



# Critical Technology Determination for Future Human Space Flight

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Prepared for the  
Global Space Exploration Conference  
sponsored by the IAF and AIAA  
Washington, D.C., May 22–24, 2012

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*Level of Review:* This material has been technically reviewed by technical management.

Available from

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## Abstract

As the National Aeronautics and Space Administration (NASA) prepares to extend human presence throughout the solar system, technical capabilities must be developed to enable long duration flights to destinations such as near Earth asteroids, Mars, and extended stays on the Moon. As part of the NASA Human Spaceflight Architecture Team, a Technology Development Assessment Team has identified a suite of critical technologies needed to support this broad range of missions. Dialog between mission planners, vehicle developers, and technologists was used to identify a minimum but sufficient set of technologies, noting that needs are created by specific mission architecture requirements, yet specific designs are enabled by technologies. Further consideration was given to the re-use of underlying technologies to cover multiple missions to effectively use scarce resources. This suite of

critical technologies is expected to provide the needed base capability to enable a variety of possible destinations and missions. This paper describes the methodology used to provide an architecture-driven technology development assessment (“technology pull”), including technology advancement needs identified by trade studies encompassing a spectrum of flight elements and destination design reference missions.

## 1.0 Introduction

NASA is preparing for the next chapter of space exploration by developing the capabilities needed to expand human activity throughout the inner solar system (Ref. 1). NASA formed the Human Spaceflight Architecture Team (HAT) to develop concepts for architectures and vehicle elements, conduct trade studies, and determine the technology and capability requirements needed for missions ranging from activities in cis-Lunar space to Mars landings. These activities provide cost and feasibility

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determinations to plan the next series of human exploration missions.

As shown in Figure 1, the HAT approach includes several processes: design reference missions consistent with NASA’s investment strategy are proposed; elements needed for the missions are conceptualized; schedule and cost estimates for each element are developed; integrated schedules and flight manifests are determined; and total costs are estimated. A key step in this process is the determination of which technologies are needed to enable these elements and missions so that full costs can be estimated. This paper describes the methodology used to provide an architecture-driven technology development assessment (“technology pull”) resulting in a list of critical technologies needed to advance human exploration of space beyond low Earth orbit.

The HAT created a Technology Development Assessment Team to manage the collection and evaluation of these technology needs. This team is comprised of representatives from across the Agency, ensuring input from and communication to a broad portion of the NASA community.

## 2.0 Architectural Elements and Destinations

Several architectural elements have been conceptualized by the HAT team, and many design reference missions have been developed to encompass a variety of destinations within the inner solar system. While still notional, these elements and missions contain enough fidelity to provide a concrete target for assessing the likely costs of similar missions, including the costs of technology development. The destinations are used to

drive transportation systems capabilities and assess impacts of changes in mission assumptions. The elements and destinations currently under consideration are listed below and notional representations of the elements are shown in Figure 2.

### Architecture Elements (Ref. 2)

- Space Launch System (SLS)
- Multipurpose Crew Vehicle (MPCV)
- Cryogenic Propulsion Stage (CPS)
- Solar Electric Propulsion Stage (SEP)
- Lander
- EVA Suit (EVA)
- Space Exploration Vehicle (SEV)
- Deep Space Habitat (DSH)
- Robotics and EVA Module (REM)
- Cargo Hauler
- Surface Elements (lunar, asteroid, Mars, and Mars moons)

### Design Reference Missions (DRM)/Destinations (Refs. 3 to 8)

- Low Earth Orbit (LEO)
- Geosynchronous and High Earth Orbit (GEO and HEO)
- Lunar Vicinity: Earth-Moon Lagrange points one and two (E-M L1 and L2)
- Lunar flyby and Low Lunar Orbit (LLO)
- Lunar surface
- Minimum capability, low energy Near Earth Asteroid (NEA)
- Full capability, high energy NEA
- Mars moon
- Mars surface

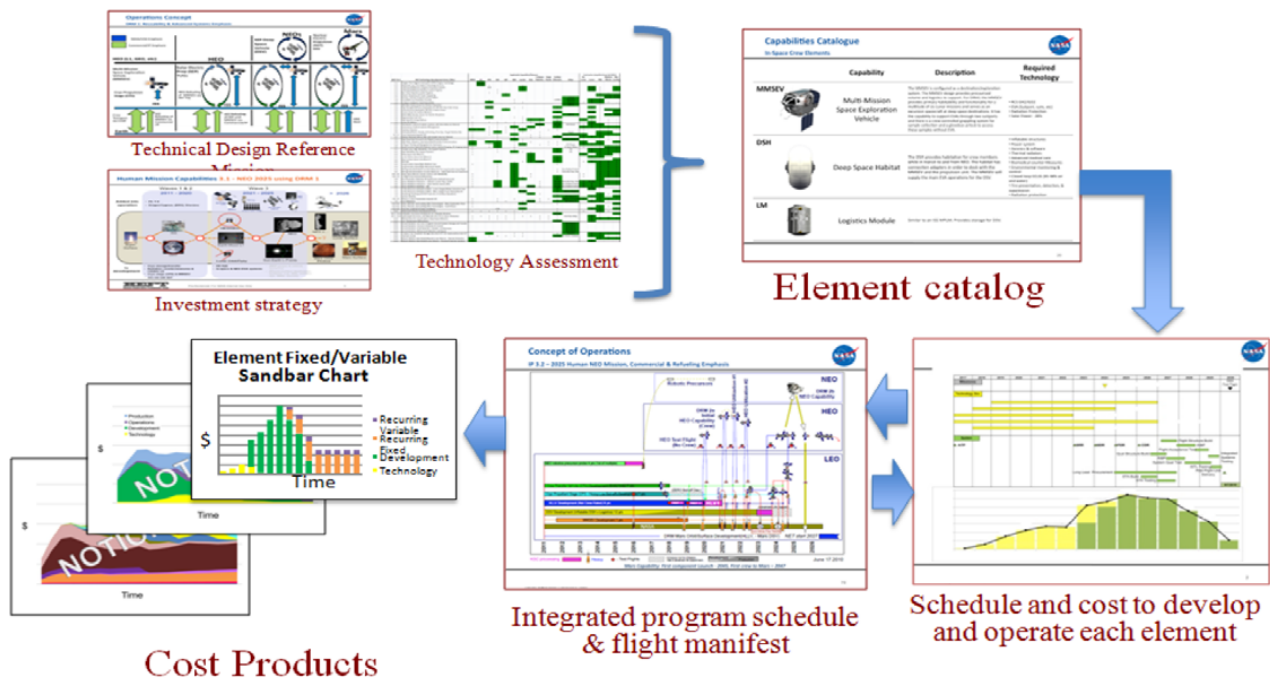


Figure 1.—HAT Cost Analysis Approach (Ref. 3).





Figure 2.—Notional HAT Architectural Elements (Ref. 2).

Note that the multipurpose crew vehicle and space launch system are needed for every destination, but the need for the other elements are destination and mission specific. Similarly, these two elements can be built with existing technology, but technology development is required for the other element concepts (dependent on destination).

### 3.0 Technology Selection Method

Conceptual designs were developed for each of the architectural elements listed in Section 2.0, and notional element performance requirements were determined for each relevant design reference mission to determine ballpark cost estimates. Element conceptual designs also provide a reasonable basis for determining whether existing technologies are sufficient to provide the expected performance or whether technical gaps need to be filled.

The determination of technology adequacy is best accomplished by collaboration between mission planners, spacecraft designers and technology developers, as the planners and designers are keenly aware of what is needed and the developers know about technologies that may change the way the missions and designs are approached. The objective is to determine a minimum but sufficient set of technologies, noting that needs are created by specific mission architecture requirements, yet specific designs are enabled by technologies.

The technical community submitted a list of technologies to the HAT element, architecture/DRM, and destination teams.

These teams reviewed each technology and judged whether technology development was *required* to enable functionality of their element or successful completion of a mission to their destination, respectively. The teams also identified additional technologies, if any, which might be required. The first set of technologies was based primarily on work that was already under development for a planned lunar mission (as part of the NASA Constellation Program), but as the broader technical community was educated about the evolving elements and destinations, new ideas came forward that might either be required or could substantially change the way the missions could be accomplished.

To simplify the review of the many technologies brought forth, each technology was described using a common format including these data elements:

- Description: Explanation as to the what and why a specific technology development is required
- Performance Characteristics: Details on what advancements beyond SOA is required, including metrics where known/applicable

If the technologists and the respective element and destination team leads reached consensus on the description and performance characteristics needed, and these team leads agreed that the technology was enabling for their vehicle or mission, then the technology was added to the list of critical technologies. Some technologies that are required for one element are also beneficial to others; an example is unsettled cryogenic propellant transfer

which is required for the CPS and beneficial for the DSH, Lander, and surface elements. Note that the need for some technologies is dependent on specific vehicle configurations, e.g., oxygen-rich stage combustion engine technology is applicable to the SLS only if liquid strap-on boosters are included in the design. The applicability data was visually mapped by noting “drivers” and “beneficiaries” in a spreadsheet containing rows of technologies and columns of elements, DRMs, and destinations. This mapping is notionally shown as the “technology assessment” plot in Figure 1 and the “summary spreadsheet” in Figure 3. The cost and schedule needed to bring the technology to a level where it could be infused into the standard Design, Development, Test and Evaluation (DDT&E) cycle was also collected, along with the current technology readiness level (TRL). “Cost fidelity” was assessed by determining the knowledge level of both the problem being addressed and the costs to develop the technology. An example of a technology with high cost fidelity is in-space cryogenic propellant storage, where the requirements are very well understood and solid plans are in place to develop the required technology. A Mars surface space suit is an example of a technology whose needs are well understood since the Mars environment is well characterized, but costs to develop the technology are not because specific technical concepts have not yet been selected. Thermal control is an example of a technology whose development costs are well understood for a given thermal system design, but the needs are uncertain because spacecraft designs are not finalized. These two examples yield a “medium” cost fidelity. Finally, a long life battery has a “low” cost fidelity because technical requirements have not yet been determined and a technical concept has not yet been developed.

Cost phasing and “need by” dates were recorded with each technology to assist with HAT’s cost estimations for each DRM.

Technologies were assumed to be matured and available by the preliminary design review for the enabled element. “Need by” dates for technologies required by multiple elements were based on the element that was expected to be completed first.

Finally, each technology was mapped into the technology classification system used by NASA’s Office of the Chief Technologist (Ref. 9). The full suite of data elements describing each technology is listed in Appendix B.

Figure 3 summarizes the use of the data collected for each technology. Subject matter experts created technology “one-pager” descriptions based on the needs of DRMs and architecture elements, and estimated technology development costs and the fidelity of those costs. Cost, schedule, and applicability data was recorded in a summary spreadsheet for use in the cost estimation process depicted in Figure 1.

## 4.0 Technologies

Using the methodology described in Section 2.0, a suite of 60 technologies was identified as being critically important for at least one mission under consideration by the HAT (“technology pull”). In addition, “common avionics” was identified as a technology which could substantially improve system level affordability, and four ground operations technologies were identified as having a similar cost reduction potential. The full suite of these 65 technologies is listed in Table 1, and their mapping to the architecture elements and destinations is shown in Table 2. Summary descriptions of each technology are included in Appendix C. Acronyms used in those descriptions are listed in Appendix A.

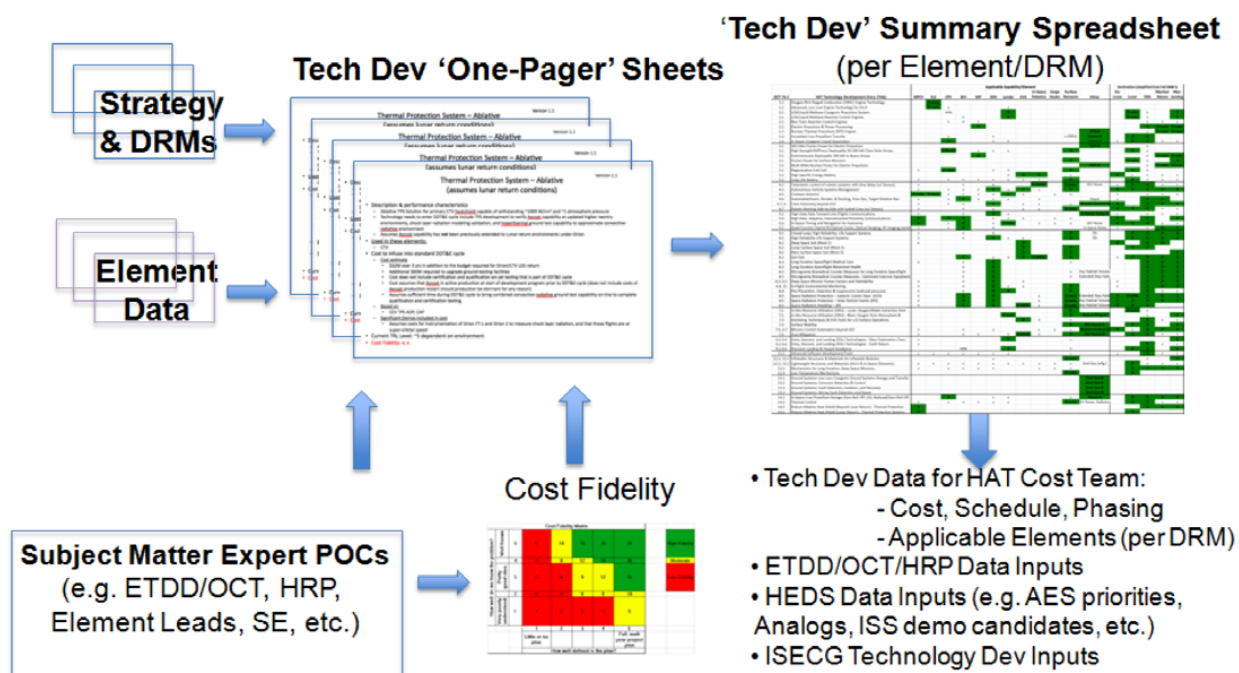


Figure 3.—HAT Technology Development Assessment: Data Capture Process (Ref. 3).

TABLE 1.—TECHNOLOGIES THAT ENABLE HUMAN SPACE EXPLORATION

Technology Area (TA)	TA Breakdown	Title
01 Launch Propulsion Systems	1.2	Oxygen-Rich Staged Combustion (ORSC) Engine Technology
		Advanced, Low Cost Engine Technology for SLS
02 In-Space Propulsion Technologies	2.1	LO <sub>2</sub> /LCH <sub>4</sub> Cryogenic Propulsion System
		LO <sub>2</sub> /LCH <sub>4</sub> Reaction Control Engines
		Non-Toxic Reaction Control Engines
	2.2	Electric Propulsion and Power Processing
	2.3	Nuclear Thermal Propulsion (NTP) Engine
	2.4	Unsettled Cryo Propellant Transfer
03 Space Power and Energy Storage	3.1	In Space Cryogenic Liquid Acquisition
		300 kWe Fission Power for Electric Propulsion
		High Strength/Stiffness Deployable 10-100 kW Class Solar Arrays
		Autonomously Deployable 300 kW In-Space Arrays
	3.2	Fission Power for Surface Missions
		Multi-MWe Nuclear Power for Electric Propulsion
04 Robotics, Tele-Robotics and Autonomous Systems	4.1, 4.5	Regenerative Fuel Cell
		High Specific Energy Battery
	4.3	Long Life Battery
		Precision Landing and Hazard Avoidance
	4.5	Telerobotic control of robotic systems with time delay
		Autonomous Vehicle Systems Management
	4.6, 4.2, 4.5	Common Avionics
		Automated/Auton. Rendez. and Docking, Prox Ops, Target Relative Navigation
4.7, 4.4	Crew Autonomy beyond LEO	
	Robots Working Side-by-Side with Suited Crew	
05 Communications and Navigation	5.2	High Data Rate Forward Link (Flight) Communications
		High Rate, Adaptive, Internetworked Proximity Communications
	5.4	In-Space Timing and Navigation for Autonomy
		Quad Function Hybrid RF/Optical Comm, Optical Ranging, RF Imaging System
06 Human Health, Life Support and Habitation Systems	6.1	Closed-Loop, High Reliability, Life Support Systems
		High Reliability Life Support Systems
	6.2	Deep Space Suit (Block 1)
		Lunar Surface Space Suit (Block 2)
		Mars Surface Space Suit (Block 3)
	6.3	Long Duration Spaceflight Medical Care
		Long-Duration Spaceflight Behavioral Health and Performance
		Microgravity Biomedical Counter-Measures for Long Duration Spaceflight
		Microgravity Biomedical Counter-Measures—Optimized Exercise Equipment
	6.3, 6.1	Deep Space Mission Human Factors and Habitability
	6.4, 11	In-Flight Environmental Monitoring
6.4	Fire Prevention, Detection and Suppression (reduced pressure)	
	Space Radiation Protection—Galactic Cosmic Rays (GCR)	
6.5	Space Radiation Protection—Solar Particle Events (SPE)	
	Space Radiation Shielding—SPE	
	Space Radiation Protection—Galactic Cosmic Rays (GCR)	
07 Human Exploration Destination Systems	7.1	In-Situ Resource Utilization (ISRU)—Lunar: Oxygen/Water Extraction from Lunar Regolith
		ISRU—Mars: Oxygen from Atmosphere and Water Extraction from Soil
	7.3	Anchoring Techniques and EVA Tools for Microgravity Surface Operations
		Suit Port
	7.5, 4.7	Surface Mobility
7.5	Mission Control Automation beyond LEO	
09 Entry, Descent and Landing (EDL) Systems	9.1, 9.4	Dust Mitigation
		EDL Technologies—Mars Exploration Class Missions
11 Modeling, Simulation, Information Technology and Processing	11.2	EDL Technologies—Earth Return
		Advanced Software Development/Tools
12 Materials, Structures, Mechanical Sys. and Mfg.	12.1, 12.2, 7.4.2	Structures and Materials for Inflatable Modules
		Lightweight and Efficient Structures and Materials
	12.3	Mechanisms for Long Duration, Deep Space Missions
13 Ground and Launch Systems Processing	13.1	Low Temperature Mechanisms
		Ground Systems: Low Loss Cryogenic Ground Systems Storage and Transfer
	13.2	Ground Systems: Corrosion Detection and Control
		Ground Systems: Fault Detection, Isolation, and Recovery
13.3	Ground Systems: Wiring Fault Detection and Repair	
	Ground Systems: Fault Detection, Isolation, and Recovery	
14 Thermal Management Systems	14.1	Ground Systems: Wiring Fault Detection and Repair
		In-Space Cryogenic Propellant Storage (Zero Boil Off LO <sub>2</sub> ; Reduced/Zero Boil Off LH <sub>2</sub> )
	14.2	Thermal Control
14.3	Robust Ablative Heat Shield (Beyond Lunar Return)—Thermal Protection System	
	Robust Ablative Heat Shield (Lunar Return)—Thermal Protection Systems	

TABLE 2.—TECHNOLOGIES MAPPED TO ELEMENTS AND DESTINATIONS

OCT TA no.	HAT Technology Development Entry (Title)	Applicable Capability/Element												Destination (simplified from full DRM's)					
		MPCV	SLS	CPS	SEV	SEP	DSH	Lander	EVA	In-Space Robotics	Cargo Handler	Surface Elements	Other	Cis-Lunar	Lunar	NEA	Martian Moons	Mars Landing	
1.2	ORSC Engine Technology		D-note																
1.2	Advanced, Low Cost Engine Technology for SLS		D-note																
2.1	LO <sub>2</sub> /LCH <sub>4</sub> Cryogenic Propulsion System																		
2.1	LO <sub>2</sub> /LCH <sub>4</sub> Reaction Control Engines																		
2.1	Non-Toxic Reaction Control Engines																		
2.2	Electric Propulsion and Power Processing																		
2.3	NTP Engine																		
2.4	Unsettled Cyo Propellant Transfer																		
2.4	In Space Cryogenic Liquid Acquisition																		
3.1	300 kW Fission Power for Electric Propulsion																		
3.1	High Strength/Stiffness Deployable 10-100 kW Class Solar Arrays																		
3.1	Autonomously Deployable 300 kW In-Space Arrays																		
3.1	Fission Power for Surface Missions																		
3.1	Multi-MWe Nuclear Power for Electric Propulsion																		
3.2	Regenerative Fuel Cell																		
3.2	High Specific Energy Battery																		
3.2	Long Life Battery																		
4.1, 4.5	Precision Landing and Hazard Avoidance																		
4.3	Telerobotic control of robotic systems with time delay																		
4.5	Autonomous Vehicle Systems Management																		
4.5	Common Avionics																		
4.6, 4.2, 4.5	Automated/Auton. Rendez. and Docking, Prox Ops, Target Relative Navigation																		
4.7, 6	Crew Autonomy beyond LEO																		
4.7, 4.4	Robots Working Side-by-Side with Suited Crew																		
5.2	High Data Rate Forward Link (Flight) Communications																		
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6.1	High Reliability Life Support Systems																		
6.2	Deep Space Suit (Block 1)																		
6.2	Lunar Surface Space Suit (Block 2)																		
6.2	Mars Surface Space Suit (Block 3)																		
6.3	Long Duration Spaceflight Medical Care																		

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OCT TA no.	HAT Technology Development Entry (Title)	Applicable Capability/Element											Destination (simplified from full DRM's)						
		MPCV	SLS	CPS	SEV	SEP	DSH	Lander	EVA	In-Space Robotics	Cargo Handler	Surface Elements	Other	Cis-Lunar	Lunar	NEA	Martian Moons	Mars Landing	
6.3	Long-Duration Spaceflight Behavioral Health and Performance																		
6.3	Microgravity Biomedical Counter-Measures for Long Duration Spaceflight																		
6.3	Microgravity Biomedical Counter-Measures—Optimized Exercise Equipment																		
6.3, 6.1	Deep Space Mission Human Factors and Habitability	x																	
6.4, 11	In-Flight Environmental Monitoring	x																	
6.4	Fire Prevention, Detection and Suppression (reduced pressure)	x																	
6.5	Space Radiation Protection—GCR	x																	
6.5	Space Radiation Protection—SPE	x																	
6.5	Space Radiation Shielding—SPE	x																	
7.1	ISRU—Lunar: Oxygen/Water Extraction from Lunar Regolith																		
7.1	ISRU—Mars: Oxygen from Atmosphere and Water Extraction from Soil																		
7.3	Anchoring Techniques and EVA Tools for Microgravity Surface Operations																		
7.3	Suit Port																		
7.3	Surface Mobility																		
7.5, 4.7	Mission Control Automation beyond LEO	x																	
7.5	Dust Mitigation	x																	
9.1, 9.4	EDL Technologies—Mars Exploration Class Missions	x																	
9.1, 9.4	EDL Technologies—Earth Return	x																	
11.2	Advanced Software Development/Tools	x																	
12.1, 12.2, 7.4.2	Structures and Materials for Inflatable Modules																		
12.1, 12.2	Lightweight and Efficient Structures and Materials	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
12.3	Mechanisms for Long Duration, Deep Space Missions	x																	
12.3	Low Temperature Mechanisms																		
13.1	Ground Systems: Low Loss Cryogenic Ground Systems Storage and Transfer																		
13.2	Ground Systems: Corrosion Detection and Control																		
13.3	Ground Systems: Fault Detection, Isolation, and Recovery																		
13.3	Ground Systems: Wiring Fault Detection and Repair																		
14.1	In-Space Cryogenic Propellant Storage (Zero Boil Off LO <sub>2</sub> ; Reduced/Zero Boil Off LH <sub>2</sub> )			D															
14.2	Thermal Control	x																	
14.3	Robust Ablative Heat Shield (Beyond Lunar Return)—Thermal Protection System	D																	
14.3	Robust Ablative Heat Shield (Lunar Return)—Thermal Protection Systems	D																	



## 5.0 Discussion

It is a challenge to identify enabling technologies for missions that are only notionally defined. Primarily this is because “enabling” is defined as “the mission cannot be done without it” but there is much flexibility on how the missions are defined. Conversations can become circular: “Why is this technology needed?” gets answered with “What does this spacecraft or mission need to do?” Or: “This technology isn’t needed because the mission can be done conventionally” is met with “But if this particular technology is available, the mission can be done differently (e.g., less expensively, more robustly, more extensibly).”

Nonetheless, forward progress is possible for many aspects where precursor information is available (for elements like SLS and MPCV) or where the need for a technology is evident regardless of element definition or DRM (e.g., very long duration missions). A particular benefit of the method described in Section 3.0 is that it fosters conversations across organizational boundaries and can lead to creative solutions.

The fidelity of the performance metrics listed in Appendix C varies among the technologies. The application of some technologies have been well studied for specific missions, and so their technical descriptions and performance characteristics are well understood. Examples include deep space suit; fire detection and suppression; nuclear thermal propulsion; and LO<sub>2</sub>/LCH<sub>4</sub> cryogenic propulsion systems. Other technologies are only now being considered because the missions are newly developed. Examples include anchoring techniques and EVA tools for micro-gravity surface operations. Some technologies are discrete and well defined (e.g., high specific energy batteries), some are innovative designs (e.g., suit port), and some are families of technology designs (e.g., surface mobility). These differences are a consequence of the iterative nature of the process—one must start somewhere to create data sets with meaning across broad constituent groups.

The original use of this technology data was as input to the HAT cost models used to assess mission feasibility as described in Section 1.0. The method has also proven useful to introduce new ideas into the mission planning activity as described above, and to focus technology development programs. For instance, NASA’s Advanced Exploration Systems Program looks to the performance metrics generated by this process to ensure that their technology development is addressing the most critical problems (Ref. 10).

The HAT technology development data is also being used as a basis of input into the Office of Chief Technologist’s “Strategic Space Technology Investment Plan.” OCT is consolidating NASA’s technology needs across the Agency’s directorates, and the HAT Technology Development data set is the basis for the Human Exploration and Operations Mission Directorate’s input.

In addition, an analysis tool has been developed to provide a relative comparison of the HAT identified technologies against

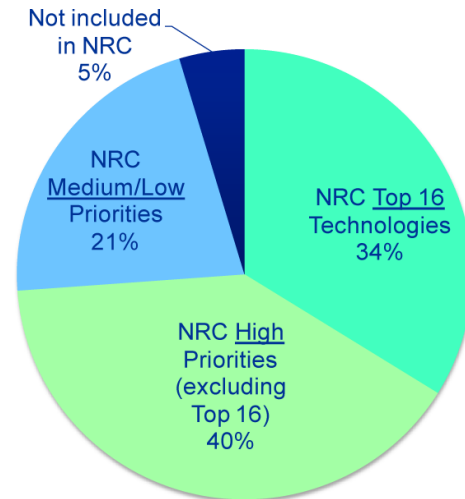


Figure 4.—Correlation between technologies identified as critically important by HAT and high priority technologies identified by the NRC.

selected Figures of Merit (FOM), DRMs, and mission timeframes. Periodically updated HAT technology development data, along with the technology ranking analysis tool, provide HEOMD with the ability to weigh the technology development portfolio as required within the Capability Driven Framework.

This data set also provides a means to clearly communicate NASA’s human exploration technology needs to the NASA field Centers and potential collaborators. This data has been provided to the International Space Exploration Coordination Group, which subsequently adopted the framework for assessing technologies for the Global Exploration Roadmap and future partnerships (Ref. 11). We expect that it will be similarly useful for discussions with other government agencies and industrial and academic organizations. We hope that these dialogs provide new ideas regarding the means and opportunities for future human exploration.

Finally, this technology information has been useful for assessing NASA’s strategic technology roadmaps as they pertain to human exploration. The National Research Council (NRC) recently reviewed those roadmaps and provided prioritization recommendations including “High”, “Medium” and “Low” priority (Ref. 12). They further identified the “Top 16” technologies from the “High” ranked technologies recommending that NASA focus on those in the next 5 yr. The HAT technology listing provides a ready means to compare the NRC’s assessment of critically required technologies to those determined by the NASA human spaceflight community, and to identify errors and/or omissions from both sides. Figure 4 shows the HAT identified technologies mapped to the NRC rankings. Fully one-third of the HAT technologies were among the NRC’s Top 16, and 74 percent were ranked “High.” This indicates excellent agreement between the two communities.

About one-fifth of the HAT technologies were ranked lower than “High” by the NRC. Primarily this occurred because long duration reliability was not a ranking factor for the NRC while HAT placed high importance on this, some HAT technologies are design specific and did not get captured by the NRC process, and the NRC did not consider ground operations to require technology development. The NRC’s “Top 16” listing is shown in Table 3, with those that overlap with the HAT listing shown in bold. Note that in some cases several HAT technologies group to form one NRC technology; for example, the NRC “Fission (Power)” encompasses three HAT technologies: fission power for surfaces, for 300 kW-class electric propulsion systems, and for multi-MW electric propulsion systems.

TABLE 3.—NRC’S “TOP 16” TECHNOLOGIES, WITH HAT HUMAN EXPLORATION FOCUSED CRITICAL TECHNOLOGIES SHOWN IN BOLD.

NRC’s “Top 16” Technologies for NASA
<b>2.2.1 Electric Propulsion</b>
<b>2.2.3 (Nuclear) Thermal Propulsion</b>
<b>3.1.3 Solar Power Generation (Photovoltaic and Thermal)</b>
<b>3.1.5 Fission (Power)</b>
<b>4.2.1 Extreme Terrain Mobility</b>
<b>6.3.2 Long-Duration (Crew) Health</b>
8.1.1 Detectors and Focal Planes
8.1.3 (Instrument and Sensor) Optical Systems
8.2.4 High-Contrast Imaging and Spectroscopy Technologies
8.3.3 In Situ (Instruments and Sensor)
<b>14.1.2 Active Thermal Control of Cryogenic Systems</b>
<b>X.1 Radiation Mitigation for Human Spaceflight</b>
<b>X.2 Lightweight and Multifunctional Materials and Structures</b>
<b>X.3 Environmental Control and Life Support System</b>
<b>X.4 Guidance, Navigation, and Control</b>
<b>X.5 Entry, Descent, and Landing Thermal Protection Systems</b>

The method described in this paper is adaptable and allows for additions and deletions as DRMs evolve. We continue to learn more uses for the data and consider it a rich set of information to guide plans for the next chapter of human spaceflight.

## 6.0 Summary

NASA’s HAT Technology Development Assessment Team has developed a method to identify technologies that will enable the next chapter of human space exploration. This method relies on dialog between system designers and technology developers to determine a minimum but sufficient set of technologies, noting that needs are created by specific mission architecture capabilities, yet specific designs are enabled by technologies.

The list of technologies that have been identified by this process was presented, along with brief descriptions and performance goals for each technology. These performance goals and descriptions may change as future exploration missions become more developed, noting that those missions will be influenced by the availability of these technologies.

In addition to contributing to cost assessments for a variety of design reference missions, this information is being used to foster collaborations with the international community through the ISECG and the Global Exploration Roadmap, to focus technology investments within NASA, and to assess the technology roadmaps being developed within NASA.





## Appendix A.—Acronyms

AAES	Aeroassist, Aerocapture, and Entry Systems	LCH <sub>4</sub>	Liquid Methane
AR	Atmospheric Revitalization	LEE	Latching End Effectors
AU	Astronomical Unit	LEO	Low Earth Orbit
BAC	Broad Area Cooling	LH <sub>2</sub>	Liquid Hydrogen
BPP	Bubble Point Pressure	LLO	Low Lunar Orbit
CDR	Critical Design Review	LO <sub>2</sub>	Liquid Oxygen
CFM	Cryogenic Fluid Management	MCC	Mission Control Center
CH <sub>4</sub>	Methane	MLI	Multilayer Insulation
COTS	Commercial Off the Shelf	MMOD	Micrometeorites and Orbital Debris
CPS	Cryogenic Propulsion Stage	MPCV	Multipurpose Crew Vehicle
CTV	Crew Transport Vehicle (aka MPCV)	NASA	National Aeronautics and Space Administration
CxP	Constellation Program	NEA	Near Earth Asteroid
DDT&E	Design, Development, Test and Evaluation	NEO	Near Earth Object
DRA	Design Reference Architecture	NRC	National Research Council
DRM	Design Reference Mission	NTP	Nuclear Thermal Propulsion
DSH	Deep Space Habitat	OCT	NASA's Office of the Chief Technologist
DSN	Deep Space Network	ORSC	Oxygen-Rich Staged Combustion
ECLS	Environmental Control and Life Support	PDR	Preliminary Design Review
EDL	Entry, Descent, Landing	PLSS	Portable Life Support System
E-M	Earth-Moon	PMAD	Power Management and Distribution
EVA	Extravehicular Activity	PSR	Perennially Shadowed Regions
FDIR	Fault Detection, Fault Isolation, and Recovery	RBO	Reduced Boil Off
GCR	Galactic Cosmic Rays	RCS	Reaction Control System
GEO	Geosynchronous Earth Orbit	REM	Robotics and EVA Module
HAT	Human Space Flight Architecture Team	RF	Radio Frequency
HEFT	Human Exploration Framework Team	RFC	Regenerative Fuel Cell
HEO	High Earth Orbit	RP	Rocket Propellant
HEOMD	NASA's Human Exploration and Operations Mission Directorate	SARJ	Solar Alpha Rotary Joint
HRP	NASA's Human Research Program	SEP	Solar Electric Propulsion stage
HSF	Human Space Flight	STS	Space Transportation System
IMM	Integrated Medical Model	SLOC	Source Line of Code
ISCEG	International Space Exploration Coordination Group	SLS	Space Launch System
ISRU	In-Situ Resource Utilization	SOA	State of the Art
ISS	International Space Station	SRR	Strategic Readiness Review
IV	Intravenous	SPE	Solar Particle Events
IVA	Intravehicular Activity	SSRMS	Space Station Remote Manipulator System
L1	Lagrange Point 1	TA	Technical Area
L2	Lagrange Point 2	TBD	To Be Determined
LAD	Liquid Acquisition Device	TRL	Technology Readiness Level
lbf	Pound-force	TPS	Thermal Protection System
		WR	Water Recovery
		ZBO	Zero Boil Off



## Appendix B.—Technology Description Format

The following information was collected for each technology listed in Table 1.

- **Title:** Brief descriptive title of the technology development
- **Discipline:** HAT categorization of the technology (e.g., Chemical Propulsion, Advanced Propulsion, etc.)
- **OCT TA no.:** Cross reference to the NASA OCT Technology Breakdown Structure
- **Version/Date:** Used for tracking revisions
- **Description:** Explanation as to the what and why a specific technology development is required
- **Performance characteristics:** Details on what advancements beyond the current SOA is required, including metrics where known/applicable
- **Applicability to Capabilities/Elements; Destinations/Con-Ops:** Identifies what Architecture Elements and DRMs are applicable to the technology entry. “Driving” indicates a technology required (i.e., technology pull) by a capability/element, (per element overview) and/or destination/con-op (per DRM), and “Beneficiary” similarly indicates those that benefit from the technology if available and matured/advanced to a sufficient degree (e.g., technology push)
- **Current TRL:** Estimate of the current technology readiness level.
- **ISS Demonstration:** Identifies International Space Station utilization for technology demonstration of the applicable technology entry (‘Planned’ = integral to the technology development plan; ‘Candidate’ = potential ISS utilization; ‘None’ = no ISS utilization identified).
- **Cost to infuse into standard DDT&E cycle:** Cost and time estimate for the technology development. The monies and time typically required for advancing the technology to TRL 6, at which time a standard DDT&E production process would integrate the technology into the flight assembly/system. Additional information is also provided on how the cost/time estimate was determined, and also any significant demonstrations included in the cost are listed.
- **Cost Fidelity:** A 5x5 matrix tool used to help understand the fidelity of the cost estimate. The two axes are “How well do we know what is required?” and “How well defined is the plan?” Requirement definition ranges from 1 (very poorly understood) to 5 (well known), and the plan ranges from 1 (little or no plan) to 5 (full, multi-year project plan).
- **Cost Phasing:** An estimate of the profile type to be used by the HAT Cost Assessment Team (Standard Phasing or Level of Effort)
- **Need By Date:** Identifies the Program or Element DDT&E milestone (e.g., reviews such as SRR, PDR, CDR) at which the technology is targeted to be matured to TRL 6 for infusion into the Program or Element.
- **Architecture Elements Mapping:** matrix shows each identified Architecture Element mapped across the full range of technology development entries. A green highlighted field with a “D” indicates that particular technology development is required for that Element (technology pull). An “x” in the matrix represents benefits of the technology developments mapped against the Elements (technology push).
- **Destination/DRM Mapping:** matrix shows each HAT Cycle 2011-C destination DRM’s mapped across the full range of technology development entries. A green highlighted field with a “D” indicates that particular technology development is required for that particular DRM (technology pull). An “x” in the matrix represents benefits of the technology developments mapped against the DRMs (technology push).
- **HAT Technology Development Assessment Team Point of Contact**
- **Subject Matter Expert Point of Contact**
- **Notes:** Any additional information applicable to the technology development entry



## Appendix C.—Technology Descriptions

The following list summarizes the technical description and performance characteristics for each of the technologies listed in Table 1. The other data entries listed in Appendix B are not included in this list. Acronyms are spelled out in Appendix A.

The technologies are grouped according to the technology areas determined by NASA's Office of the Chief Technologist. In some cases a single HAT technology maps to multiple OCT technical areas. Technology Area TA 08 *Science, Instruments, Observatories and Sensor Systems*, and TA 10 *Nanotechnology*, are not used by the HAT.

Note that this summary is still a work in progress, and differences exist in the level of detail provided. Some of these differences are caused by differing levels of fidelity currently existing between the reference missions; others are caused by differing TRL levels of the technology.

This data is based on information collected during 2011 Cycle-C of the HAT process, and is current as of December 8, 2011.

### C.1 TA 01—Launch Propulsion

Enhance existing solid or liquid propulsion technologies by lower development and operations costs, improved performance, availability and increased capability.

#### C.1.1 Oxygen-Rich Staged Combustion (ORSC) Engine Technology

##### *Chemical Propulsion (OCT TA 1.2)*

###### *Description*

- ORSC LO<sub>2</sub>/RP engine supports the Space Launch Systems (SLS) evolution to larger Payloads. ORSC LO<sub>2</sub>/RP engine has significant DDT&E risks associated with closed cycle and high system pressures (combustor/turbomachinery).

###### *Performance Characteristics*

- Improved capability for Hydrocarbon performance +17 percent Isp, +60 percent T/W, -30 percent cost, and -75 percent failure rate over SOA

#### C.1.2 Advanced, Low Cost Engine Technology for SLS

##### *Chemical Propulsion (OCT TA 1.2)*

###### *Description*

- By mitigating the largest contributor to recurring costs, low-cost advancements in near- and far-term engine manufacturing technology would enable exploration systems to meet affordability and sustainability requirements. This includes innovative approaches to metals and non-metals engineering and fabrication that significantly minimize operations and reduce touch labor with minimal to no compromise in material properties (e.g., metal stereo lithography, chemical etching, and advanced welding/joining techniques).

###### *Performance characteristics*

- Subscale demonstration for booster application with full-scale benefits for in-space technology
- Develop and demo technologies to reduce touch labor during manufacture (number of welds, machining, joints, parts, assembly w/o sacrifice to performance)
- Reduce chemical propulsion recurring cost of near-term engines suitable for SLS
- Provide acceptable performance at half the price of currently available systems

### C.2 TA 02—In-Space Propulsion

Advancements in conventional and exotic propulsion systems, improving thrust performance levels, increased payload mass, increased reliability, and lowering mass, volume, operational costs, and system complexity.

#### C.2.1 LO<sub>2</sub>/LCH<sub>4</sub> Cryogenic Propulsion System

##### *Chemical Propulsion (OCT TA 2.1)*

###### *Description*

- An In-Space Stage, powered by a demonstrated workhorse engine, intended for mission applications beyond LEO.
- The oxygen and methane propellant combination has the potential for good engine performance, which can result in lower vehicle mass and greater payload-carrying capability.

###### *Performance characteristics*

- Improved handling and non-toxicity benefit of the LCH<sub>4</sub>/oxygen combination (hours rather than days ground operations)
- Approximately 10 percent specific impulse performance improvement relative to hypergolic systems.

#### C.2.2 LO<sub>2</sub>/LCH<sub>4</sub> Reaction Control Engines

##### *Chemical Propulsion (OCT TA 2.1)*

###### *Description*

- The oxygen and methane (LCH<sub>4</sub>) propellant combination has the potential for greater engine performance, which can result in lower vehicle mass and greater payload-carrying capability.
- Demonstrated performance of a TRL 6 engine including:
  - Specific impulse of 317-s; Impulse bit of 4 lbf-s; 50,000 cycles with a cryogenic valve;
  - Ignition and operation over a range of propellant inlet conditions (liquid/liquid to gas/gas)

###### *Performance characteristics*

- Improved handling and non-toxicity benefit of the LCH<sub>4</sub>/oxygen combination (hours rather than days ground operations).
- Approximately 10 percent specific impulse performance improvement relative to hypergolic systems.

## Non-Toxic Reaction Control Engines

### *Chemical Propulsion (OCT TA 2.1)*

#### *Description*

- Propulsion system technologies for non-toxic or “green” propellants for use in reaction control systems.
- Non-toxic technologies for RCS engines over the thrust range of 25 to 1000 lbf. Propellant options include hypergolic ionic liquids and nitrous oxides monopropellants, both of which can be easily stored in space and on the ground.

#### *Performance characteristics*

- Improved handling and non-toxicity benefit of hours rather than days ground operations.
- Non-toxic bipropellant or monopropellants that have higher specific impulse (greater than hypergolic) and/or high specific impulse density (greater than hypergolic) with better safety and reduced handling risks

### **C.2.3 Electric Propulsion and Power Processing**

#### *Advanced Propulsion (OCT TA 2.2)*

#### *Description*

- Solar electric vehicles are required for the economical transport of equipment from LEO to HEO and crew from HEO to a NEO, as well as cargo from LEO to Mars, because they can significantly reduce the number of heavy lift launches required and can decrease sensitivity to mass growth of other in-space elements. They also increase crew safety by providing multiple engines for more robust off-nominal operations.
- A propulsion system requiring nominally 300 kW of electrical power is required for these missions; likely an array of 30 to 50 kW thrusters will be used. In addition to designing, building, and testing high power thrusters, technology development is required for power processing, power distribution, and propellant storage. Determining the performance of the integrated power and propulsion system is needed to design the subsystems since the required performance represents such a large increase relative to the SOA. Data of interest include the interaction of the thruster plumes with the high-voltage solar array, array degradation from the Van Allen belts, and guidance, navigation and control of the SEP vehicle with large, flexible solar arrays.

#### *Performance characteristics*

- High power (~400 kW power at beginning of life)
- High specific impulse (~2000 s)
- Low mass (< ~45 mt wet mass with mass growth allowance to fit within a 100 mt launch vehicle)

### **C.2.4 Nuclear Thermal Propulsion (NTP) Engine**

#### *Advanced Propulsion (OCT TA 2.3)*

#### *Description*

- Nuclear thermal propulsion (NTP) was identified by NASA’s DRA 5.0 as required for economical transport of crew to Mars because it provides the high thrust and high specific impulse needed to significantly reduce launch mass for the heavy payloads identified (Ref. 13). The NTP system would also reduce the cost of transits to the Moon, E-M L1, NEOs, and orbital missions to Mars and its moons. The NTP system consists of two principal components. The first component is the primary NTP stage that includes the nuclear thermal rocket engines, RCS, avionics, auxiliary power, long duration CFM for the LH<sub>2</sub> propellant and docking capability. The second component is an integrated saddle truss and LH<sub>2</sub> drop tank assembly connecting the NTP stage to the mission payload that provides additional propellant storage for a wide range of mission and payload needs.
- NTP has strong synergy with chemical rocket hardware and can use the same LH<sub>2</sub> tanks in the launch vehicle. It can be developed in a timely manner at reasonable cost and can service both NEOs and Mars with same vehicle components helping to reduce overall cost.

#### *Performance Characteristics*

- High thrust (10’s of klbf)
- High Isp (~900 s) propulsion
- Three 25,000 lbf nuclear thermal rocket engines with either NERVA-derived or ceramic-metallic (cermet) fuel.
- Long duration cryogenic fluid management.

### **C.2.5 Unsettled Cryogenic Propellant Transfer**

#### *Cryogenic Fluid Systems (OCT TA 2.4)*

#### *Description*

- Efficient transfer of cryogenic fluids in-space is required for propellant resupply to a Cryogenic Propulsion Stage (CPS) and/or oxygen resupply to a Deep Space Habitat (DSH) and has direct planetary application to ISRU Surface Systems. The SOA for propellant transfer in cryogenic upper stages requires the use of an ancillary propulsion system to settle the cryogenic propellants at the tank outlets and a helium pressurant system to maintain a constant tank pressure (LO<sub>2</sub> only) during propellant transfer. After engine start up the thrust generated by the propulsion system maintains the propellants at the tank outlet and the LH<sub>2</sub> tank uses an autogenous gaseous hydrogen pressurant system. This is not possible for tank-to-tank transfers; “unsettled” transfer is also beneficial for propellant resupply of large tank-to-propulsion systems.
- A pumped transfer at unsettled conditions and without a liquid acquisition device in the storage requires a two-phase fluid tolerant pump for liquid transfer. A transfer process requires a robust leak-free fluid transfer coupling to mate the storage tank and the propulsion system receiver tank, an efficient transfer line chill down technique to minimize the liquid used to chill down the transfer line and a micro-g gauging concept to verify the

high fill fraction of the propulsion system receiver tank. An automated propellant leak detection system would ensure the safe in-space transfer operation.

- These technologies are also directly applicable to LO<sub>2</sub>/Methane propellant systems.

#### *In-Space Performance Characteristics (< 0.00003 g).*

- Two Phase Fluid Tolerant Transfer pump: operation to a vapor fraction of ~ 0.8 with cryogenic fluids
- Automated Fluid Coupling: leakage < 10-3 sccs gHe after 1000 cycles
- Leak Detection: TBD
- Mass gauging: < 2 percent uncertainty of measurement
- Fill Fraction of propulsion system receiver tank: > 0.9
- Minimum Fluid used to chill transfer lines: <1 percent of transfer line mass

### **C.2.6 In Space Cryogenic Liquid Acquisition**

#### ***Cryogenic Fluid Systems (OCT TA 2.4)***

##### *Description*

- Cryogenic liquid acquisition technology is needed for 1) unsettled tank-to-tank propellant transfer, 2) unsettled tank-to-engine propellant transfer, and 3) propellant transfer into heat exchangers needed to maintain propellant tanks at required temperature and pressure. It is important to transfer only cryogenic liquids for these applications, without transferring ullage gas. Propulsive maneuvers can be used to settle the cryogenics to ensure liquid-only transfer, but this parasitic propellant burn increases system mass, particularly for the frequent transfers needed for the thermodynamic vent system for tank pressure and temperature control.
- In micro- and reduced-gravity, liquid tends to cling to the walls of the tank, making it difficult to sufficiently cover the tank outlet during fluid outflow.
- An in-space liquid acquisition device (LAD) is required to acquire vapor-free liquid from a propellant tank in micro-g. LADs represent the first stage in successful fluid transfer from a tank to a propulsion system (or another tank). LADs rely on surface tension forces to separate liquid and vapor in the tank and capillary flow to maintain communication between liquid and the outlet during expulsion.
- A second system required for in-space liquid acquisition for large propellant storage and long duration missions is an autogenous pressurant system. Helium pressurant supply is impractical for these missions due to the helium mass required and the large launch mass penalty. An alternative to helium pressurization would be to extract a small amount of liquid or two phase fluid and feed it through a heat exchanger to vaporize the liquid and return it to the tank as a pressurant.
- These technologies are directly applicable to LO<sub>2</sub>/CH<sub>4</sub> propellant systems.

- LADs have a proven flight heritage when using higher surface tension storable liquids (e.g., hydrazine), but have not yet been tested in cryogenic liquids (H and O) in low-g environments.

#### *In-Space Performance Characteristics (< 0.00003 g)*

- Ratio of LAD delivery system pressure drop to BPP drop at maximum outflow rate - < 0.75 to 0.5
- Percent of LAD residual LH<sub>2</sub> mass to total tank LH<sub>2</sub> mass (Expulsion efficiency) - < 1 to 3 percent
- Ratio of total autogenous pressurant system mass to the mass of equivalent helium pressurant system - < 0.8 to 1.0

### **C.3 TA 03—Space Power and Energy Storage**

Improvements to lower mass and volume, improve efficiency, enable wide temperature operational range and extreme radiation environment over current SOA space photovoltaic systems, fuel cells, and other electrical energy generation, distribution, and storage technologies.

#### **C.3.1 300 kWe Fission Power for Electric Propulsion**

##### ***Power Systems (OCT TA 3.1)***

##### *Description*

- Fission power systems being developed for surface applications can be used to power electric propulsion vehicles.

##### *Performance characteristics*

- Moderate power, low mass (<30 kg/kWe) power system for Nuclear Electric Propulsion
- 1200 K Li-cooled unfueled reactor, 2 x 340 kWe Brayton power conversion, 500 V power management and distribution

#### **C.3.2 High Strength/Stiffness Deployable 10 to 100 kW Class Solar Arrays**

##### ***Power Systems (OCT TA 3.1)***

##### *Description*

- High power, high voltage, autonomously deployable surface solar arrays in 1/6<sup>th</sup> to 1/3<sup>rd</sup> gravity environments are needed to generate reliable electric power for surface outpost elements over the mission duration. In addition, applications for in-space use with flight elements requires operations during low-g accelerations under propulsion (0.1g). Enabling features include compact stowage, reliable deployment in partial gravity, on an irregular surface and dusty environment, Martian wind load strength, EVA compatibility, dust mitigation to limit photovoltaic power degradation and robust to surface arcing environment (Martian surface triboelectric charging). Few options exist and only at the conceptual level. These include mast deployed vertical, Sun-tracking blanket solar arrays for lunar polar surface mission and horizontally deployed, fixed tent like solar arrays. Solar array panels would employ low mass, flexible panel substrates

populated with advanced photovoltaic cells, like inverted metamorphic triple junction solar cells, with bandgap tuning for the Martian surface solar spectrum substrates.

- These solar arrays would power outpost surface elements (e.g., habs/labs, rovers, ISRU, lander/ascent stages, etc.)
- These solar arrays would power in-flight space elements (e.g., CPS, DSH)

#### *Performance characteristics*

- High power (10-100 kW),
- High voltage (<~200 V)
- Autonomously deployable surface solar arrays in 1/6<sup>th</sup> to 1/3<sup>rd</sup> gravity environments
- Operational under low-g propulsion accelerations (0.1g)

### **C.3.3 Autonomously Deployable 300 kW In-Space Solar Arrays**

#### ***Power Systems (OCT TA 3.1)***

##### *Description*

- High power, high voltage, autonomously deployable solar arrays are required to generate reliable electric power for the SEP Stage over its mission duration. Enabling features include compact stowage, reliable deployment, ~0.1-g deployed strength and robust performance through the mission end-of-life. Leading options include large, dual-wing structures (2 x 200 kW) and modular, sub-wing structures (20 x 20 kW) employing advanced photovoltaic cells on flexible substrates. Fine pointing requirements for concentrator-based arrays may limit functionality for some missions, so both planar and concentrator architectures should be considered.

#### *Performance characteristics*

- High power (~400 kW at beginning of life)
- High voltage (~350 V)
- Low mass and low stowed volume (TBD W/kg and W/m<sup>3</sup>)
- Cost (2X reduction)

### **C.3.4 Fission Power for Surface Missions**

#### ***Power Systems (OCT TA 3.1)***

##### *Description*

- Abundant power for surface missions is enabled by a surface-emplaced fission reactor. The availability of substantial amounts of continuous power provides opportunities for significant science, exploration, and engineering activities on Mars and the Moon.

#### *Performance characteristics*

- 40 kWe Fission Power System (reactor, power conversion, heat rejection, PMAD)
- 900 K reactor, 10 kWe Stirling convertors, 400 K radiators, 400 V PMAD
- 150 kg/kWe for surface missions

### **C.3.5 Multi-MWe Nuclear Power System for Electric Propulsion**

#### ***Power Systems (OCT TA 3.1)***

##### *Description*

- Nuclear power system development for very high power electric propulsion vehicles to deliver cargo and/or crew to Mars. Once built, this system would also reduce the cost of transits to the Moon, E-M L1, NEOs, and the Martian moons.

#### *Performance characteristics*

- High (>1 MWe) power, low mass (<15 kg/kWe) power system for nuclear electric propulsion.
- Flight power system development and qualification

### **C.3.6 Regenerative Fuel Cells**

#### ***Power Systems (OCT TA 3.2)***

##### *Description*

- Long duration energy storage is required for extended surface missions to store solar energy and provide power during low insolation. Applicable to Lunar or Mars surface applications requiring high power and/or long sortie durations.
- RFC system includes a fuel cell and an electrolyzer, each of which can be used independently for power/water generation and H<sub>2</sub>/O<sub>2</sub> generation, respectively. Electrical power can be used for any vehicle. Water and O<sub>2</sub> can be used for life support for crewed vehicles. Also applicable to ISRU.
- Technology development includes reducing the number of ancillary components to increase reliability and operational lifetime, and reduce parasitic power losses, mass, and volume.

#### *Performance characteristics*

- Power generation >10 kWe for 8 hr or more
- Operable with reactants at >2000 psi to reduce tank volume
- Round trip energy conversion efficiency > 50 percent
- Minimize mass (TBD Wh/kg)
- Operational life >10,000 hr

### **C.3.7 High Specific Energy Batteries**

#### ***Power Systems (OCT TA 3.2)***

##### *Description*

- Batteries with very high specific energy and energy density are required to enable untethered EVA missions lasting 8 hr within strict mass and volume limitations. Batteries are expected to provide sufficient power for life support and communications systems, and tools including video and lighting. Advanced batteries are enhancing for every other vehicle.



#### *Performance characteristics*

- Battery-level specific energy > 325 Wh/kg and energy density > 540 Wh/liter
- 8 hr operation per mission over an operating temperature of 10 to 30 °C.
- Nominally 100 cycles and 5 yr calendar life

#### **C.3.8 Long Life Batteries**

##### ***Power Systems (OCT TA 3.2)***

#### *Description*

- Long life and low temperature survivable batteries will enable lunar night survival and operations. Polar Craters Ops will require batteries that can survive a cryogenic thermal environment.

#### *Performance characteristics*

- Battery-level specific energy > 220 Wh/kg and energy density > 410 Wh/liter at a C/10 discharge rate
- Operate at lunar night temperatures for 14 d
- Operate in a perennially shadowed region such as a polar crater

#### **C.4 TA 04—Robotics, Tele-Robotics, and Autonomous Systems**

Improvements in mobility, sensing and perception, manipulation, human-system interfaces, system autonomy are needed. Advancing and standardizing interfaces for autonomous rendezvous and docking capabilities will also be necessary to facilitate complex in-space assembly tasks.

##### **C.4.1 Precision Landing and Hazard Avoidance**

##### ***EDL (OCT TA 4.1, 4.5)***

#### *Description*

- Need autonomous landing and hazard avoidance systems, including terrain relative navigation, that operate in all lighting conditions, including darkness. Autonomous Landing and Hazard Avoidance Technology would enable a first of a kind development for planetary precision landing and hazard avoidance.

#### *Performance characteristics*

- The components and techniques have been simulated and tested to TRL 5 but a full set of integrated field test is needed to show TRL 6 and applicability to future missions
- Need 90-m accuracy at 3- $\sigma$  uncertainty relative to pre-mission identified landing location. Need 0.3 m hazard recognition and avoidance.

##### **C.4.2 Telerobotic Control of Robotic Systems with Time Delay**

##### ***Robotics and Mobility (OCT TA 4.3)***

#### *Description*

- Enable astronauts in vehicle, habitat, or EVA to remotely operate robots at destinations (natural environment and variable time-delay) to collect samples, deploy instruments, etc.
  - IVA SOA = control of robot arm in structured environment with man-made payloads and zero-delay (e.g., ISS crew uses SSRMS to move/position cargo modules).
  - EVA SOA = none (no EVA control of external space robots exists).
- Enable Earth ground control to remotely operate robots in dynamic environments beyond LEO to support crew (e.g., reconnaissance, survey, site prep, follow-up, etc. during sleep periods)
  - Ground control SOA = Single command sequence per day of slow ground robot in static environment without humans (e.g., Mars Exploration Rovers driving few m/d)
- Enable use of robots deployed by precursor mission, race-ahead or crew in mixed ops modes: before—supporting—after crew, ground control and crew, IVA and EVA

#### *Performance characteristics*

- IVA: Advance SOA to enable telerobotics from inside crew vehicle (e.g., approach/orbit NEO)
- Robot functions: detail reconnaissance, sample collection, worksite prep, etc.
  - Time-delay: 5 s (orbit-to-surface) to 5 min (for race-ahead mission architectures)
- EVA: Advance SOA to enable telerobotics from suited crew (in-space or on-surface)
  - Robot functions: mobile camera, materials/payload transport, etc.
  - Time-delay: up to 10 s
- Ground control: Advance SOA to enable telerobotics in dynamic environments (e.g., tumbling NEO)
  - Robot functions: initial reconnaissance, systematic survey, site prep, follow-up, etc.
  - Time-delay: up to 40 min (Earth to Mars orbit round-trip)

##### **C.4.3 Autonomous Vehicle Systems Management**

##### ***Avionics and Software (OCT TA 4.5)***

#### *Description*

- Enables autonomous vehicle management with limited crew effort and little to no ground oversight. This autonomous capability is required to ensure safe vehicle operations and monitoring of complex systems, especially at increased distances from Earth where communications time delays are present.

#### *Performance characteristics*

- Enable on-board vehicle systems management for mission critical functions at destinations with > 3 s time delay
- Enable autonomous nominal operations and FDIR for crewed and uncrewed systems

- Reduce on-board crew time to sustain and manage vehicle by factor of 2x at destinations with > 6 s time delay (see “Crew Autonomy” description)
- Reduce Earth-based mission ops “back room engineering” requirements for *distant* mission support delay (see “Mission Control Automation” description)

#### C.4.4 Common Avionics

##### *Avionics and Software (OCT TA 4.5)*

###### *Description*

- Develop common avionics components such as flight computers, sensors, high performance, environmentally tolerant, interoperable computing and data busses which can be utilized by multiple vehicles. This approach provides support for:
  - Multiple architectures to enable single spares to fulfill multiple electronic functions,
  - Adaptability to system failures,
  - Redundancy by providing adaptable spares, and
  - Multiple interconnection options.

###### *Performance characteristics*

- Exceed 75 percent commonality of avionics components across HAT DRM elements for reusability (on-orbit spares) and supportability
- Enable up to 1/3 of Planning and Analysis software tools (used in MCC “backroom” today) to be run onboard the vehicle
- Reduce power use by 30 percent for same processing power
- Reduce avionics weight by 50 percent for same processing power
- Improve reliability of avionics components, thereby improving crew safety and reducing logistics mass

#### C.4.5 Automated/Autonomous Rendezvous and Docking, Proximity Operations and Target Relative Navigation

##### *AR&D (OCT TA 4.6, 4.2, 4.5)*

###### *Description*

- Maturation of subsystem technologies (relative navigation sensors, GN&C flight software, system managers, and mechanisms) to accomplish autonomous rendezvous and proximity operations for various in-space destinations such as satellite servicing and NEA exploration. The benefit of this technology development is to improve human safety, improve mission performance and flexibility by enabling autonomous rendezvous and proximity operations interactions with complex or uncontrolled planetary bodies.

###### *Performance characteristics*

- System performance driven by the need for autonomous operations; high reliability, rapid missionization, rendezvous with non-cooperative targets with unknown geome-

try, tumbling attitude, and unknown surface features; and mass/power constraints. Rendezvous missions include flybys of destinations without landing or docking. Proximity operations require loiter at destinations with zero relative velocity. Major challenges include the ability to rendezvous and dock in all ranges of lighting, work across near to far range, and achieve a docked state in all cases.

#### C.4.6 Crew Autonomy Beyond LEO

##### *Avionics and Software (OCT TA 4.7, TA 6)*

###### *Description*

- Autonomous Crew Operations (planning, commanding, fault recovery, maintenance) in Beyond LEO missions. Systems and Tools to provide the crew with independence from Earth-based ground operations support. Such crew autonomy is essential to accommodate the ground communication delays and blackouts at distant locations.

###### *Performance characteristics*

- Enable crew nominal operation of vehicle or habitat at destinations with > 6 s time delay to ground
- Enable coordinated ground and crew nominal operations at destinations with > 6 s time delay (See “Mission Control Automation” description)
- Enable crew to detect off nominal situations and put vehicle in safe configuration without ground coordination

#### C.4.7 Robots Working Side-by-Side with Suited Crew

##### *Robotics and Mobility (OCT TA 4.7, 4.4)*

###### *Description*

- Human mission activities can be performed more effectively if robotically assisted. Coordinated efforts between humans and machines/robots can improve the mission risk/productivity trade space.
- The top technical challenges in human-robot interactions are multi-sensor feedback, understanding and expressing intent between humans and robots, and supervised autonomy of dynamic/contact tasks.
- When robots and humans need to work in close proximity, sensing, planning, and autonomous control system for the robots, and overall operational procedures for robots and humans, will have to be designed to ensure human safety around robots.
- The goal is to enable EVA crew and machine interaction without real-time control and support needed from IVA or ground control personnel.

###### *Performance Characteristics*

- Avoid need for IV robot controller Avoid need for IV spotter/checker Avoid dependence on Mission Control
- Create force level safety for proximity operations.
- Create multi-modal human-robot interfaces and autonomy software.

- Create fault tolerant free flyer and EVA positioning technology.
- Create asteroid sampling, processing, manipulation.
- Create asteroid grappling and anchoring technology.

## C.5 TA 05—Communication and Navigation

Technology advancements to enable higher forward and return link communication data rates, improved navigation precision, minimizing latency, reduced mass, power, volume and life-cycle costs.

### C.5.1 High Data Rate Forward Link (Flight) Communications

#### *Communications (OCT TA 5.2)*

##### *Description*

- Combine transmitters on the ground across an array of antennas to produce uplink data rates 3-4 orders of magnitude higher performance than current DSN capabilities.
- Supports uplinked video, imagery and software uploads. Enables spacecraft receiver to receive high data rate with reduction avionics size, weight and power burden to Elements. Leverages navigation improvements in orbit determination accuracy and trajectory management from improved communication link.

##### *Performance characteristics*

- Enable uplink rates: 25-50 Mbps at 1 AU using X-band
- Size and weight reduction: compared to currently achievable receiver: >50 percent
- Leverage navigation improvements in orbit determination accuracy and trajectory management from improved communication link

### C.5.2 High-Rate, Adaptive, Internetworked Proximity Communications

#### *Communications (OCT TA 5.4)*

##### *Description*

- Enable high data rate communications between multiple in-space elements for situational awareness, enable element proximity radios to sense RF conditions and adapt autonomously, enable elements to store, forward, and relay/route information to other elements intelligently and when communications is available, enable element radios to be reprogrammed from ground based on in-situ characterization of the NEO environment. The benefit of this technology development is to improve situational awareness and communications, improving operational efficiency.

##### *Performance characteristics*

- Data rate: >20 Mb/s simultaneously between peers
- Employ multiple frequency/modulation/coding/ power schemes, including low frequency schemes to enable low rate, non-line of sight communication through small NEO's when relay through other elements is not available.

(Max range: < 20 km. Max NEO size for penetration: < 50 m)

- Max storage time: <5 min/Element at 20 Mb/s
- Max routing: <20 destinations and/or elements
- Enable radios to be adapted in frequency of operation, modulation and coding to information as it is discovered about the NEO environment in near real-time. (Near real-time: < 30 min of each NEO characterization performed by in-space elements)

### C.5.3 In-Space Timing and Navigation for Autonomy

#### *Communications (OCT TA 5.4)*

##### *Description*

- Enable elements to perform independent navigation during complex in-space maneuvers, enable precision required for absolute and relative navigation for in-space elements, enable increased element onboard reference timing generation, timekeeping, distribution and inter-element synchronization to eliminate dependence on Earth-based systems. The benefit of this technology development is to improve situational awareness and communications, improving operational efficiency. High-precision timekeeping significantly reduces accumulated navigation error over long periods of time, enabling mission autonomy for long periods of time without synchronization events with ground or other (x-ray, etc.) synchronization.

##### *Performance characteristics*

- Complex maneuvers: navigating amongst multiple in-space elements plus 1-3 NEO objects in dynamic motion in proximity to elements
- Absolute position required for navigation: < 0.4 m. Relative position required for navigation: < 0.4 m
- This requires space-qualified clocks that are 10 to 100 times more stable than existing space qualified clock. (Element timekeeping accuracy required: milliseconds to nanoseconds depending on mission)

### C.5.4 Quad Function Hybrid RF/Optical Comm, Optical Ranging, RF Imaging System

#### *Communications (OCT TA 5.5)*

##### *Description*

- This technology provides the capability to perform four functions with a single system: RF and optical communication, optical ranging and RF imaging. This enables:
  - Reduced avionics size, weight and power burden to Elements through combined RF/Optical capability in a single system.
  - Multiple elements to aggregate communications through a single element to solve spectrum and 'multiple spacecraft located in the same aperture' issues on the Earth side.
  - Reliable high data rate communications between in-space elements and ground regardless of distance

from Earth and availability of assets on the ground-side, to conserve element power whenever possible,

- Simplified tracking of terminal by providing simultaneous RF beacon capability with terminal while optical system is operating.
- This is a recommended technology for missions where both imaging and long-range, high rate communications are required for the mission.

#### *Performance characteristics*

- Power savings during optical mode: < TBD W. Size and weight reduction compared to dual systems: <40 percent
- Optical data rate to 0.5 AU from Earth: >1 Gb/s simultaneous uplink and downlink with ground
- NEO's/NEA's at 0.5 AU distance or greater, including Mars missions

### **C.6 TA 06—Human Health, Life Support, and Habitation Systems**

Improvements in reliability, maintainability, reduced mass and volume, advancements in biomedical counter-measures, and self-sufficiency with minimal logistics needs are essential for long duration spaceflight missions. In addition, advancements in space radiation research are required, including advanced detection and shielding technologies.

#### **C.6.1 Closed-Loop, High Reliability, Life Support Systems**

##### ***Life Support (OCT TA 6.1)***

##### *Description*

- Enhance and develop new, flexible Environmental Control and Life Support (ECLS) process technologies and systems to reliably increase system closure and reduce logistics, enabling autonomous long duration human exploration missions.
- Based on systems analysis and trade studies, targeted functions and technologies may include:
  - Close the Atmosphere Revitalization (AR) loop by furthering O<sub>2</sub> recovery, and reducing logistics. Technologies may include Bosch, methane processing, and solid oxide electrolysis as well as advanced trace contaminant control and filtration.
  - Further closure of the Water Recovery (WR) loop by processing brines. Reduce clothing logistics and enhance crew health by enabling water recovery from laundry and hygiene wastewaters, respectively. May also include purification of water derived from ISRU sources.
  - Processing of solid waste to recover water, reduce volume, and stabilize for long-term storage. Technologies include compaction, drying and mineralization of solid wastes, including trash, feces and solid by-products from AR and WR processes.
  - Opportunities to develop common technologies, processes, and components suitable for multiple vehicle

and mission applications can enhance the overall sustainability of human space exploration.

- Bring technologies to TRL 6 through progressive levels of ground-based integrated testing and ISS flight demonstrations. Perform long duration human in the loop testing to flush out hardware closed-loop issues such as contaminant buildup.
- NOTE: “High Reliability Life Support Systems” is a subset of this technology item.

#### *Performance Characteristics*

- Approach 100 percent closure for water and oxygen. Enable vehicle and mission autonomy through high reliability, significantly reduced consumable mass, and reduced dependency on logistics.  
Meet new vehicle requirements including operation in more extreme cabin environments (reduced pressure [8 psia] and elevated O<sub>2</sub> [≈32 percent]), reclamation of more complex process streams, and planetary protection. High Reliability Life Support Systems

#### ***Life Support (OCT TA 6.1)***

##### *Description*

- Development and validation of open and closed-loop Environmental Control and Life Support Systems (ECLSS), including Atmosphere Revitalization, Water Recovery, Waste Management and Crew Accommodations, focused at improving reliability and reducing logistics over the SOA.
- Base technology selection and development on systems analysis and trade studies. Deliver new gap-filling technologies identified by vehicle elements including common adjustable pressure regulator capable of controlling a range of cabin, suit loop, and EVA suit pressures, low maintenance human waste collector and trash compactor, clothing, washer and dryer.
- Bring technologies to TRL 6 through progressive levels of ground-based integrated testing and targeted flight demonstrations for selected process technologies. Perform long duration testing to address hardware reliability issues.
- Opportunities to develop common technologies, processes, and components suitable for multiple vehicle and mission applications can enhance the overall sustainability of human space exploration

#### *Performance Characteristics*

- Meet or exceed performance over current state of the practice (≈90 percent recovery of water from urine and humidity condensate, and ≈50 percent of O<sub>2</sub> from CO<sub>2</sub>).
- Meet new vehicle element requirements:
  - More robust and reliable common components (e.g., fans, separators, pumps, sensors) to support longer (unmanned) loiter and extended mission durations that withstand the launch/landing loads environments and thermal/dust environments.

- Increased vehicle autonomy, including high reliability, reduced logistics and in-flight reparability;
- More extreme cabin environmental conditions (reduced pressure [8 psia] and elevated O<sub>2</sub> [≈32 percent])
- More complex process streams for recycling (wastewater from trash, hygiene and laundry).

### C.6.2 Deep Space Suit (Block 1)

#### *EVA (OCT TA 6.2)*

##### *Description*

- EVA suit with rear entry capability and crew-cabin pressure matching for compatibility with Suit Port; improved life support systems for increased life, reliability, and flexibility; and improved power-avionics-software to increase crew autonomy and work efficiency.

##### *Performance characteristics*

- Suit—rear entry suit, capable of operations at ~8 psid (SOA is 4.3 psid)
- DSH needs: Dexterous gloves for IVA contingency repairs while the cabin is depressurized.
  - Experience shows that EVA repair inside a cabin is not practical (suits are too bulky), but IVA suited repair *may* be possible, if gloves are flexible enough for fine motor skill work.
- Portable Life Support System (PLSS)
  - Variable set point oxygen regulator provides more flexibility for interfacing with multiple vehicles, the ability to start an EVA at an 8 psid pressure driven by a suit port and then decrease pressure mid-EVA for improved mobility, and treat decompression sickness in the suit (variable between 0 and 9 psid)
  - On-back regenerable CO<sub>2</sub> and humidity control (eliminates consumables)
  - Robust water loop that can handle low quality water, long duration missions, low pressure operations, and bubbles (> 50 EVA life)
- Power-Avionics-Software (PAS)
  - Compatible with high specific energy battery (> 235 kW-hr/kg)
  - Radio that is network capable for missions involving multiple assets (vehicles and suits) and has data rates that support transmitting high definition video (> 10 Mbps)
  - EVA display (either helmet mounted or handheld) that improves upon the 12 character LCD and laminated flip cards used on ISS
  - EVA information system that increases crew autonomy and work efficiency

### C.6.3 Lunar Surface Space Suit (Block 2)

#### *EVA (OCT TA 6.2)*

##### *Description*

- Suit Port-compatible EVA suit for surface destinations with small gravity field and hard vacuum atmosphere (e.g., Lunar surface)

##### *Performance characteristics*

- Assumptions:
  - Block 2 development occurs after Block 1 (deep space suit). Block 1 development is successful and technologies can be transferred to Block 2 as appropriate
  - Pressurized rover concept of operations with suit port
  - Lunar surface or other mission with small gravity field and hard vacuum atmosphere
    - For example, a Mars mission with 1/3 g and low pressure CO<sub>2</sub> atmosphere would require additional development due to environmental constraints
- Technical changes from Block 1 to Block 2
  - Suit: improved lower torso mobility
  - Portable Life Support System (PLSS): upgrade to dust tolerant components (quick disconnects, relief valves, etc.)
  - Power-Avionics-Software: upgrade to dust tolerant electrical connectors, switches, and controls; increase the capabilities of the information system for additional autonomy; take advantage of advances in battery or avionics components as appropriate

### C.6.4 Mars Surface Space Suit (Block 3)

#### *EVA (OCT TA 6.2)*

##### *Description*

- Suit Port-compatible EVA suit for surface destinations with intermediate gravity field (1/3 g) and low pressure atmosphere (Mars)

##### *Performance characteristics*

- Assumes Block 3 development occurs after Block 1 (deep space suit) and Block 2 (surface suit for moons).
- Technical changes from Block 2 to Block 3
  - All EVA systems components have an increased need for decreased mass
  - Suit: additional emphasis on boots, thermal insulation for CO<sub>2</sub> atmosphere
  - Portable Life Support System (PLSS): Evaluate existing technologies for use in CO<sub>2</sub> atmosphere, may need to develop a new PLSS schematic
  - Power-Avionics-Software: increase the capabilities of the information system for additional autonomy (even bigger time delay); take advantage of advances in battery or avionics components as appropriate

### C.6.5 Long Duration Spaceflight Medical Care

#### *Life Sciences/HRP (OCT TA 6.3)*

##### *Description*

- Strong evidence from spaceflight and analogs indicate that medical conditions of different complexity, severity, and emergency will inevitably occur during long-term Exploration missions. Long duration missions (>1 yr) increase the risk of serious medical conditions due to lim-

ited options for return to Earth, no resupply, highly limited mass, volume and some communication delays. Plans for medical care consider the most likely medical conditions, their operational and health consequences and the resources needed for treatment. Plans for the medical system seek to minimize the probability of mission failure or loss of crew.

- HRP's Integrated Medical Model (IMM) simulates medical events during space flight missions and estimates the impact of these events on crew health and mission success. A three-crew, 386 d, asteroid mission simulation with 28, 2-crew EVAs suggests an optimized medical kit having a mass of 62 kg and a volume of 0.15 m<sup>3</sup>. (These figures do not include all of the medical equipment needed for diagnosis).
- The medical system must monitor and treat crewmembers during the mission. The requirements for the medical system are impacted by mission duration; number of EVAs; age and gender of the crew; and crew medical expertise
- The return of biological samples is required to assess human system response to the mission in order to efficiently mitigate risks in future missions.
- Technologies will be tested on ISS and in flight analog environments

#### *Performance characteristics*

- Rapidly evolving technologies in this area will be developed to help select and prepare crew and optimize care during the mission.
- Platforms that integrate multiple diagnostic and therapeutic smart medical devices, focusing on early detection and intervention of high-consequence and remediable conditions, with consideration for dual-use technologies. Capabilities include: diagnostic imaging, oxygen concentrator, ventilator, laboratory analysis (saliva, blood, urine), bone fracture stabilization and healing, medical suction, rapid vascular access, dental care, kidney stone diagnosis and treatment, IV solution preparation and delivery, medical consumables inventory tracking, and medical data management.

### **C.6.6 Long-Duration Spaceflight Behavioral Health and Performance**

#### ***Life Sciences/HRP (OCT TA 6.3)***

##### *Description*

- Behavioral health and interpersonal relations among crewmembers are critical to the success of long duration exploration missions in isolated, confined and extreme environments. Technologies are required for crew selection and composition, training, support, monitoring, and intervention.

##### *Performance characteristics*

- The habitable volume must be large enough and laid out to execute the necessary tasks and to provide a psycho-

logically acceptable space for the long period of confinement.

- Sensory stimulation (e.g., variable lighting, virtual reality) must be augmented to offset the physically and socially monotonous environment.
- Cognitive performance deficits, stress, fatigue, anxiety, depression, behavioral health, task performance, teamwork, and psychosocial performance must be unobtrusively monitored.
- Devices must mitigate the effects of fatigue, circadian misalignment, work-overload.
- Communication tools must offset communication delays ranging from seconds to minutes.

### **C.6.7 Microgravity Biomedical Counter-Measures for Long Duration Spaceflight**

#### ***Life Sciences/HRP (OCT TA 6.3)***

##### *Description*

- Prolonged exposure to weightlessness deconditions bone, muscle, and the cardiovascular system. Other physiological systems (e.g., sensorimotor and immune) are also altered. These changes may cause decrements in both health and performance. Countermeasures must mitigate these changes with limited resources (mass, power, volume).
- A recently discovered health risk, On-Orbit Intracranial Hypertension, would limit missions to 6 months or less. 20 percent of long duration ISS crewmembers have experienced clinical symptoms; some of these changes were temporary and others have been, to date, permanent.

##### *Performance characteristics*

- Assess sensorimotor function within 20 min with a portable hand-held device that also provides rehabilitation.
- Integrate multiple diagnostic and therapeutic smart medical devices, focusing on early detection and intervention of high-consequence and remediable conditions, with one platform.
- Non-invasively measure intracranial pressure
- Worst case solution for On-Orbit Intracranial Hypertension: Artificial gravity would be required.

### **C.6.8 Microgravity Biomedical Counter-Measures—Optimized Exercise Equipment**

#### ***Life Sciences/HRP (OCT TA 6.3)***

##### *Description*

- Exercise equipment is necessary to address muscle atrophy, cardiovascular atrophy, and bone loss associated with long-duration missions in the weightless environment of space.
- Current ISS exercise equipment is too large and heavy to be used on a long duration missions (~1 yr duration): the latest equipment deployed on ISS occupies 3 International Standard Payload Racks.

#### *Performance characteristics*

- Provide integrated aerobic and resistive exercises with a device no larger than 45- by 25- by 25-cm, with a mass of no more than 5.4 kg, requiring no external power, and accommodating a range of motion of at least 1 m.
- Assess the quantity and quality of bone and muscle at multiple times over the course of a long-duration space mission.

### **C.6.9 Deep Space Mission Human Factors and Habitability**

#### ***Life Sciences/HRP (OCT TA 6.3, 6.1)***

##### *Description*

- Human factors technologies are required in design and operations planning to ensure adequate human performance, reduce likelihood of human errors, and increase mission safety.
- Technologies are required in the habitable volumes (e.g., suit, capsule, habitat, exploration vehicle, lander) to provide an adequate food system, and to meet human environmental standards for air, water, and surface contamination.

##### *Performance characteristics*

- Onboard decision support tools assist crew with real-time detection and diagnosis of vehicle and habitat operational anomalies
- In-situ capability to assist the crew with contingency mission planning and development and execution of contingency operational procedures.
- Ground-based decision support tools assist crew with mission operational anomalies with stale telemetry and operationally significant communications delays.
- Reduce food packaging volume (30 percent) and mass (34 percent) so that supplies for one crew member for 1 yr require 440 kg and 1.2 m<sup>3</sup> consistent with food shelf-life requirements, especially for long duration missions.
- An EVA suit injury countermeasures garment protects against injury caused by hard points in the suit and minimize movement of the crewmember within the volume of the suit. The garment protects the arms, legs, and torso.
- The EVA suit supports delivery of nutrition and medication to suited crew
- Microbial and chemical contamination are identified and measured in real-time with minimal resupply

### **C.6.10 In-Flight Environmental Monitoring**

#### ***Life Support (OCT TA 6.4, 11)***

##### *Description*

- Extended duration missions from beyond low Earth orbit will require autonomous capabilities for environmental monitoring to assess the habitation environment and recycled life support consumables and to enable the crew

to anticipate, react, and mitigate any risks to continued human occupancy.

##### *Performance characteristics*

- In-flight analysis capabilities are necessary—Returning samples to Earth for ground analysis will not be feasible for future missions. Environmental habitat problems on ISS are solved by sending air and water samples to Earth for lab analysis, which yields data for diagnosing the problems.
- Rapid detection of hazardous environmental events must be monitored and controlled with high accuracy. Chemical (whether predicted or not) hazards are highest in urgency, followed by microbiological threats, based on rapidity of impact.
- Detect contaminants introduced via surface activities (dust, etc.) and of importance to planetary protection.
- Air Monitoring is well developed the system size should be reduced. Some specific tests for chemicals in water and for microorganisms have been flown, but analysis needs must be specified and developed.

### **C.6.11 Fire Prevention, Detection and Suppression (Reduced Pressure)**

#### ***Life Support (OCT TA 6.4)***

##### *Description*

- For longer duration missions, the habitable atmosphere will likely be at a lower pressure and higher percent O<sub>2</sub> than on STS or ISS increasing the risk of fire. Small crew cabins (e.g., MPCV, SEV) preclude use of some of the current countermeasures such as the Portable Breathing Apparatus. Even with larger cabins (e.g., DSH, Surface Elements), immediate evacuation to Earth is not an available option and the crew is more dependent on replenishment of a fire protection capability than resupply.

##### *Performance characteristics*

- The crew is best protected from a fire hazard by an integrated fire protection strategy including:
  - Accurate definition of the risk from flammable materials in low-g.
    - Identify material flammability limits in low-g ambient environment.
    - Develop/validate non-flammable materials for conditions of use.
- Early fire detection from structurally integrated distributed sensors.
- Emergency breathing apparatus with filtering respirator.
- ECLS-compatible and re-chargeable fire extinguisher.
- ECLS-compatible emergency air purifier
- Contingency air monitor for relevant chemical markers of post-fire cleanup.

### C.6.12 Space Radiation Protection—Galactic Cosmic Rays (GCR)

#### *Life Sciences/HRP (OCT TA 6.5)*

##### *Description*

- Current estimates of crew risk from GCR radiation exposure with long duration (~>1 yr) missions beyond LEO exceed the NASA acceptable career standards for Risk of Exposure Induced Death for fatal cancers. In many cases, the risk estimates (Cancer Risk Projection Model currently under review with National Academy of Science) greatly exceed the acceptable limit.
- Research indicates that mortality risk from radiation induced degenerative disease may further exacerbate the problem. GCR is difficult to shield against due to its high charge and energy, however shielding systems must minimize exposure levels to the maximum extent practical.
- In addition, there are large associated uncertainties in the modeling of the biological damage caused by GCR. These uncertainties limit our ability to accurately evaluate risks and the effectiveness of biological and physical mitigation strategies.

##### *Performance characteristics*

- Technological approaches include: risk quantification and uncertainty reduction through radiobiology research, selection of crew based on individual sensitivity for major risks, new biomedical countermeasures, cost/mass efficient multi-use shield systems, and mission planning away from solar minimum.

### C.6.13 Space Radiation Protection—Solar Particle Events (SPE)

#### *Life Sciences/HRP (OCT TA 6.5)*

##### *Description*

- Shielding from solar particle events (SPEs) is much easier than shielding from GCR and is required to mitigate the risk of early Acute Radiation Syndromes as well as increased risk of late radiation carcinogenesis. Protecting humans from SPEs may be a solvable problem in the near-term through technology maturation of identified shielding solutions, through design and configuration. However, mission operational planning has a major knowledge gap of forecasting the occurrence and magnitude, as well as all clear periods, of SPEs. NASA's radiation exposure standards permit a 3 percent risk of radiation exposure induced death. This standard limits mission durations at solar minimum to 5 to 6 months for males and approximately 3 months for females. At solar maximum, the recommended limits become 154 d for 35-yr old females to 300 d for 55-yr old males.
- Management of the risk of exposure to SPEs requires an overall risk model, SPE forecasting for mission planning, SPE warnings and alerts to change mission planning, shielding options for the crew under different operational

scenarios, in-mission dosimetry readings, and biological countermeasures to mitigate exposures.

##### *Performance characteristics*

- Risk projection models.
- Forecasting/probabilistic models of events and all-clear periods.
- Heliospheric environmental monitoring technology that provides accurate alerts for SPEs.
- Multi-functional SPE shield systems including shelters.
- Active miniaturized dosimetry.
- Acute biological countermeasures.

### C.6.14 Space Radiation Shielding—SPE

#### *Life Sciences/HRP (OCT TA 6.5)*

##### *Description*

- Significant risk to crew, digital equipment, and vehicle systems associated with Solar Particle Events (SPEs).
- Current NASA goals necessitate the need to develop radiation mitigation schema for the next generation of exploration including materials and their integration into vehicle architecture systems.
- Technology development is required to ensure systems are capable of providing structural integrity for architectural element design, while also providing sufficient radiation protection (and potentially others, e.g., thermal, MMOD, etc.) properties to negate any need for the addition of parasitic shield mass.

##### *Performance characteristics*

- Candidate radiation protection materials currently exist but require ground and flight-testing to vet candidates and ensure radiation protection viability and multi-functionality.
- NASA should invest in both ground based testing and flight testing to investigate the feasibility of concepts to protect astronaut crews from the harmful effects of radiation, both in low Earth orbit and while conducting long-term missions away from Earth.

## C.7 TA 07—Human Exploration Destination Systems

Technology advancements with ISRU to produce fuel, O<sub>2</sub>, and other resources, improved mobility systems including surface, off-surface and Extravehicular Activity and Extravehicular Robotics, advanced habitat systems, and advancements in sustainability and supportability technologies.

### C.7.1 Lunar ISRU: Oxygen/Water Extraction From Regolith

#### *ISRU (OCT TA 7.1)*

##### *Description*

- ISRU involves the extraction and processing of local resources, both natural and discarded, into useful prod-



ucts and services. In particular the extraction of oxygen, water, and other volatiles that can be used for life support, propellants, fuel cell power systems, and radiation protection can significantly reduce the mass, cost, and risk of short term and sustained human exploration of the Moon. Lander reusability and in-space propellant depots for Cis-lunar transportation are enabled. The two lunar ISRU products and processes that have the biggest impact on human mission architectures are:

- Oxygen extraction from lunar regolith: This involves excavation of loosely consolidated surface regolith, regolith transfer and handling (size sorting and mineral beneficiation), and chemical/thermal processing to remove oxygen from mineral oxides. The Moon is ~42 percent oxygen by mass. Operations occur in nominal lunar day/night cycle conditions.
- Water and volatile extraction from lunar polar regolith: This involves first locating and characterizing lunar polar ice/volatile deposits, then excavation (down to 1 m possible), regolith transfer and handling (possibly crushing), heating to evolve water and volatiles, and volatile capture and separation. Operations may occur at extremely low temperatures (40 to 100 K).

*Performance characteristics*

- Pilot plant to produce oxygen from lunar regolith; 250 to 500 kg/yr; Extraction efficiency >1 percent oxygen by weight; Mass Payback (break-even point) is <1 yr compared to bringing oxygen from Earth, considering the mass of a complete ISRU system (excavator, plant, power system, and storage system).
- Full Scale plant to produce oxygen from lunar regolith: 1000 to 10,000 kg/yr (depending on crew size and propellant need); Mass Payback (break-even point) is <1 yr compared to bringing oxygen from Earth, considering the mass of a complete ISRU system (excavator, plant, power system, and storage system).
- Water Extraction Plant from polar regolith: TBD. Water usage as well as currently unknown polar water/ice concentration significantly influence metrics.

**C.7.2 Mars ISRU: Oxygen from Atmosphere and Water Extraction from Soil**

**ISRU (OCT TA 7.1)**

*Description*

- ISRU involves the extraction and processing of local resources, both natural and discarded, into useful products and services. In particular the production of oxygen, water, and methane that can be used for life support, propellants, fuel cell power systems, and radiation protection can significantly reduce the mass, cost, and risk of short term and sustained human exploration of Mars. The two Mars ISRU products and processes that have the biggest impact on robotic sample return and human Mars mission architectures are:

- Oxygen production from Mars atmosphere CO<sub>2</sub>: This involves the collection and separation of CO<sub>2</sub> from the 6 to 10 torr Mars atmosphere and processing the CO<sub>2</sub> to extract oxygen. Oxygen can make up >75 percent of propellant mass.
- Oxygen and fuel production from Mars soil water and atmosphere CO<sub>2</sub>: This involves excavation of Mars soil and processing/heating to release water. Water is electrolyzed to make oxygen and hydrogen (for processing). This also involves collection and separation of CO<sub>2</sub> from the 6 to 10 torr Mars atmosphere and processing with hydrogen to make methane (or other hydrocarbon) and water.

*Performance characteristics*

- Atmospheric CO<sub>2</sub> processing; 3.5 kg O<sub>2</sub>/hr and 1 kg CH<sub>4</sub>/hr, 24 hr/d, 300 d. <7 KWe/kg O<sub>2</sub> produced.
- Water extraction from soil: 2 kg H<sub>2</sub>O/hr, 24 hr/d, 300 d. ~40 kg soil/hr excavation and processing. <15 KWe/kg water extracted.

**C.7.3 Anchoring Techniques and EVA Tools for Micro-G Surface Operations**

**EVA (OCT TA 7.3)**

*Description*

- Anchoring/mobility for a NEO mission, Exotic Geology Sample Acquisition, Real time Geology Sample Analysis

*Performance characteristics*

- Anchoring techniques for vehicles and EVA systems are needed for asteroid missions
  - ISS uses well defined interfaces such as hand rails as opposed to unknown rocky surfaces
- The ability to collect geological samples without damaging the sample (minimal heat or stress) or from a location with difficult access (bottom of a crater or top of a cliff) is needed
- Increased ability to analyze the chemical or physical properties of samples collected maximizes the useful data collected and minimizes the need to bring samples back to Earth
- All tool development must consider environmental factors and EVA compatibility (safety, mobility limitations)

**C.7.4 Suit Port**

**EVA (OCT TA 7.3)**

*Description*

- A suit port provides a method of rapidly starting and ending EVAs and provides an increased level of environmental containment of potentially hazardous substances that could be encountered during the EVA.

*Performance characteristics:*

- Reduce airlock operations time from 4 hr pre- and post-EVA to 30 min

- Reduce exposure of habitable volume to dust, particulates, heat transport fluids, propellants, gases such as atmospheric CO<sub>2</sub>, etc.
- Reduce consumable losses from habitable volume by 660 kg over two weeks (assumes multiple EVAs/day)

### C.7.5 Surface Mobility

#### *Robotics and Mobility (OCT TA 7.3)*

##### *Description*

- Surface mobility systems allow for the movement of cargo, instruments and crew on the surface of an object or planetary body. Examples include roving, climbing, crawling, hopping or burrowing into the surface. Systems for moving cargo include prepositioning cargo for future human use, or repositioning payloads for re-use. Instruments can be pointed by mobility systems, or pushed into contact for data collection, approaching simple manipulation by using the mobility system’s transport mechanisms. Crew mobility aids expand crew range, speed and payload capacity while also providing power, habitation and environmental shelter. NASA’s experience with crew mobility on the lunar surface was limited to unpressurized rovers for short stays. NASA now faces new challenges of working on the exteriors of satellites, on asteroid surfaces, on planetary surfaces for long durations, or providing access to lunar craters. Complexities of dust management and human interaction with NEA during extended should also be addressed.

##### *Performance characteristics*

- Microgravity climbing for satellite or asteroid missions
- Precursor roving in soft/steep soils for lunar crater access
- Ballistic crater explorer, fires projectile into crater for data
- Concurrent design of crew rover and SEV for re use
- Mobile landers for repositioning spacecraft on small bodies

### C.7.6 Mission Control Automation Beyond LEO

#### *Avionics and Software (OCT TA 7.5, 4.7)*

##### *Description*

- Support Missions beyond LEO in problem solving activities during remote or long-duration exploration missions, where space crew reliance on mission control is critical and dependent upon minimum reaction time. Advanced decision-support systems are needed in Mission Control to reduce operations costs and to maximize mission safety with Earth-based operators.

##### *Performance characteristics*

- Enable Earth-based nominal operation of vehicle or habitat at destinations with > 6 s round-trip time delay to Earth
- Enable hand-offs in Mission Ops between ground and crew for operations in transit and at destinations with > 6 s round-trip time delay

- Enable Tools to help Flight Controllers resolve off nominal situation after detection and initial response
- Enable highly efficient, small staff Earth-based Mission Control for Beyond LEO Crewed Missions

### C.7.7 Dust Mitigation

#### *Space Environment (OCT TA 7.5)*

##### *Description*

- Technologies are required to address adverse regolith effects in order to reduce life cycle cost and risk, and increase the probability of mission success. Based on Apollo lunar surface experience, there is a risk of regolith induced system degradation. The NEO environment may include suspended “clouds” of particulates, and is in any case an unknown. Particulate mitigation will be accomplished by:
  - Identification of NEO soil contamination issues for mechanisms and thermal systems.
  - Investigate specific risk mitigation technologies (e.g., seals) applicable to NEO missions. Develop technologies to limit regolith contamination, or mitigate its effects.
  - In a relevant environment, integrate and test mechanical component-level technologies to TRL 6.
- NEO simulants are required to develop tools for anchoring, sample acquisition, etc., and Mars simulants are needed to develop ISRU technology.
- Regolith dust self-cleaning radiators needed for surface operations.
- Dust tolerant components or self-cleaning capability is needed for Lunar Surface Space Suits (Block 2).
- Active dust removal technology (SPARCLED) can also be used to acquire small-sized samples from NEOs or dust-sized samples from reduced-gravity bodies.

##### *Performance characteristics*

- Mitigation technologies must:
  - Maintain the solar absorptivity of a dust contaminated radiator surface within +20 percent of the pristine surface value,
  - and
  - Provide negligible dynamic seal wear to 2 million cycles (approx. 6 month life) or 20 million cycles for a 5 yr life.

### C.8 TA 08—Science Instruments, Observatories and Sensors Systems

Not applicable for this report.

### C.9 TA 09—Entry, Descent, and Landing Systems

Human-class capabilities for Mars entry, descent, and landing; technologies advancing low mass high velocity Thermal Protection Systems (TPS), atmospheric drag devices, deep-throttling engines, landing gear, advanced sensing, aero-

breaking, aero-capture, etc. Soft precision landing capability is also needed, e.g., for Moon and NEA's.

### **C.9.1 Entry, Descent and Landing (EDL) Technologies—Mars Exploration Class Missions**

#### **EDL (OCT TA 9.1, 9.2, 9.3, 9.4)**

##### *Description*

- EDL systems for Mars exploration-class missions require large surface payloads. This technology enables reliable and safe delivery of multiple 40 mt payloads to the surface of Mars in order to support human exploration. The benefits of focused EDL technology activities include: increased mass delivery to a planet surface (or deployment altitude), increased planet surface access (both higher elevation and latitudes), increased delivery precision to the planet's surface, increased robustness of landing system to surface hazards, and enhanced safety and probability of mission success for EDL phases of atmospheric flight.

##### *Performance characteristics*

- Aeroassist, Aerocapture, and Entry—AAES are defined as the intra-atmospheric technologies that decelerate a spacecraft from hyperbolic arrival through the hypersonic phase of entry. Options include deployable, inflatable, and mid-L/D vehicles, which need to be actively guided to limit loads and achieve accurate landings.
- Descent—These technology advancements primarily focus on providing greater deceleration in the supersonic and subsonic regimes in a manner that does not reduce landing accuracy or result in transient unsteadiness or loss of performance in the transonic regime. For human-class missions, inflatable and retropropulsion technologies are options.
- Landing—The key areas of technology development are the systems to sense the surface and avoid hazards, descent propulsion motors and plume-surface interaction mitigation, touchdown systems, high-G survivable systems, and small-body guidance. Landed payloads include: Large Robotic Landers (100 to 1500 kg) and Human Class (1500 to 45000 kg)
- Vehicle Systems—EDL systems are by their nature an integrated framework of technologies that necessitate system level validation for robust maturation.
- Modeling and simulation along with atmospheric and surface characterization activities are essential for advancing these technologies.

### **C.9.2 EDL Technologies—Earth Return**

#### **EDL (OCT TA 9.1, 9.2, 9.3)**

##### *Description*

- Earth Return entry, descent and landing systems for Human exploration architecture missions include high-velocity (8 to 14 km/s) Earth entries from beyond LEO—from HEO, NEAs, libration points, the Moon, and Mars.

This technology enables reliable and safe return of crew and/or logistics, and may have reusability requirements. The benefits of focused Earth return technology activities include: human safety during return from missions beyond LEO, lower-mass return capsules, increased landing system robustness, enhanced safety and probability of mission success, architecture flexibility and element reusability, and for robotic missions, sample return reliability and planetary protection. Technology developments must begin immediately in order to enable early exploration architectures. Extensive ground testing and flight tests in Earth's atmosphere will be necessary to meet reliability requirements.

##### *Performance characteristics*

- Aeroassist, Aerocapture, and Entry- AAES are defined as the intra-atmospheric technologies that decelerate a spacecraft from hyperbolic arrival through the hypersonic phase of entry. Ablative materials are an enabling technology needed for high velocity entries (>8 km/s, up to 16 km/s for robotic comet sample return missions), possible aerocaptures for reusability or skip entries for downrange capability, and possible dual heat pulse entries. Keys are low-cost, high-reliability manufacturing and subsystem/system performance modeling and validation.
- Descent—At Earth, these are usually parachutes; systems for this flight regime could have increased requirements due to higher entry velocities. For sample return capsules, inherently stable vehicles without parachutes are preferred to meet the reliability requirements for minimal mass.
- Landing—The key area of technology development is the impact attenuation system; some large-system progress has been made through Orion (sample return capsules will likely have different requirements)
- Vehicle Systems—EDL systems are by their nature an integrated framework of technologies that necessitate system level validation for robust maturation.
- Modeling and simulation are essential for quantifying the reliability of these systems.

### **C.10 TA 10—Nanotechnology**

Not applicable for this report.

### **C.11 TA 11—Modeling, Simulation, Information Technology and Processing**

Advancements in technologies associated with flight and ground computing, integrated s/w and h/w modeling systems, simulation and information processing.

#### **C.11.1 Advanced Software Development/Tools**

##### ***Avionics and Software (OCT TA 11.2)***

##### *Description*

- Reliable software engineering tools and technologies to ensure system reliability and reduce software costs (and hence system and mission costs).

### *Performance Characteristics*

- Increase software design productivity and reduce lifecycle software DDT&E and maintenance costs, greatly lowering cost/SLOC (source line of code)
  - Qualification of model-based software development methods
  - Dynamic certification/recertification of software developed through model-based and other highly automated methods
  - Software system infrastructure to leverage multi-core avionics
  - Reusable software platforms suitable for human-rated spaceflight
- Ensure on-board software reliability for long-duration human missions with light-time delay
- Enable verification of advanced software-based functions for: crew autonomy, autonomous systems, vehicle systems health management, and situational awareness capabilities

## **C.12 TA 12—Materials, Structures, Mechanical Systems and Manufacturing**

Technology advancements for lightweight structures providing radiation protection, multifunctional structural design and innovative manufacturing. In addition, new technologies associated with reducing design, manufacturing, certification and life-cycle costs.

### **C.12.1 Structures and Materials for Inflatable Modules**

#### ***Structures/Materials (OCT TA 12.1, 12.2, 7.4.2)***

##### *Description*

- The primary advantage of inflatable/expandable structures is the readily collapsible walls that reduce stowage volume for the launch package, but provide extra volume for living space when expanded. The resulting mass-to-volume ratio for expandable structures can be lower than that for conventional hard shell structures.
- The objective is to develop expandable structures technology for application as pressurized elements such as crew habitats, logistics add-ons, and airlocks. The goal is to develop expandable technology for increased deployed-habitable volume for minimal packing volume, with improved confidence in structural and thermal performance in the space environment.

##### *Performance characteristics*

- Long-term creep performance characterization of the structural shell of the inflatable module
- Inflatable Structure Restraint Layer damage tolerance (predictive modeling validated with testing).
- Multi-layer insulation performance degradation prediction after folding/deployment (predictive modeling validated with testing).
- Bladder material selection.

- Bladder-to-metal interface seal.
- Predictive modeling of deployment dynamics.

### **C.12.2 Lightweight and Efficient Structures and Materials**

#### ***Structures/Materials (OCT TA 12.1, 12.2)***

##### *Description*

- Efficient Structures and Materials that demonstrate significant weight and cost savings for aerospace applications to provide a total systems based efficiency. This includes multifunctional, lightweight and robust (i.e., inspectable, repairable, damage tolerant, etc.) structures and materials specifically tailored for mission applications.
- Emerging Innovations in Manufacturing Technology that offer significant improvement over SOA, critical to achieving the destination, performance, and affordability objectives for exploration
- Design and Certification Methods to ensure timely introduction of advanced, multifunctional structures and materials into future reliable space systems
  - Damage models for reliability (certification and sustainment)
  - Optimized analysis and test for verification and validation
  - Streamlined Design-Analysis-Certification processes
  - Rapid material properties development

##### *Performance Characteristics*

- Lightweight structures and materials optimization to realize structural system dry mass savings (minimum of 20 to 25 percent) and operational cost savings.
- Multifunctional structures that offer improvements in radiation protection, MMOD shielding, thermal management, structural health management, and system damping benefits over conventional structures. Includes composite and metallic materials.

### **C.12.3 Mechanisms for Long Duration, Deep Space Missions**

#### ***Mechanical Systems (OCT TA 12.3)***

##### *Description*

- Recent high impact, infant mortality and pre-mature hardware failures aboard the ISS (e.g., SARJ, Urine Processor bearings, Ammonia cooling pump, Canada Arm LEE, etc.) accentuate the need for tribological and mechanical component innovations to enable future HSF missions. Reliable, long-life, mission critical systems such as cooling pumps, circulators and components for Zero Boil-Off systems, control moment gyros, robotic manipulation hardware, docking/hatch devices and pointing mechanisms must be more resilient and capable than current COTS technology allows. New lubricants, bearing and gear materials and designs are needed to ensure mission success.

- Emerging lightweight superelastic materials (Nitinol alloys), advanced lubricants (ionic fluids), and novel mechanism designs (low sliding high contact ratio gears) are poised to help avoid mission ending/crippling mechanism failures but must be matured. Such innovations will enable silent, ultra-reliable spacecraft systems such as cabin blower motors and fans, thermal management pumps, etc. Innovative power transfer technologies (magnetic gears) can significantly reduce cabin noise levels enhancing astronaut health and operational efficiency over long duration missions.

#### *Performance Characteristics*

- Mission critical systems (e.g., cooling pumps, circulators, control moment gyros):
  - Current SOA: <10yr, sustain 6 g loads (designs must be 2X mission life and 2X Shuttle launch load)
  - Goal: >10 yr at + or -50 °C from operating temperature sustaining 10 g loads (2X mission life, 2X launch load of 5g's)
- Bearing and Gear Materials to handle higher loads:
  - Current SOA: steel
  - Goal: 15 percent weight reduction with comparable capability (superelastic materials)

#### **C.12.4 Low Temperature Mechanisms**

##### *Mechanical Systems (OCT TA 12.3)*

#### *Description*

- Future deep space missions will demand of the mechanical system technologies both safety and reliability over long durations, and in extremely challenging environments such as cryogenic temperatures and ultra-high vacuum. Long life, cryogenic actuators are a key technology challenge, and enabling for outer planet and deep space probe missions. Long-life-by-design, modular (for ease of integration) actuators consisting of motors, gearboxes, position/speed sensors, and motor controller electronics will need to be capable of operating in dusty NEO or lunar environments at temperatures between 400 and 40 K, for years, in order to meet those reliability demands.

#### *Performance characteristics*

- Current SOA calls for heating to keep liquid lubricated actuators above -55 to -70 °C, with control electronics housed separately in a “warm electronics box” above -55 °C. Cryogenic compatible actuator components (lubricants, bearings, gears, position sensor) and control electronics operational to -230 °C allow integration of the motor controller with the actuator, greatly enhancing reliability, modularity and scalability. Cryo-compatible actuators/electronics would eliminate the hardware and wiring for heating (with ~30 percent power savings), and reduce by two orders of magnitude the interconnect cables, resulting in up to 50 percent reduction in mass of the electronics and electronic housings.

#### **C.13 TA 13—Ground and Launch Systems Processing**

Technologies to optimize the life-cycle operational costs, increase reliability and mission availability, improve mission safety, reduce mission risk, *and reduce* environmental impacts (i.e., green technologies).

##### **C.13.1 Low Loss Cryogenic Ground Systems Storage and Transfer**

##### *Ground Ops/Systems (OCT TA 13.1)*

#### *Description*

- Reducing the cost of ground operations is important to reduce the life cycle costs of exploration.
- Thermal inefficiencies in cryogenic storage and transfer systems increase vehicle safety risk, drive costly commodity boil off losses, and limit the distance over which these commodities can be transferred.
- Lower life cycle costs, increase supply capacity/launch availability, reduce propellant losses with zero boil off, zero loss chilldown, propellant conditioning/densification systems; reduce large volume consumption of helium (nonrenewable, finite resource)
- Examples include approaches for insulation systems materials/structures, active refrigeration (cryocoolers), high-efficiency fluid conditioning, recovery, purification, and reliquefaction systems, in-situ measurements to reduce/eliminate He over-purging

#### *Performance characteristics*

- Percent fluid loss, SOA: 50 percent of propellants lost per launch/test
  - Active refrigeration systems target: zero boil-off storage in tank, reliquefaction of vapors lost in transfer line chilldown, recovery of losses. Goal: eliminate boiloff, recover 75 percent of losses.
  - Insulation systems target is 40 percent reduction in convective/radiative heat transfer (storage tank materials) and 25 percent reduction in conductive heat transfer (load supporting insulation for supports and penetrations). Goal: < 10 percent losses
- Reduce overall He usage by at least 50 percent compared to current Shuttle purge operations

##### **C.13.2 Corrosion Detection and Control for Ground Systems**

##### *Ground Ops/Systems (OCT TA 13.2)*

#### *Description*

- Preclude the severe degradation of structures from corrosion to lower maintenance/inspection costs, reduce corrosion-related damage/structural failures, mitigate environmental impacts, and prevent liberation of material from flame trench during launch

- Examples include approaches for environmentally friendly corrosion protective coatings and corrosion resistant flame trench refractory materials

*Performance characteristics*

- Percent of occurrences of hidden corrosion identified, SOA: Visual detection of rust on surfaces and/or structural failures, no detection of hidden corrosion. Goal: Identify 90 percent of occurrences of hidden corrosion with damage responsive coatings
- Number of launch exposures the refractory material can withstand before damage occurs and repairs are necessary, SOA: 0 launch exposures without damage. Goal: 10 launch exposures

**C.13.3 Fault Detection, Isolation, and Recovery for Ground Systems**

***Ground Ops/Systems (OCT TA 13.3)***

*Description*

- Currently, ground and launch systems design strategies and operations concepts depend heavily on the use of redundant systems and elimination of single points of failure to help ensure system reliability and availability
- Lack of insight into the system's health and status requires a high level of redundancy
- Minimize the dependence on humans to isolate failures and diagnose problems, identify fault propagation paths and speed the identification and isolation of suspected or failed components, decrease the time to maintain, test, and repair systems
- Examples include approaches for functional fault modeling of the ground systems; intelligent devices that can self-detect and identify faults, failures or anomalous reporting; fault isolation and diagnostics to reduce troubleshooting time; automated recovery of select failures; and prognostics of subsystem/component performance leading to condition based maintenance

*Performance characteristics*

- Preventing launch scrub costs due to technical failures. Goal: reduce 50 percent of technical issues using detection, isolation, problem resolution
- Calibration and maintenance of transducers. Goal: extending calibration cycles (through the use of prognostics and anomaly detection)  $\geq 1$  yr

**C.13.4 Wiring Fault Detection and Repair for Ground Systems**

***Ground Ops/Systems (OCT TA 13.3)***

*Description*

- SOA wiring constructions and manufacturing have remained essentially unchanged for decades

- Wiring insulation tends to crack and fray as it ages, is susceptible to maintenance-related damage during ground processing
- Wiring failures have caused significant delays/costs for Shuttle and catastrophic system failures in other spacecraft/aircraft
- Reduce labor and ground processing costs for investigation, troubleshooting, repair of wiring failures, invasiveness, unnecessary removal of structures and equipment, occurrences of wire insulation damage and potential system failures
- Reduce exploration program risk (loss of crew due to system failures) and life cycle costs (for logistics re-supply)
- Examples include approaches for in-situ monitoring/detection systems to locate wiring failures/intermittent faults and predict remaining useful life; reconfigurable components, rerouting and self-healing systems to isolate and repair a wire once damaged

*Performance characteristics*

- Detect potential or actual wiring problems, SOA: limited detection capability for intermittent failures cannot be used on 'live' wires. Goal: Conductive polymer with  $< 50$  ohms resistance; thermally stable above  $260$  °C; no delamination upon bending; near  $1000$  S/cm conductivity; and increases wire weight by  $< 10$  percent with added detection capability. Goal: detects conductor damage that is intermittent on "live" wire networks.

**C.14 TA 14—Thermal Management Systems**

Technology advancement for cryogenic systems performance and efficiency, effective thermal control systems for heat acquisition/transport/rejection, and *increased* robustness and *reduced* maintenance for thermal protection systems.

**C.14.1 In-Space Cryogenic Propellant Storage—Zero Boil Off (ZBO) LO<sub>2</sub> and Reduced/Zero Boil Off (RBO) LH<sub>2</sub>**

***Cryogenic Fluid Systems (OCT TA 14.1)***

*Description*

- Thermal control technologies to extend the in-space and planetary storage of cryogenic propellants include both passive and active thermal control technologies. The former reduce heat input to a propellant tank through a low thermal conductivity support structure and advanced insulation, and the latter intercept the remaining heat with a refrigeration technique such as employing a cryocooler integrated with a broad area cooling (BAC) shield attached to the propellant tank surface or embedded within the tank insulation. These technologies can significantly reduce propellant launch mass, required on-orbit margins and the complexity of vehicle operations.

- LO<sub>2</sub> ZBO in-space storage: uses passive thermal control technology and the integration with an active thermal control system such as a 90 K cryocooler with cooling tubes attached to the walls of the LO<sub>2</sub> storage tank.
- LH<sub>2</sub> RBO in-space storage: uses passive thermal control technology integrated with an active thermal control system such as a 90 K cryocooler integrated with the tank support structure and a BAC shield embedded in the storage tank MLI.
- LH<sub>2</sub> ZBO in-space storage: uses passive thermal control technology such as a cryocooler with two-stages of cooling. The first stage of the cryocooler operating at 90 K and integrated with the tank support structure and a BAC shield embedded in the storage tank MLI and the second stage operating at 20 K and integrated with cooling tubes attached to the walls of the LH<sub>2</sub> storage tank.
- These technologies are directly applicable to LO<sub>2</sub>/LH<sub>2</sub> and LO<sub>2</sub>/CH<sub>4</sub> propellant systems.

#### *In-Space Performance Characteristics*

- LO<sub>2</sub> Storage: Less than 8.0 W of active storage system power per watt of heat removal at 90 K; ZBO for >400 d
- H<sub>2</sub> Storage: Less than 120 W of active storage system power per watt of heat removal at 20 K; ZBO for >400 d
- Cryocooler mass must be less than mass of propellant saved.

### **C.14.2 Thermal Control**

#### ***Thermal Systems (OCT TA 14.2)***

##### *Description*

- All future vehicles (both crewed and uncrewed) will require thermal control systems (TCS)
- Improve thermal control system performance and reliability to reduce mass transportation requirements and enable performance over a wide range of mission requirements.
- Thermal control in day/night with dust mitigation on radiators is critical for continuous ops and survival.
- Technologies that will be required include:
  - TCS fluids and variable heat rejection radiators enabling single-loop TCS architecture
  - Low mass/volume heat exchangers and coldplates
  - Advanced Supplemental Heat Rejection Devices including evaporative heat sinks and fusible heat sinks
  - Solid state devices (thermal electric) and thermal sensors/health monitoring

- Operations in Lunar Perennially Shadowed Regions at Cryogenic Temperatures (40 K)

##### *Performance Characteristics*

- Capable of maintaining system setpoint for large turn-down ratio requirements (12 to 1 kW)
  - Exacerbated by low load in cold environment (~0 K) and high load in hot environment (~220 K)
- Capable of efficient operation in rapidly changing thermal environments and/or transient heat rejection requirements
- Reduces component and system mass

### **C.14.3 Robust Ablative Heat Shield (Beyond Lunar Return Conditions)—Thermal Protection System**

#### ***Structures and Materials (OCT TA 14.3)***

##### *Description*

- A robust, scalable heat shield TPS architecture is required that can be used for multiple missions. Ablative TPS solution for primary MPCV heat shield protection for beyond Lunar return conditions. Improve human safety by detecting critical issues with MPCV TPS or structure prior to entry.

##### *Performance characteristics*

- Ablative TPS Solution for primary CTV heat shield capable of withstanding ~2500 W/cm<sup>2</sup> under 0.8 atm pressure
- Peak heat rate dominated (~90 percent) by shock layer radiation
- Technology needs to enter DDT&E cycle including TPS development, aerothermal and shock layer radiation modeling validation, reliability/margin quantification methodology, integrated system health monitoring, and hyperthermal ground test capability to approximate convective-radiative environment.

### **C.14.4 Robust Ablative Heat Shield (Lunar Return Conditions)—Thermal Protection System**

#### ***Structures and Materials (OCT TA 14.3)***

##### *Description*

- A robust, scalable heat shield TPS architecture is required that can be used for multiple missions. Ablative TPS solution for primary MPCV heat shield protection. Improve human safety by detecting critical issues with MPCV TPS or structure prior to entry.

##### *Performance Characteristic*

- Capable of withstanding ~1000 W/cm<sup>2</sup> (about 33 percent radiation) and ~1 atm pressure

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
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1. REPORT DATE (DD-MM-YYYY) 01-09-2012		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Critical Technology Determination for Future Human Space Flight			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Mercer, Carolyn, R.; Vangen, Scott, D.; Williams-Byrd, Julie, A.; Stecklein, Jonette, M.; Rahman, Shamim, A; Rosenthal, Matthew, E.; Hornyak, David, M.; Alexander, Leslie; Korsmeyer, David, J.; Tu, Eugene, L.; Alfano, David, D.; Kundrot, Craig, E.; Wiley, Dianne, S.; Davison, Stephen, C.; Balint, Tibor, S.			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER WBS 717302.01.04		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-18215-1		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITOR'S ACRONYM(S) NASA		
			11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2012-217670		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category: 01 Available electronically at <a href="http://www.sti.nasa.gov">http://www.sti.nasa.gov</a> This publication is available from the NASA Center for AeroSpace Information, 443-757-5802					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT As the National Aeronautics and Space Administration (NASA) prepares to extend human presence throughout the solar system, technical capabilities must be developed to enable long duration flights to destinations such as near Earth asteroids, Mars, and extended stays on the Moon. As part of the NASA Human Spaceflight Architecture Team, a Technology Development Assessment Team has identified a suite of critical technologies needed to support this broad range of missions. Dialog between mission planners, vehicle developers, and technologists was used to identify a minimum but sufficient set of technologies, noting that needs are created by specific mission architecture requirements, yet specific designs are enabled by technologies. Further consideration was given to the re-use of underlying technologies to cover multiple missions to effectively use scarce resources. This suite of critical technologies is expected to provide the needed base capability to enable a variety of possible destinations and missions. This paper describes the methodology used to provide an architecture-driven technology development assessment ("technology pull"), including technology advancement needs identified by trade studies encompassing a spectrum of flight elements and destination design reference missions.					
15. SUBJECT TERMS Technology assessment					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)
U	U	U	UU	44	STI Help Desk (email:help@sti.nasa.gov) 443-757-5802



