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PREPARING FOR HUMAN EXPLORATION

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Abstract

NASA's Human Exploration and Development of Space (HEDS) Enterprise[1,2] is defining architectures and requirements for human exploration that radically reduce the costs of such missions through the use of advanced technologies, commercial partnerships and innovative systems strategies. In addition, the HEDS Enterprise is collaborating with the Space Science Enterprise to acquire needed early knowledge about Mars and to demonstrate critical technologies via robotic missions. This paper provides an overview of the technological challenges facing NASA as it prepares for human exploration. Emphasis is placed on identifying the key technologies including those which will provide the most return in terms of reducing total mission cost and/or reducing potential risk to the mission crew. Top-level requirements are provided for those critical enabling technology options currently under consideration.

Introduction

Previous studies have identified a wide variety of technologies needed to support the design, development and ultimate implementation of human expeditions beyond low Earth orbit (LEO)[3,4,5]. These technologies span a wide range of needs and technology disciplines which have been focused more or less on specific mission implementations. The current exploration is to identify leading technologies which can radically reduce the cost and risk of human deep space exploration, and to drive out top-level performance requirements for these technologies.

Key technology thrust areas for human exploration are divided into five major categories including: 1) Human Support, 2) Advanced Space Transportation, 3) Advanced Space Power, 4) Information and Automation, and 5) Sensors and Instruments. A broad overview of each of these technology are discussed below. A draft version of human exploration technology goals and requirements have been developed and are currently under review[6].

Human Support

The human support thrust includes research and technology development areas pertaining to the health and human performance of crews in the conduct of deep-space exploration missions[7,8]. Key focus areas for the human support thrust include: Health and Human Performance, Advanced Life Support, Advanced Habitation Systems, and Extra-Vehicular Activity and Mobility.

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Health and Human Performance

A key element of deep-space exploration missions is ensuring human health and safety throughout all mission phases. Key technology efforts within this area include radiation protection research, zero-g countermeasure development, medical care and environmental health, and human factors (see Table 1).[9]

Human exploration missions beyond low-Earth-orbit, namely to Mars, expose the crew to the harsh environment of deep-space for potentially long periods of time. Of particular importance are the health affects of radiation, both solar particle events and galactic cosmic radiation, and long transit times (on the order of six months) to and from planetary destinations. Understanding the effects of this deep space environment on biological systems, as well as developing countermeasure protocols, are essential for reducing the risks to the crew.

Systems that characterize and enable the prediction of solar radiation events would substantially contribute to the health and safety of future explorers. Such systems might involve a range of technologies, including various sensors (e.g., X-ray detectors, visible light imagers and others), predictive software and associated database systems. In conjunction with such general systems, local sensors (e.g., attached to habitats) as well as personal radiation hazard monitors would improve crew safety. Radiation research to understand the impacts to biological systems from the deep-space radiation environment including the interaction of the habitat structures and materials is critical to the HEDS Enterprise.

Sufficient equipment, tools, and techniques must be in place to support the crew's medical care, environmental monitoring, and systems interface needs during the long-duration isolated missions. Emphasis is being placed on determining potential risks, defining acceptable levels of risk, and developing risk mitigation strategies. Risk areas include medical and medical care, psychosocial factors, air and water contamination, and forward and back contamination including methods of control.

Radiobiology
• Characterization of the deep-space radiation
• Beam line ground reasearch (HZE) to simulate GCR exposure and sutides to understand the effects of HZE expousres on biological systems
• Establish carcinogenesis dose response for HZE radiation
• Develop accurate biodosimetry techniques
• Determine individual variation susceptibility to radiation effects
• Determine feasibility of using pharmacological agents to inhibit radiation
• Examine how biological effects vary with shielding thickness and types
• Establish radiation exposure limits for design and operational use
Zero-G Countermeasures
• Short-arm centrifuge
• Ultra-light-weight, multi-axis head and binocular 3-D video eye movement measurement systems
• Angular and linear whole body acceleration devices
• Dynamic visual acuity test
• EVA free-gas phase monitor
• Ambulatory sensors
• Body composition monitor
• Advanced urine collection system
• Telemetry system for non-invasive cardiovascular monitoring
• Phase plane steerable array
Medical Care
• Wearable or implantable sensors
• Blood component storage
• Non-invasive surgery techniques
• Imaging and telemedicine systems
• More autonomous diagnostic, treatment systems
Environmental Health
• Detection and identification of potential Mars mission contaminants
• First alert capabilities
• Rapid microbial detection
• Minaturized, highly reliable systems requiring less crew time and ground support than ISS systems for operations, maintenance, and data interpretation
• Decontamination capabilities
Human Factors
• Diagnostic tools and countermeasures to monitor and maintain crew performance
• Systems to collect and analyze data on flight systems status
• On-board training concepts, techniques, and procedures
• Light-weight, efficient personal hygiene systems
• Food preservation and processing techniques to increase shelf-life and process raw products grown in-situ

Table 1. Summary of Human Health and Performance Technology Needs.

Advanced Life Support

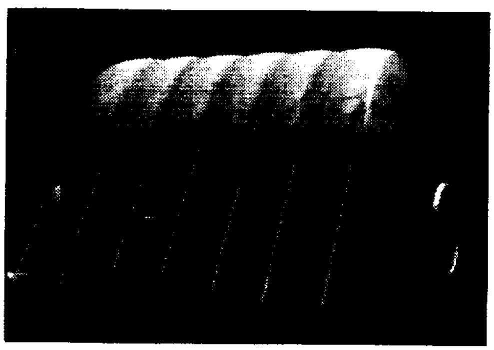
Developing technologies which can significantly reduce the consumables required to support the crew during long-duration is also critical for human exploration. Technologies include air and water loop closure, environment monitoring, solid waste processing, thermal control, and food production.

Advanced sensor technologies to monitor and intelligent systems to control the environmental "health" of the advanced life support system, including air and water, are also needed. Studies have shown that incorporation of advanced biological air and recovery systems can save as much as 25% as compared to previous approaches[10] (Figure 1). Key performance requirements for the advanced life support systems are provided in Table 2.

Advanced Life Support System
• Require essentially no crew time for operations or maintenance
• Provide 99% closure of air and water
• Evolve to provide at least 50% closure of food production for planetary surface crews
• Be capable of utilizing local planetary resources
• Be capable of performing waste processing and recovery of useful resources

Table 2. Summary of Advanced Life Support System Technology Needs.

Advanced Habitation



Structural and materials advancements to provide large livable volumes, both in-transit to and from planetary destination as well as during surface explorations, while minimizing mass are desired for human exploration missions. Advanced inflatable structures which protect the crew from the harsh space environment are actively being pursued.

Key technology thrusts include habitat concepts and emplacement methods (including robotic emplacement), advanced light-weight structures (inflatable versus traditional "hard" shells), and developing integrated radiation protection for crew health and safety. Incorporation of light-weight inflatable structures have been shown to save up to 25% structural mass (Figure 1). Key performance requirements for the advanced habitation systems are provided in Table 3.

Advanced Habitation
• Provide mass savings of at least 40% when compared to conventional designs
• Provide radiation protection withoug significantly increasing habitation system mass
• Be capable of autonomous operations of the integrated systems
• Be capable of performing deployment, assembly, and checkout autonomously and/or robotically

Table 3. Summary of Advanced Habitation Technology Needs.

Extra-Vehicular Activity & Mobility

Advanced technologies which enable routine surface exploration are critical to the HEDS Enterprise. This includes advanced EVA suits and short and long-range surface mobility (rovers) for advanced surface exploration. Systems which provide routine, and continuous surface exploration are key to maximizing mission return.

Key technologies include: advanced materials research which provide enhanced mobility and dexterity while maximizing radiation and puncture protection; low-weight, fast recharge batteries; low-weight efficient thermal control; consumable supply technologies including cryogenic backpacks; humidity control systems; advanced sensors for environmental monitoring including oxygen, carbon-dioxide, nitrogen, temperature, etc.; and advanced avionics such as heads-up displays, communications, and navigation. Key performance requirements for the advanced extra-vehicular activity systems are provided in Table 4.

Advanced Extra-Vehicular Activity
• Weight of the total EVA systems shall be reduced by 40%
• Volume of the portable life support system shall be reduced by 30%
• Be capable of utilizing local planetary resources
• Be robust and capable of protecting the crew from dangers of sharp rocks and objects as well as operating effectively in a dusty environment

Table 4. Summary of Advanced EVA Technology Needs.

During the technology development process, emphasis is being placed on understanding the benefits and leverage of the various options. Benefits can come in the form of risk reduction (to the crew) or through system performance (reduced mass). An example of the performance leverage provided by of some of the human support technologies is shown in Figure 1.

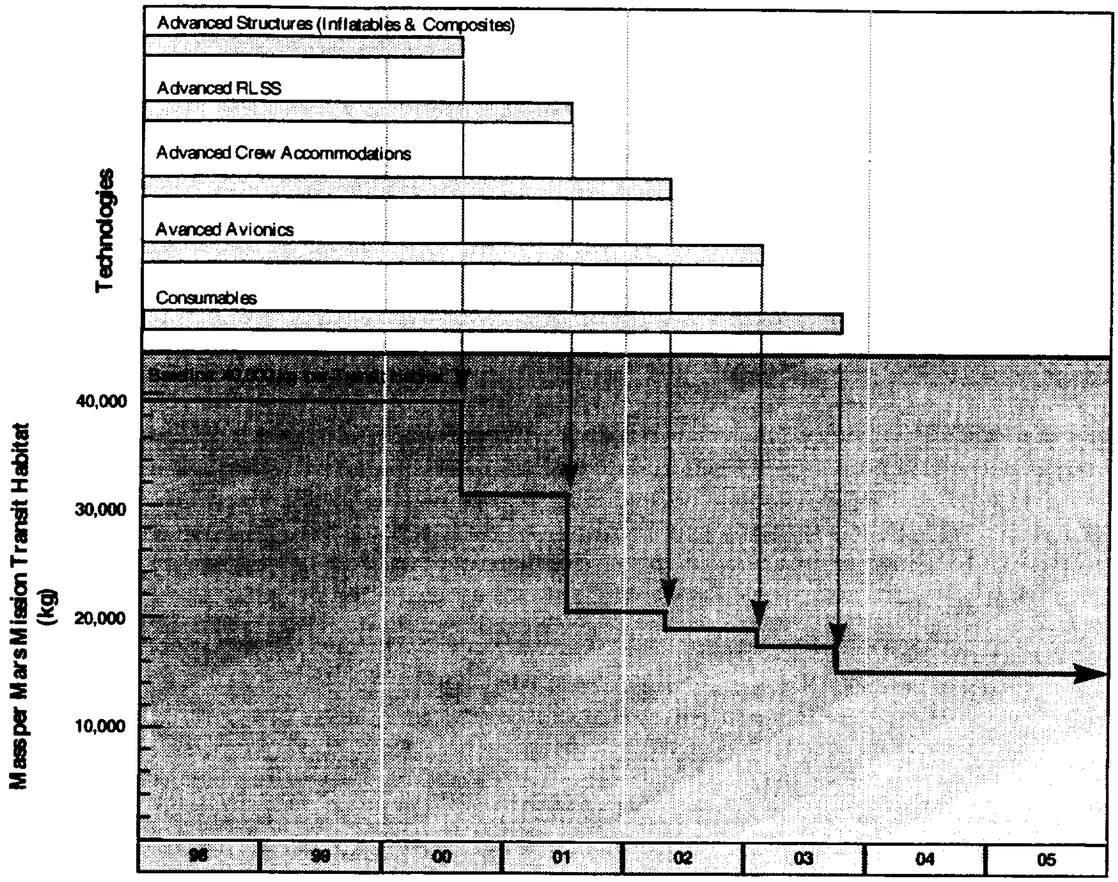
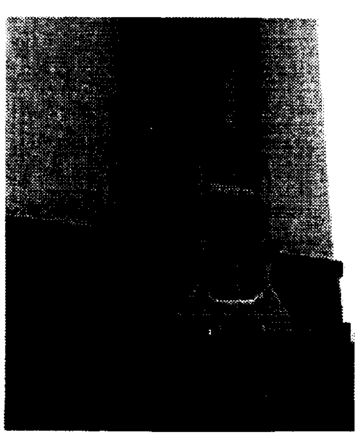


Figure 1. Example Benefits of Human Support Technologies.

Advanced Space Transportation

The advanced space transportation technology thrust includes all technology development areas pertaining to the transportation system architecture and elements of the transportation architecture including propulsion and vehicle concepts to enable routine human exploration. The advanced space transportation technology thrust includes: Affordable Earth-to-Orbit Transportation, Advanced Interplanetary Propulsion, Cryogenic Fluids Management, Aeroassist, and In-Situ Resource Utilization. A summary of the key technology performance requirements for the advanced space transportation thrust is provided in Table 5.

Affordable Earth-to-Orbit Transportation



Advances in the earth-to-orbit launch vehicle technology area focus primarily on reducing the life-cycle costs associated with launching large payloads. Key to this technology area are low-cost technologies which can be scaled to a large launch vehicles. Examples include tanks and structures; propulsion systems; shrouds; upper stages; launch vehicle/payload integration; launch operations; and automated on-orbit assembly and check-out.

Cryogenic Fluid Management

Significant technology advances in long term storage and handling of cryogenic fluids will be required to accomplish human exploration missions. Technologies for low heat leak extremely long duration (years) cryogenic storage vessels; boiloff fluid recapture and reliquification both in-space and on the planetary surface; liquification , transfer and storage of the products of in-situ resource utilization processes; long term pressure control; and fluid mass gauging on both zero and low g environments. Though on a smaller physical scale, many of these technologies are needed to improve/enable future science and Earth observation systems which require cryogenic fluids as coolants or working fluids.

Advanced Interplanetary Propulsion

A key element in achieving low-cost human exploration missions is the efficient and cost effective interplanetary propulsion system. Emphasis is being placed on providing quick trips to and from planetary destinations while at the same time reducing overall system size and mass.

Numerous technology options are currently under investigation including: Solar electric and nuclear electric propulsion, nuclear thermal propulsion, all chemical propulsion, and various hybrid combinations of these systems. Advanced propulsion technologies can reduce total mission mass by as much as 55% A comparison of the performance advantages of the various interplanetary propulsion options, as implemented in the current Mars Design Reference Mission, is shown in Figure 2.

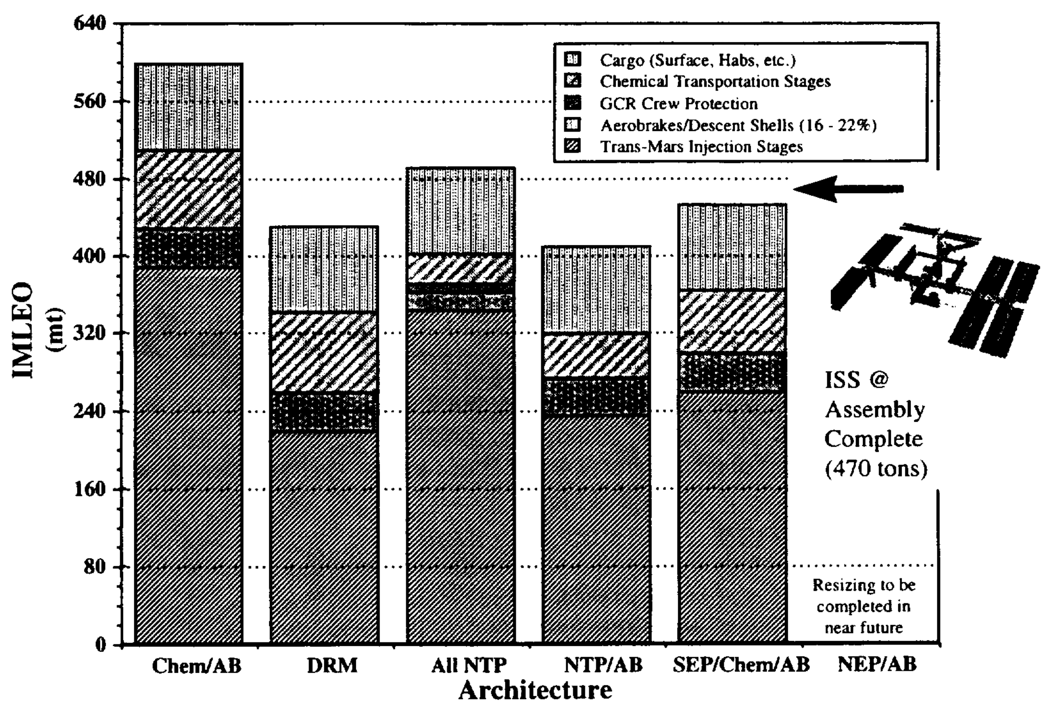


Figure 2. Example Benefits of Advanced Space Transportation Technologies.

Aeroassist

In order to support future human exploration missions, significant advances in aeroassist technologies are required. Utilizing the atmosphere of Mars to decrease the speed of the vehicle and capture it into the orbit of Mars can significantly reduce the overall transportation system mass.

Technology advances in aerothermodynamics; thermal protection systems; guidance, navigation and control; and vehicle design/integration must be accomplished. These technologies provide high leverage in exploration of solar system bodies which have atmospheres (e.g., for human Mars missions aerocapture reduces initial mass in low Earth orbit by as much as 40% when compared with an all chemical propulsion transportation architecture).

ADVANCED SPACE TRANSPORTATION		
Affordable Earth-to-Orbit Transportation		
• ETO system cost goal of delivering payloads to Earth orbit for costs <$1000/pound of payload		
• Deliver on the order of 80 metric tons to Low-Earth-Orbit (28.5° inclination, 407 km altitude)		
• Payload volume on the order of 7-8 m diameter by 28 m length		
Electric Propulsion	High Earth Orbit Departure	Continuous EP Scenario
• Specific Impulse	~2000 seconds	~4000 seconds
• Thruster Power	~50-100 kWe	~250-500 kWe
• Thruster Lifetime	10,000 hours	10,000 hours
Nuclear Thermal Propulsion	Reference Approach	All Propulsive Approach
• Thrust Level	15 klbf/engine	15 klbf/engine
• Specific Impulse	940-960 seconds	940 seconds
• Engine Burn Duration	45-55 minutes total	45-60 minutes total
Aeroassist		
• Transit times shall be no greater than 180 days to and from Mars		
• Aerobrake large volume comparable to a volume 14.9 meters long by 10 meter base		
• Entry speeds up to 8.7 km/sec at Mars		
• Entry speeds up to 14.5 km/sec at Earth return		
• Precision landing at least 1 x 3 km ellipse		
• Be capalbe of supporting external system connections such as power, com., and thermal		
Cryogenic Fluid Management		
• Be capable of storing and maintaining 4-60 metric tons of oxygen, hydrogen, and methane for up to 1700 days in free space		
• Be capable of storing and maintaining 4-30 metric tons of oxygen, hydrogen, and methane for up to 1200 days on the surface of Mars		
In-Situ Resource Utilization		
• ISRU process shall be synergistic with transportation systems, surface power generation, life support systems, and extra-vehicular activity systems		
• Shall be capable of operating autonomously for months/years		
• Propellant production shall provide the following production rates for ascent systems Mars Robotic = 1-2 metric tons Mars Human = 30-40 metric tons		

Table 5. Summary of Advanced Space Transportation Technology Needs.

In-Situ Resource Utilization

Technologies for "living off the land" are needed to support a long-term strategy for solar system exploration. Utilizing available resources for transportation purposes rather than transporting these resources from Earth is the first step in maximizing the use of local planetary resources.

Technologies for capturing and processing planetary resources to produce ascent stage propellants provides significant leverage for the human missions (20% reduction in initial mass in low Earth orbit when compared with an all chemical architecture in which the ascent propellants are transported from Earth). In-situ resource utilization for future robotic missions can have significant effects for larger science sample returns from the surfaces of solar system bodies.

Advanced Space Power

A key focus of the advanced power systems technology thrust is to develop technologies to provide continuous high power at low cost in order to enable robust exploration activities. The advanced space power technology thrust includes: Advanced Power Generation, Energy Storage, and Power Management. In addition, the advanced space power technology thrust includes all functional areas of human exploration including space transportation, stationary surface power, mobile power (rovers), and human portable systems (EVA). A summary of the advanced space power technology needs is provided in Table 6.

Advanced Power Generation

Technologies which provide high continuous power capability are enabling for robust human exploration. High power generation can enable other high leverage technologies, such as in-situ propellant production, which greatly reduce overall system mass and launch costs.

High power generation enables technologies such as electric propulsion and in-situ resource utilization for reduced transportation propellant mass, and highly closed loop life support and plant cultivation for reduced life support consumables mass. Both solar and nuclear power technologies are under consideration. Key technology areas include advanced solar systems with very low specific mass and cost and relatively high radiation resistance; efficient energy conversion systems for radioisotope and nuclear systems; high temperature materials for increasing system efficiency and reducing system mass; and materials compatibility with planetary environments.

Energy Storage

Advances in energy storage techniques are enhancing across a range of HEDS applications and likely enabling for the practical implementation of large solar surface power systems. Potential HEDS applications with significant electrical energy storage requirements include night time energy storage for solar-powered surface systems, temporary emergency power for surface systems and spacecraft, and mobile rovers and spacesuits. Technology options for addressing these needs include chemical energy storage in advanced batteries and fuel cells, mechanical storage via flywheels, and direct storage within electrical capacitors. Generally desirable characteristics of advanced energy storage options include low mass and cost per unit energy storage, and low or nonexistent restrictions on depth of discharge. Additional specific system requirements include a high storage capacity for rover primary propulsion and surface habitat systems with high night-time power requirements, and volumetric compactness for mobile rovers and spacesuits.

Power Management

Advances in lower mass and increased efficiency power management, conditioning, and distribution technologies are necessary to reduce the overall mass of HEDS power systems. Applications span a broad range of potential powers, from kWe's to Mwe's. Specific needs include the development of reconfigurable fault tolerant power networks, and high voltage processing and distribution for surface transmission and electric propulsion systems.

ADVANCED SPACE POWER		
Electric Propulsion Power Needs	High Earth Orbit Departure	Continuous EP Scenario
• Total Power	~500-1000 kWe	~4 Mwe
• Specific Mass	~10 kg/kWe	~7 kg/kWe
• Operating Lifetime	~1-3 year	~3 years
• Radiation Degradation (solar)	<30%	Not applicable
NTP Power Needs (Bi-Modal)	Reference Approach	All Propulsive Approach
• Total Power	15-25 kWe/engine	15-25 kWe/engine
• Power Generation Time	< 1 hour	4-5 years
Surface Stationary Power		
• Capable of providing continuous power for many years (7 years)		
• Provide 100-200 kWe electrical power for surface systems		
Mobile Power		
• Power sources include: dynamic isotope, photovoltaic with regenerative fuel cells, advanced batteries, and internal combustion		
• 10 kWe for pressurized rovers and power carts		
• 4 kWe for unpressurized rovers		
• 50-100 W for EVA suits		

Table 6. Summary of Advanced Space Power Needs.

Information and Automation

The key focus for the information and automation thrust is to enable robust human exploration by providing the crew with highly intelligent and autonomous systems in the presence of a data-rich environment. The information and automation technology thrust includes: Communications and Networks, Intelligent Systems and Advanced Operations, and the Intelligent Synthesis Environment. Technologies that enable autonomous system health maintenance will be essential to low cost operations for exploration missions. These include advances in artificial intelligence, integration of data from multiple sensors and intelligent signal analysis to enable systems to perform self-diagnosis and operational decision-making. Also, technologies that enable increasingly effective modeling, mission analysis and design are needed for various ambitious HEDS missions.

Communications and Networks

Advanced communications and networks includes technologies for providing fast and reliable data acquisition, transmission, and delivery to remote operations sites; high-bandwidth communications; and robust communications capabilities at exploration destinations.

Intelligent Systems & Advanced Operations

Due to the remoteness of exploration destinations, new advanced operations concepts and technologies are required to account for the long time-delay of communications. The intelligent systems and advanced operations thrust focuses on autonomous system operations for remote operations independent of direct earth-based control and includes technologies such as systems health management and performance support systems for both the flight crew and ground operations personnel. In all systems, advances in mission operations technologies are needed, including automated mission design and planning, automated operations, and increased operability in all systems.

Intelligent Synthesis Environment
The intelligent synthesis environment thrust includes technologies associated with the development of a state-of-the-art simulation based system engineering and analysis environment for all phases of development and execution of HEDS missions. The intelligent synthesis environment integrates remote teams in virtual environments including scientists, technology developers, and project engineers, providing for rapid and efficient systems analysis and integration.

Sensors and Instruments

The sensors and instruments technology thrust includes: Science and Engineering Field Labs, Planetary Prospecting, Environmental and Medical Monitoring, and Sample Curation.

Science and Engineering Field Labs
The focus of the science and engineering field labs technology thrust is to develop advanced technologies to enable in-situ analysis of the planetary environment. Included are technology advancements in areas such as organic chemistry and age dating, electron microscopy, chemical and mineral analysis, imaging, and remote sensing.

Environmental and Medical Monitoring
Sensor and instrument development, particularly in the area of miniaturization, calibration, and portability are key for advanced exploration missions. Sensor technology areas include alarm monitors (fire, toxins, radiation), environmental monitors (food, air, water), human health monitors (EVA suit, IVA, routine check-ups), emergency medical systems, telemedicine, and global monitoring and hazard avoidance (e.g. dust storms).

Planetary Prospecting
The focus of the planetary prospecting technology thrust is primarily on planetary environmental characterization and understanding. For instance, site safety and selection, resource identification and mapping, as well as sample acquisition (including drilling to depth) are included here.

Sample Curation
Key sample curation technologies include long-term packaging and preservation, "witness plate" monitoring, hazards and contamination analysis, and on-site caching and archival.

Micro/Nano Technologies
Micro-miniaturization of advanced analytical sensors and instrumentation, including scanning electron microscopy (SEM), scanning tunneling microscopy (STM) and other approaches would greatly enhance the returns from extended human expeditions to other planetary bodies. Similarly, these technology developments could enable significant improvements in the systems used to assure crew health in the presence of toxins, particulate irritants or related hazards. Similarly, miniaturized biotelemetry sensors and systems are needed for human crew monitoring (clinical), as well as portable clinical laboratory diagnostics systems.

Conclusions

The exploration community is continuing to refine and advance the technologies and mission approaches needed to support future human exploration missions. The primary goal of these efforts is to develop mission architectures, including technology options, which can significantly reduce the cost of human exploration. During the technology development planning process, emphasis is being placed on those technologies which can provide the most leverage in terms of risk reduction and cost reduction.

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