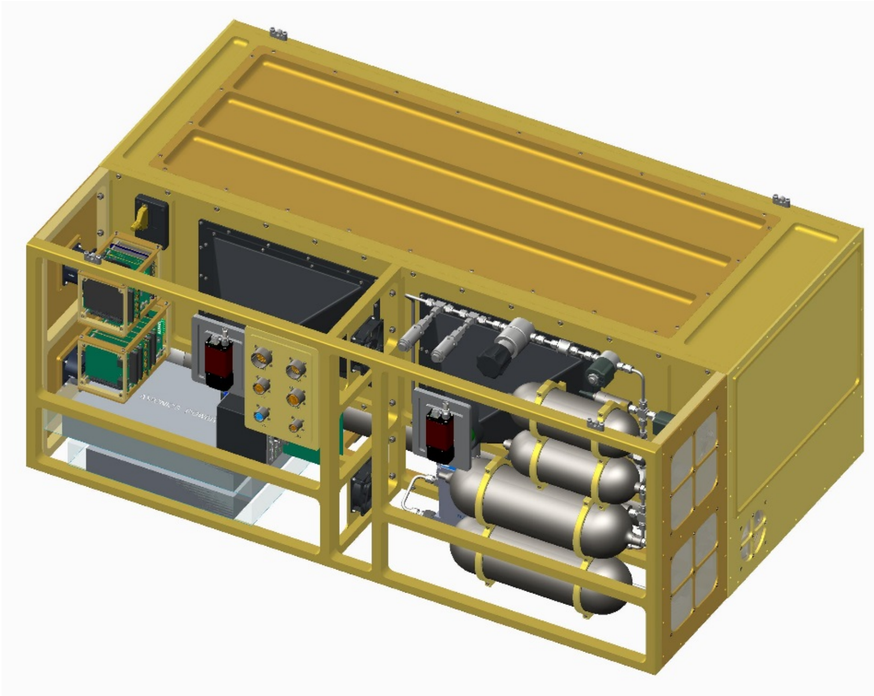
Saffire-IV, V, and VI Overview

Needs:

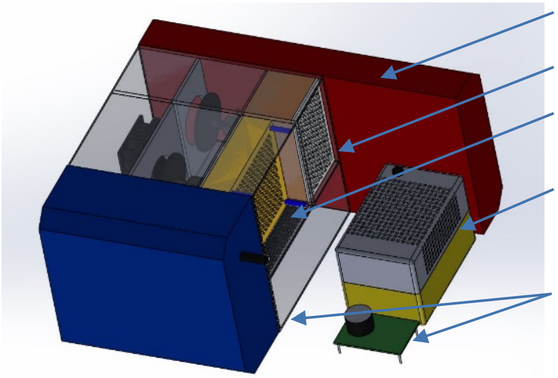
- *Demonstrate spacecraft fire detection, monitoring, and cleanup technologies in a realistic fire scenario*
- *Characterize fire growth high O_2/low pressure atmospheres*
- *Provide data to validate models of realistic spacecraft fire scenarios*

Objectives:

- *Saffire-IV*: Assess flame spread of large-scale microgravity fire (spread rate, mass consumption, heat release) in exploration atm
- *Saffire-V*: Evaluate fire behavior on realistic geometries
- *Saffire-VI*: Assess existing material configuration control guidelines
- All flights will demonstrate fire detection, monitoring, and cleanup technology



Conceptual design of Saffire-IV-VI experiment module.
Dimensions are approximately 53- by 90- by 133-cm. additions from previous Saffire include side view of sample card and oxygen addition.



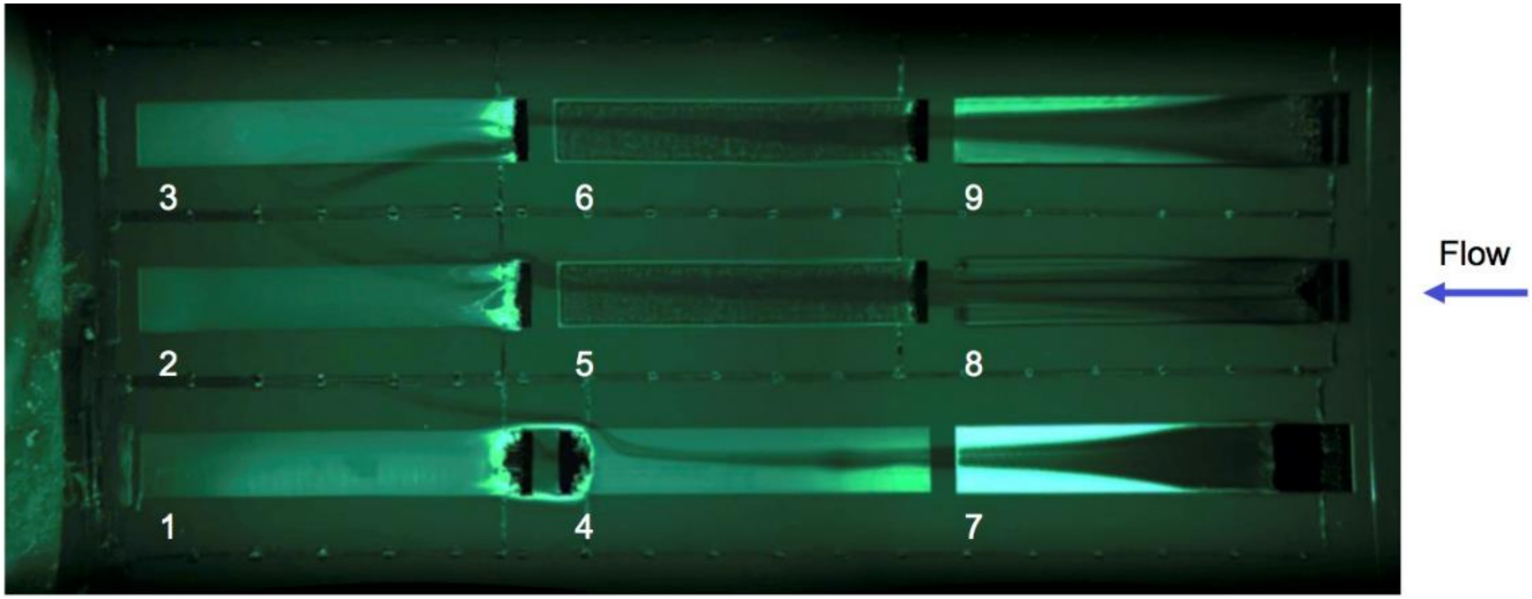
Spacecraft Fire Safety: Saffire-II

- The Saffire-II fire safety flight experiment was successfully conducted on board the Cygnus vehicle after it undocked from ISS on Nov. 21.

- The experiment investigated the flammability of nine material samples consisting of four different materials: Silicone, PPMA (acrylic), SIBAL (cotton on fiberglass substrate), and Nomex. Over 38 Gb of image and sensor data were received.

- The silicone samples of varying thickness ignited but did not burn as anticipated based on flammability testing conducted at 1-g. The PPMA samples burned for 12 minutes. The flame spread rates for the SIBAL cloth samples were comparable to Saffire-I.

- Saffire-III launch scheduled for OA-7.



Environmental Control & Life Support Systems Maturation Team Status

HEO NAC, March 29, 2017

Robyn Gatens | Deputy Director, ISS Division | NASA HQ

Specific Deep Space Habitation Systems Objectives

Habitation Systems Elements

1 LIFE SUPPORT
Atmosphere Management, Water Management, Waste Management

2 ENVIRONMENTAL MONITORING
Pressure O_2 & N_2, Moisture, Particles, Microbes, Chemicals, Sound

3 CREW HEALTH
Monitoring, Exercise, Diagnostics, Treatment, Food Storage & Management

4 EVA: EXTRA-VEHICULAR ACTIVITY
Mobility, Life Support, Science and Exploration

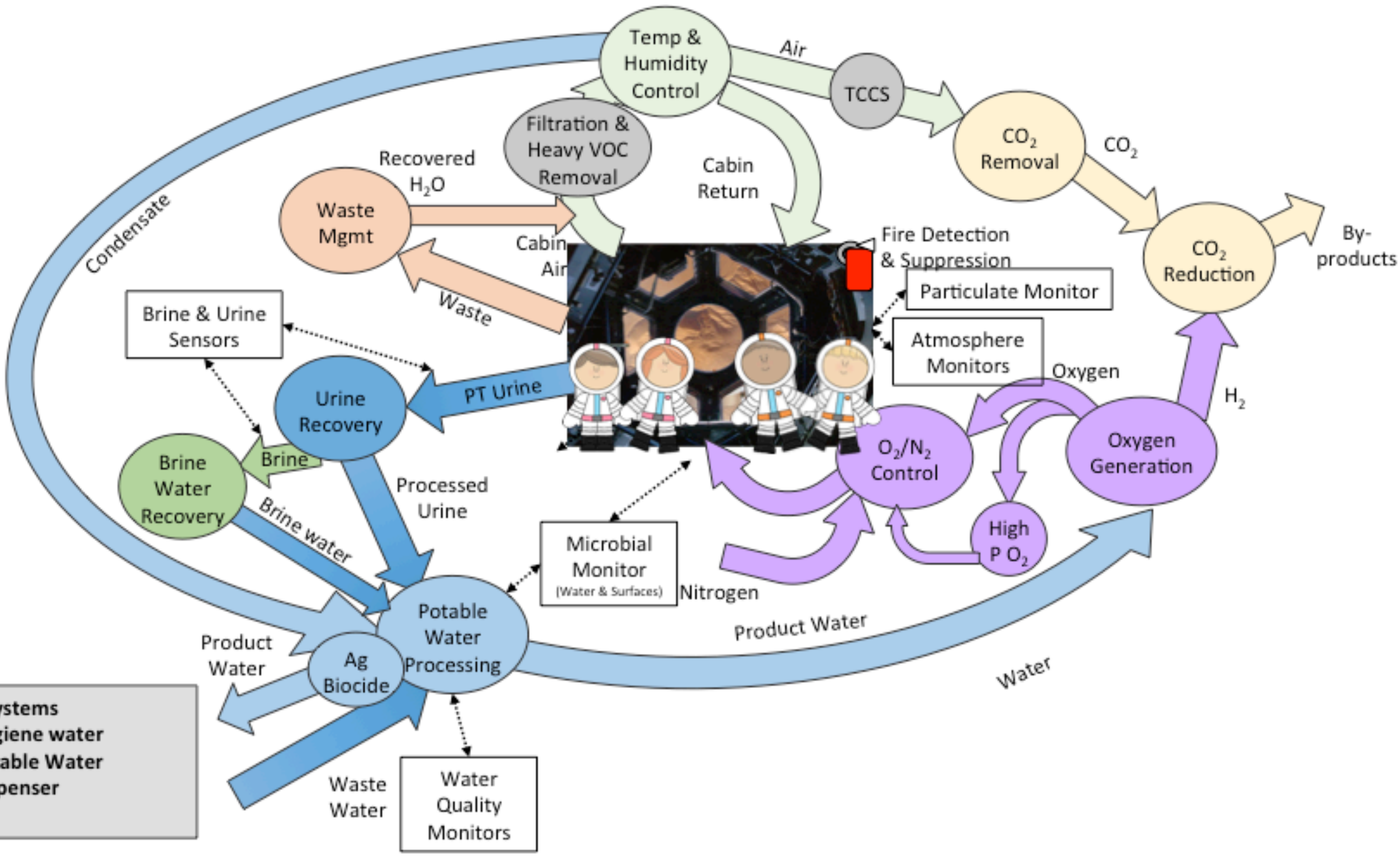
	TODAY ISS	FUTURE Deep Space
1 Life Support	42% O_2 Recovery from CO_2 90% H_2O Recovery < 6 mo mean time before failure (for some components)	75%+ O_2 Recovery from CO_2 98%+ H_2O Recovery >30 mo mean time before failure
2 Environmental Monitoring	Limited, crew-intensive on-board capability Reliance on sample return to Earth for analysis	On-board analysis capability with no sample return Identify and quantify species and organisms in air & water
3 Crew Health	Bulky fitness equipment Limited medical capability Frequent food system resupply	Smaller, efficient equipment Onboard medical capability Long-duration food system
4 EVA	High upper body mobility for limited sizing range Low interval between maintenance, contamination sensitive, and consumables limit EVA time Construction and repair focused tools; excessive inventory of unique tools	Full body mobility for expanded sizing range Increased time between maintenance cycles, contamination resistant system, 25% increase in EVA time Geological sampling and surveying equipment; common generic tool kit

Specific Habitation Systems Objectives

Habitation Systems Elements

Element	Components	TODAY Space Station	FUTURE Deep Space
RADIATION PROTECTION	Monitoring, Tracking, Modeling, Mitigation	Node 2 crew quarters (CQ) w/ polyethylene reduce impacts of proton irradiation. RAD, REM – real-time dosimetry, monitoring, tracking, model validation & verification TEPC, IVTEPC – real-time dosimetry CPD, RAM – passive dosimeters	Solar particle event storm shelter, optimized position of on-board materials and CQ Distributed REM/HERA system for real-time monitoring & tracking CPAD – real-time dosimeter
FIRE SAFETY	Detection, Protection, Suppression, Cleanup	Large CO_2 Suppressant Tanks 2-cartridge mask Obsolete combustion prod. sensor Only depress/repress clean-up	Water Mist portable fire extinguisher Single Cartridge Mask Exploration combustion product monitor Smoke eater
LOGISTICS	Tracking, Clothing, Packaging, Trash	Manual scans, displaced items Disposable cotton clothing Packaging disposed Bag and discard	Automatic, autonomous RFID Long-wear clothing/laundry Bags/foam repurposed w/3D printer Resource recovery, then disposal
CROSS-CUTTING TECHNOLOGIES	Robotics, Power, Communication, Docking, Avionics, Autonomy & Software, Thermal, Materials	Minimal on-board autonomy Near-continuous ground-crew comm Some common interfaces, modules controlled separately	Ops independent of Earth & crew Up to 40-minute comm delay Widespread common interfaces, modules/systems integrated Manufacture replacement parts in space

Exploration ECLSS Diagram



Crew Systems

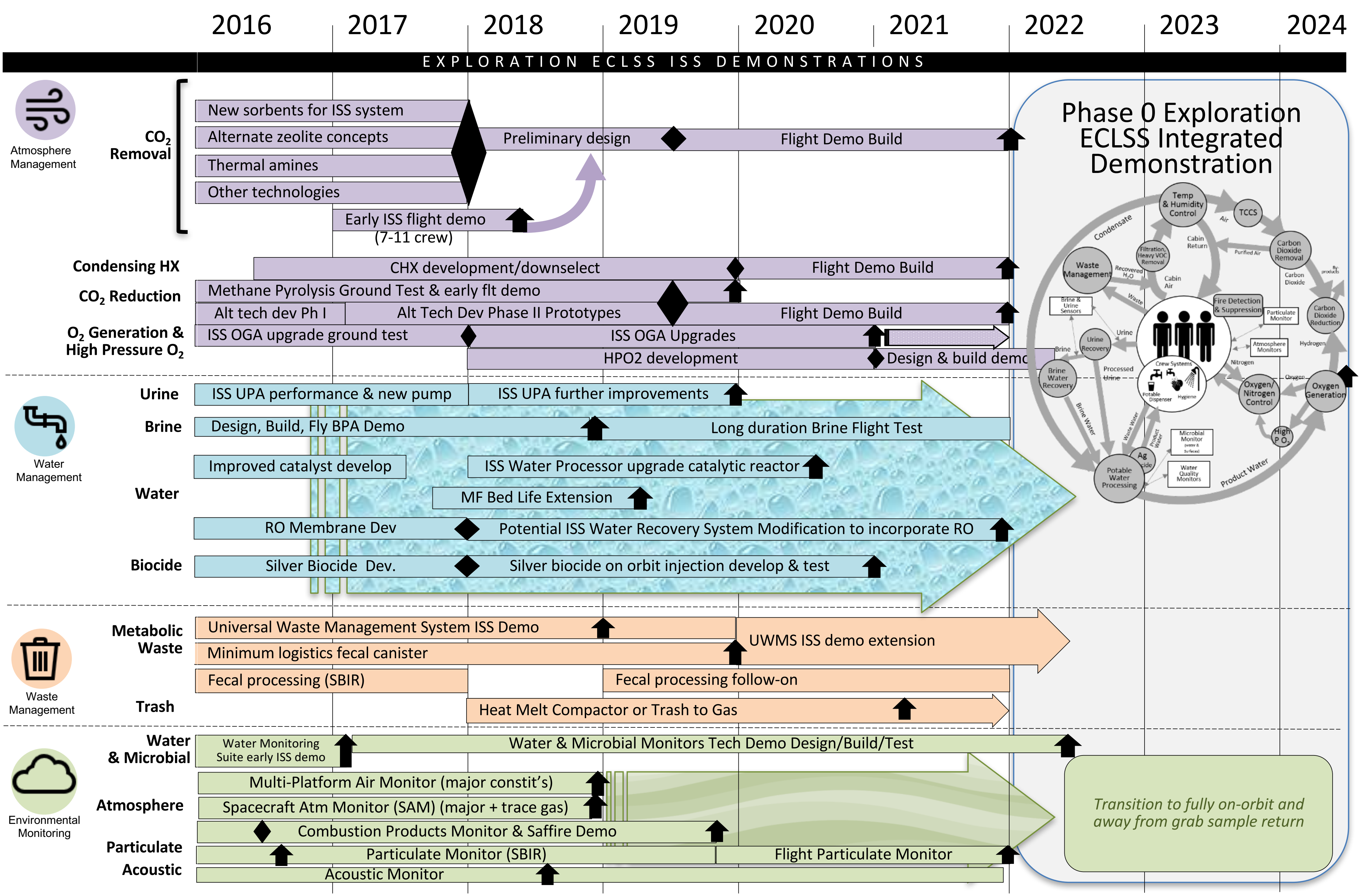
- **Hygiene water**
- **Potable Water Dispenser**

ECLSS & Environmental Monitoring Capability Gaps

Gap Criticality:
5 = high
1 = low

Function	Capability Gaps	Gap criticality as applicable to μg transit Hab	Orion Need
CO_2 Removal	Bed and valve reliability; $ppCO_2$ <2 mmHg	5	
O_2 recovery from CO_2	Recover >75% O_2 from CO_2	5	
Urine brine processing	Water recovery from urine brine >85%	5	
Metabolic solid waste collection	Low-mass, universal waste collection	5	X
Trace Contaminant Control	Replace obsolete sorbents w/ higher capacity; siloxane removal	4	X
Condensing Heat Exchanger	Durable, chemically-inert hydrophilic surfaces with antimicrobial properties	4	
Water microbial control	Common silver biocide with on-orbit redosing	4	
Contingency urine collection	Backup, no moving parts urine separator	4	X
Urine processing	Reliability, 85% water from urine, dormancy survival	4	
Atmosphere monitoring	Small, reliable atmosphere monitor for major constituents, trace gases, targeted gases	4	X
Water monitoring	In-flight identification & quantification of species in water	4	
Microbial monitoring	Non-culture based in-flight monitor with species identification & quantification	4	
O_2 generation	Smaller, reduced complexity, alternate H_2 sensor	3	
High pressure O_2	High pressure (3000 psi) O_2 for EVA/on-demand O_2 supply for contingency medical	3	
Wastewater processing (WPA)	Reliability (ambient temp, reduced pressure catalyst), reduced expendables, dormancy survival	3	
Non-metabolic solid waste	Volume reduction, stabilization, resource recovery	3	
Particulate monitoring	On-board measurement of particulate hazards	3	
Particulate Filtration	Surface dust pre-filter; regen filter	2	
Atmosphere circulation	Quiet fans	2	
Logistics Reduction	10:1 volume reduction logistical and clothing	2	
Metabolic solid waste treatment	Useful products from metabolic waste	1	

Exploration ECLSS Roadmap



Current Status – Atmosphere Management

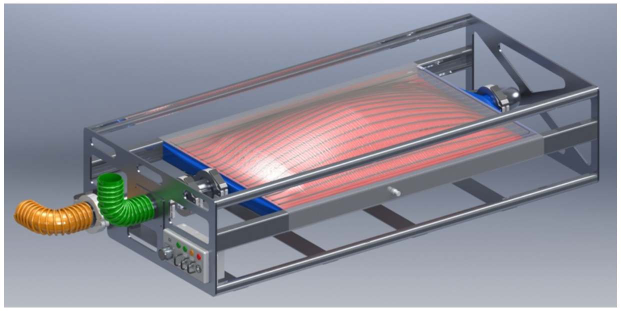
- **CO2 Removal**
  - Have initiated work on early thermal amine ISS flight demo targeted for 2018
  - Downselect among all options planned end of 2017
    - Using NRA thrust area announcement to ensure all options considered
- **Oxygen Generation & High Press O_2**
  - Testing to reduce complexity complete; team to assess ISS OGA recommended upgrades as a result
- **Oxygen Recovery/CO_2 Reduction**
  - STMD awarded two Phase II oxygen recovery projects:
    - Honeywell methane pyrolysis
    - Umpqua continuous Bosch
  - NASA development of methane plasma pyrolysis continues
  - ISS on-orbit Sabatier degrading; planning for return and troubleshooting
    - 2 of 3 oxygen recovery options include Sabatier

Current Status – Atmosphere Management, cont.

- **Condensing Heat Exchanger**
  - Several options under assessment with downselect in early FY19 for flight demonstration
  - Received NRA thrust area proposals – SMT evaluating
- **Trace Contaminant Control**
  - Alternate commercial sorbent testing
  - Supporting efforts to solve ISS siloxane problem
- **Particulate Filtration**
  - Pre-filter and regenerable filter development ongoing

Current Status – Water Management

- **Urine processing**
  - New pretreat formula on ISS improves recovery to 85-90%
  - Pump reliability improved by change to planetary gear
  - Improvements to distillation assembly in work
- **Water processing**
  - Improved catalyst development
  - Operational filter life extension
  - Alternate technology/reverse osmosis testing & trade
- **Brine processing**
  - ISS flight demonstration by Paragon in development – flies in 2018



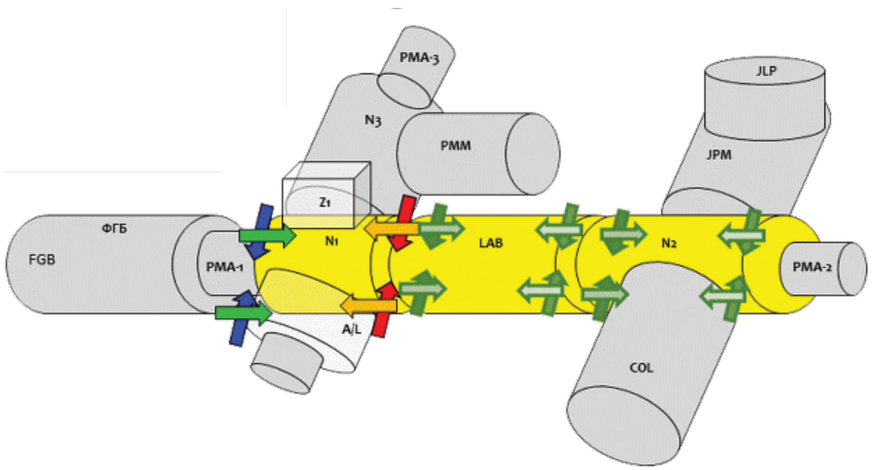
- **Silver biocide**
  - development of on orbit injection capability through SBIR projects

Progress – Waste Management

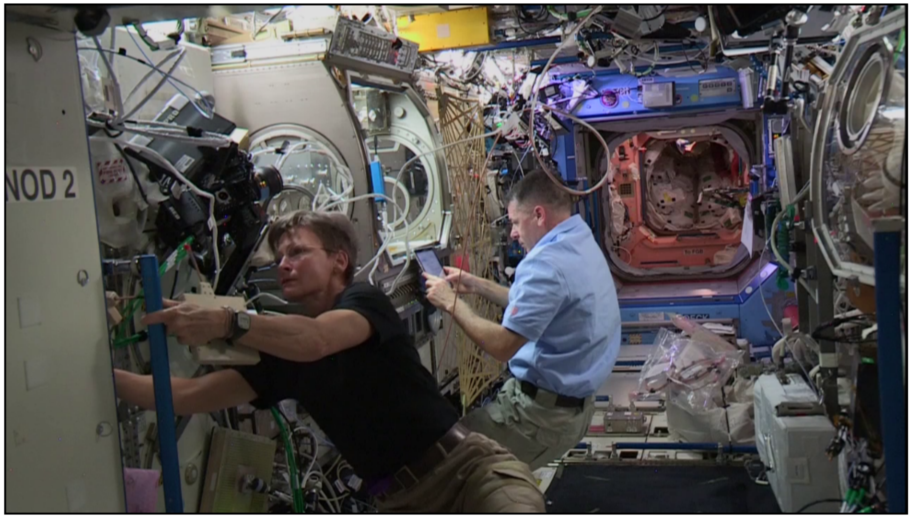
- **Commode**
  - Universal waste management system for ISS demo & Orion (2018) – ISS working integration for permanent ISS installation side by side with current Waste & Hygiene Compartment/Russian Commode
  - Minimum mass fecal container development
- **Fecal processing**
  - Torrefaction SBIR development
- **Trash management**
  - Heat melt compactor and trash to gas development
- **Logistics Reduction**
  - Long wear clothing demonstrated on ISS
  - Repurposing of packaging and cargo bags

Progress – Logistics Management

- **RFID Enabled Autonomous Logistics Management (REALM)**
  - 6 RFID readers and 24 antennas (REALM-1) were launched on HTV6 in December and deployed in February
  - Successfully demonstrated end-end data transfer and down linked over 600 million tag reads from over 3,000 unique tags
  - Responded to unplanned real-time ISS request to locate missing cargo bag slated for SpX-10 return. Manually searched data to predict missing bag location which demonstrated ‘find’ capability
  - A mobile RFID reader (REALM-2) for the Astrobee free flyer is under development for FY19



Location of 24 REALM-1 antennas in Node 1, US Lab, and Node 2



Astronaut Peggy Whitson installing 1 of 24 REALM-1 antennas (tan square in her left hand)

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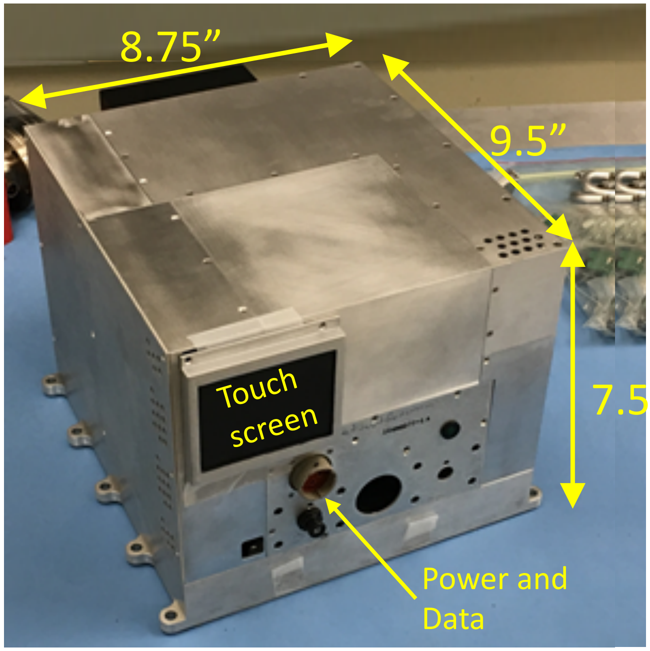
Current Status – Environmental Monitoring

- **Atmosphere Monitoring**
  - Spacecraft Atmosphere Monitor (SAM) micro GC/MS for major constituents and trace gases ISS tech demo planned (2018)
  - Laser-based monitors for combustion products and targeted gases planned for Saffire demonstration, upgrade of ISS combustion products monitor and Orion Anomaly Gas Analyzer implementation
  - Improved mass spec for ISS & Orion use
- **Water Monitoring**
  - Requirements in development
  - Front end to atmosphere monitor for water samples



Development Model of the Spacecraft Atmosphere Monitor (Front-View)

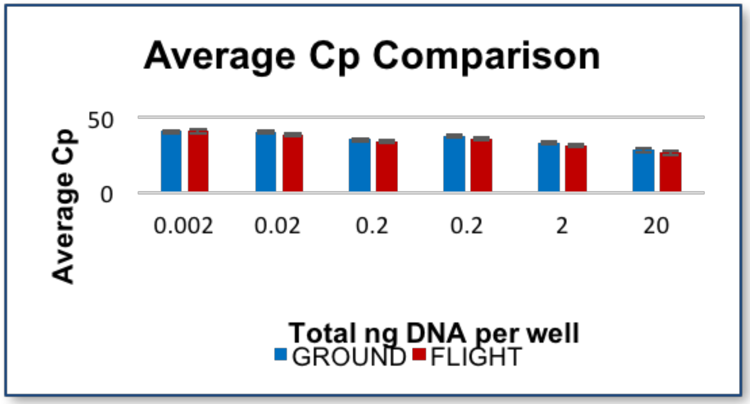
Current Status – Environmental Monitoring, cont

Microbial Monitoring

- **RAZOR**
  - COTS Polymerase Chain Reaction (PCR) unit launched to ISS in July 2016 aboard SpX-9 – detect & identify microorganisms
  - First device to perform quantitative PCR using ISS water samples in the microgravity environment of space – "sample to answer"
  - 9 successful test runs completed Sept 2016 – March 2017

- **Mini-PCR DNA sequencer demonstrated on ISS as part of Genes in Space**

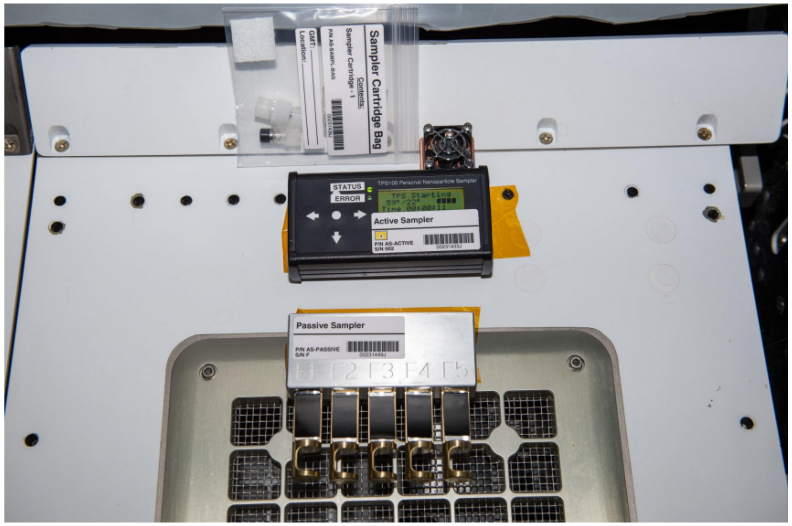
Flight testing of RAZOR hardware on 9/20/2016. NASA image iss049e007041



COTS Oxford Nanopore Technologies MinION™ DNA Sequencer

Current Status – Environmental Monitoring, cont

- **Particulate Monitor**
  - Aerosol sampler (flown on OA-5) just completed ISS ops, samples stowed for return on SpaceX-10.
    - Analysis will begin immediately upon return and will include a variety of microscopic techniques to determine particle morphology, composition, and long-term average concentrations
    - Data will inform the design of particulate monitors for future long-term missions
  - SBIR particulate monitor development



Progress – ISS Integration

- **ISS actively working on integration concepts for Exploration ECLSS**
  - Water system will be evolution of current ISS Water Recovery System in Node 3
    - Upgrades to WPA and UPA could require retrofit in a rack space nearby
  - Air system must be co-located and may incorporate new CO2 removal/reduction technologies – plan is to move to USL as Node 3 cannot accommodate this string
    - Oxygen Generation System rack must move to USL to enable integration in adjacent rack space(s)
    - Will require racks in USL to be moved to other locations

Next Steps

- **Team is currently refining budget estimates and detailed plans**
- **Working with International Partners through the I-SMT**
  - ECLSS Interoperability standards (e.g. atmosphere quality, water quality)
  - Following partner activities and planned ECLSS ISS demonstrations
- **Continue to execute Exploration ECLSS plan!**

NASA