National Aeronautics and Space Administration

Technology Frontiers:
Breakthrough Capabilities for Space Exploration

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EXECUTIVE SUMMARY

NASA is transforming the path for space exploration, and the development of innovative and transformational technologies is fundamental to NASA's new direction. This report was conceived with the goal of identifying technology pathways to a robust, flexible space infrastructure to support human exploration through 2050.

Easy Access To Space: cheap, reliable, frequent access to space

Efficient Interplanetary Travel: lightweight, highly-maneuverable, and rapid transportation to and around locations in space

Space Oasis: way stations for resupply, service, assembly, and maintenance on orbit

Healthy, Happy Astronauts: enhancing astronaut well-being with protective, medical, genetic, and behavioral solutions

Super Humans: augmented/enhanced physical and mental capabilities for exploration

Self-Sustaining Habitats: completely closed-loop life support for human environments

Go-Anywhere Roving: vehicles for transportation on planetary bodies allowing unconstrained exploration on, over, and under the surface

Ubiquitous Access To Abundant Power: energy generation, storage, and distribution

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On-Demand Manufacturing: self-replicating machines and autonomous, free-form manufacturing

Environmental Omniscience: pervasive, sensing networks enabling comprehensive awareness of environments and manufactured systems

Everyday Supercomputing: supercomputing capabilities available for routine applications in human exploration of space

Seamless Human-Computer Interaction: virtual, neural, and intelligent interfaces to enable information-rich exploration

Figure ES - 1 Breakthrough Capabilities

Goals

The goal of this study is to provide NASA with a tool to help identify areas of promising technology advancement, which will help to overcome the biggest challenges in human space exploration. Results will inform NASA's long-term technology investment planning as well as identify near and far-term partnership opportunities. Studying these challenges will illuminate likely solutions and potential partners.

This effort is designed as a companion document to an earlier report, *Technology Horizons: Game-Changing Technologies for the Lunar Architecture*. The studies differ in timeline and scope. With the longer timeline of *Technology Frontiers*, and a greater range of possibilities for NASA operations, this study focused more on space-related technologies and used a top-down approach to identify technology concepts.

Process

Under the direction of NASA's Exploration Systems Mission Directorate (ESMD), Directorate Integration Office (DIO), The Tauri Group study team identified the thirteen biggest challenge areas to all types of human exploration of space and envisioned future solutions to these challenges that could be accomplished by 2050. Each of these envisioned future solutions was called a **breakthrough capability**.

The breakthrough capability areas were reviewed and prioritized in an initial workshop with a select group of NASA decision makers, external technology experts, futurists, and technologists on March 19, 2010. The study team then identified technology concepts that could help make the future described in the breakthrough capability possible. The team conducted a very thorough literature review, drawing upon academic publications, conference proceedings, space agency studies, and publications by reputable futurist organizations.

A Breakthrough Capability describes the technological achievements required to overcome significant challenges facing the future of human space exploration.

Figure ES - 2 Breakthrough Capability Definition

Detailed workshops followed, focused on each of the breakthrough capability areas. In May and June of 2010, NASA DIO hosted a series of eight workshops in Washington, D.C., with over 120 subject matter experts from across NASA, industry, and academia. Each of the breakthrough capabilities was reviewed in detail, as were each of the supporting technology concepts.

This report is the culmination of the workshops and research. There is a chapter for each breakthrough capability, with details on all of the supporting technology concepts, information on the technology hurdles faced by each concept, details on the technology trajectory for the capability area, and highlights on potential partnering opportunities.

In addition to the thirteen breakthrough capability areas, nine crosscutting technology areas that touch many or most of the capability areas were also identified. These are addressed in detail in the Crosscutting Technologies chapter.

Breakthrough Capabilities

Below, each breakthrough capability area and their supporting technology concepts are listed, with a list of the Crosscutting technologies following:

Easy Access to Space: Cheap, reliable, and frequent access to space

Systems provide transportation to orbit from planetary surfaces. These systems provide cheap, reliable, and frequent access to space from Earth, the Moon, Mars, and other exploration targets. Breakthroughs in access to space increase total payload mass and enable larger, more complex exploration missions.

Supporting Technology Concepts

- **Skyhook:** Provide access to space through a system of tethers, climbers, and counterweights to lift a payload into orbit.
- **Air-Breathing Access to Space:** Propel launch vehicles using atmospheric gas as reaction mass.

- **Nuclear Rockets:** Heat propellant with nuclear reactors.
- **Beamed Power Launch Vehicles:** Provide energy for propulsion from off-board systems located on the ground or in a stable orbit.
- **Surface Propulsion Systems:** Provide some or most of the energy necessary to reach orbit with ground-based acceleration.
- **New Physics:** May provide breakthrough capabilities that extend well beyond performance of systems based on currently validated physics.

Efficient Interplanetary Travel: Lightweight, highly maneuverable, and rapid transportation to and around locations in space

Systems provide transportation between and around locations in space. New technologies enable flexible interplanetary transportation. Inexpensive, very efficient transportation systems exist to allow for prepositioned cargo. Low-mass, highly-maneuverable, rapid transportation reduces travel time for crew.

Supporting Technology Concepts

- **Nuclear Reactor Propulsion Systems:** Provide power for propulsion with nuclear reactors.
- **Nuclear Pulse Propulsion:** Propulsion with controlled explosions of nuclear fuel.
- **Solar-Powered Propulsion:** Propulsion with power from the Sun.
- **High-Thrust, High-Isp Electric Propulsion Systems**: Provide propulsive force through electrically-powered thrusters.
- **Beamed Power Propulsion:** Provide energy for propulsion from off-board systems.
- **Matter-Antimatter Propulsion:** Use stored antimatter to provide high energy for propulsion.
- **Tethers:** Use momentum exchange tethers to propel payload between orbits.

Space Oasis: Way stations for resupply, service, assembly, and maintenance on orbit

Servicing and assembly stations in space are available for routine, autonomous refueling, assembly, and robotic maintenance of spacecraft. Stations range from small mobile refueling stations to monolithic concepts capable of supporting crew accommodations.

Supporting Technology Concepts

- **In-Orbit Propellant Storage and Transfer:** Storage and transfer of propellants for in-orbit refueling of spacecraft.
- **Autonomous Robotic Assembly:** Robots to autonomously assemble large space structures or spacecraft in orbit.
- **Service and Maintenance Robots:** Robots designed to autonomously inspect, diagnose, and repair spacecraft and structures in-orbit.
- **Swarm Robotics:** The coordination and control of a large number of simple robots that collectively produce complex swarm behaviors.

Healthy, Happy Astronauts: Enhancing astronaut well-being with protective, medical, genetic, and behavioral solutions

Space travel combines technologies and processes that allow for comfortable, safe, and productive travel. The risk of radiation and microgravity are limited; automated first aid technologies manage contingencies; living spaces are comfortable and private; and virtual communications maintain connections to family and friends.

Supporting Technology Concepts

- **Food and Nutrition:** Technologies and techniques for nourishment, satiation, and enjoyment.
- **Anti-Radiation Pharmaceuticals**: Pharmaceutical approaches to mitigating the risks and damage associated with radiation exposure.
- **Meditation Research and Technologies**: Technologies and techniques for mental strength, stamina, focus, and positive social orientation.
- **Virtual Communications and Human Computer Interaction**: Immersive environments to augment communications and increase available experiences.
- **Artificial Gravity:** Applications of centrifugal force to simulate a gravitational environment.
- **DNA and Genomics:** Genetic manipulations to optimize health and prevent disease.
- **Nanomedicine:** Molecular-scale medical interventions.
- **Regenerative Concepts:** Organ and tissue regrowth and revitalization.

Super Humans: Augmented/enhanced physical and mental capabilities for exploration

Techniques and technologies expand the limits of human capabilities; reducing the need for sleep, increasing alertness, and mitigating stress. Building and maintenance can be accomplished manually, with strength-augmenting exo-skeletons.

Supporting Technology Concepts

- **Regenerative Medicine:** Organs can be replaced or regenerated largely using stem cells.
- **Genetic Manipulation:** Can customize human capabilities, for disease resistance, increased strength, and essentially unlimited, long-term opportunities.
- **Anti-Aging:** Includes genetic therapy to slow the aging process and cessation of disease in other areas.
- **Performance Enhancement:** Training, techniques, and medical intervention to increase performance and prevent physical damage.
- **Mammalian Hibernation:** Mimics hibernating mammals to produce a similar sleep process in humans.
- **Physical Interfaces:** External technologies that digitally or biologically interface with humans; includes exo-skeletons and infrared vision.

Self-Sustaining Habitats: Completely closed-loop life support for human environments

Planetary and spacecraft life-support systems within habitats are fully self-sustaining. All required consumables are grown, manufactured, or recycled within the habitat or on the planetary surface, using biological or physicochemical life-support systems as well as in-situ resources.

Supporting Technology Concepts

- **Bioregenerative Life Support:** Life-support systems that use organic components within the system to achieve a safe, self-regulating, chemically balanced environment.
- **Higher Plant Growth Technologies:** Advanced technologies that allow photosynthetic plants to grow in enclosed environments.
- **Carbon Nanotube Membranes for CO_2 Capture:** Membranes created from carbon nanotubes for capturing CO_2. These membranes have an ultra-high permeability, higher selectivity, and better stability than polymer membranes.
- **Synthetic Enzymes for Carbon Capture:** A synthetic analog of carbon anhydrase being developed to capture carbon in harsh environments.
- **Organic Coatings:** Coatings created using natural organisms that have useful characteristics, such as bacteria that produce light or recycle carbon dioxide.
- **Antimicrobial Materials:** Specially designed polymers to capture the molecules bacteria use to signal the start of an infection (quorum sensing). These polymers also limit the bacteria's ability to cluster and form biofilms.
- **Biomimetic Architecture:** In this type of architecture, buildings are no longer inert objects but are living, either operating with or adapting to their environment.
- **Biological Conversion Technologies for Refuse:** Biological processes that use microorganisms to transform refuse into usable products.

Go-Anywhere Roving: Vehicles for transportation on planetary bodies allowing unconstrained exploration on, over, and under the surface

Vehicles and personal mobility systems enable quick, easy, safe, and reliable transportation on planetary bodies. Unconstrained access to surface, atmospheric, and liquid environments increases scientific return and enables sustainable exploration.

Supporting Technology Concepts

- **Shape-Changing Rovers:** Provide access to remote locations that cannot be reached by rigid rovers.
- **Roving Hoppers:** Provide long-distance mobility through suborbital hops.
- **Reconfigurable Robots:** Can dynamically reconfigure to provide new capabilities that address unforeseen challenges.
- **Mobile Ice Probes:** Provide mobility through thick ice sheets and polar ice caps.
- **Mechanical Counter-Pressure Suits:** Increase astronaut mobility while exploring without a rover.
- **Rotorcraft and VTOL Fixed-Wing Vehicles:** Provide atmospheric exploration capabilities with minimal surface infrastructure.

- **Flapping Wing Rovers:** An alternative approach to powered flight for increased lift in rarified atmospheres.
- **Balloons, Montgolfiere-Curie, Airships, and Tumbleweed Rovers:** Inflatable rovers that provide a range of passive and active navigation capabilities for exploration.
- **Boats and Sailboats:** Provide access to rare, but significantly interesting, bodies of liquid.
- **Small Crewed or Uncrewed Submersibles:** Enable exploration under liquid surfaces and liquid environments buried under icy crusts.

Ubiquitous Access to Abundant Power: Energy generation, storage, and distribution

All exploration systems require power. High-power, low-mass power generation systems enable interplanetary travel, life support, and ISRU. Dense energy storage systems increase the capability of rovers, suits, and sensors. Spacecraft and outposts require advanced, lightweight power management and distribution systems.

Supporting Technology Concepts
- **Advanced Nuclear Reactors:** Systems that provide energy through controlled fusion or fission reactions.
- **Antiproton-Driven Fusion:** A type of pulse reactor that uses antiprotons to initiate fusion and provide energy.
- **Multifunctional Photovoltaic Materials:** Photovoltaic materials that provide two or more primary functions.
- **Microradioisotope Power Sources:** Small-scale power systems that capture energy released from radioisotope decay and convert it to electricity.
- **Extraterrestrial Wind or Geothermal Power Plants:** Surface power plants that extract energy from natural process.
- **New Physics:** May provide breakthrough capabilities that extend well beyond performance of systems based on currently validated physics.
- **Power Beaming and Wireless Power Transfer:** Systems that transmit power between two points without a physical connection.
- **High-Temperature Superconducting Wires:** Wires that can transmit electricity without resistance or power loss.
- **Optical Fiber:** Physical links that transmit power as light.
- **Thermal Capacitor:** Energy storage system that stores thermal energy in a physical medium.
- **Matter-Antimatter Reactor:** Energy storage system consisting of an antimatter production plant and a remote matter-antimatter reactor.

Living Off The Land: Using in-situ resources for supporting human exploration or transforming external environments

Astronauts are able to source consumables and building materials from the outpost site location. Oxygen and hydrogen are extracted from surface materials for use in respiration, water, power generation, and propellants. Other materials can be extracted for use in photovoltaics and as structural materials.

Supporting Technology Concepts

- **Autonomous Mining Technologies:** Autonomous machines for mining and processing regolith, including extracting volatiles, breaking down feedstocks into component materials, and sifting for metals and ores.
- **Biomining:** The employment of microorganisms that are naturally capable of or genetically engineered to process raw materials to produce metals, ores, or minerals for use in other applications.
- **In-Situ Solar Cell Production:** The creation of solar cells for power generation using only materials found in situ.
- **Molten Oxide Electrolysis:** A process to extract elements from ores; uses an electric current sent through a molten material.
- **Ecopoiesis:** The initiation of a living, self-sustaining ecosystem in a planetary environment through the initial seeding of microbial life.

On-Demand Manufacturing: Self-replicating machines and autonomous, free-form manufacturing

Autonomous, self-replicating printing machines allow for free-form manufacture of any part or product using different feedstock materials including those mined in-situ. Reconfigurable robots and nanomachines can configure themselves into macro-level systems, such as robotic rovers or haulers.

Supporting Technology Concepts

- **3-D Printers:** Desktop fabricators that create parts through additive layering of feedstock materials.
- **Digital Materials:** A digital manufacturing process that creates a macroscopic product through the alignment of discrete, multimaterial, microscale parts.
- **Programmable Matter:** A functional form of matter where intelligence is built into the materials.
- **Molecular Manufacturing:** A construction technology, referring to the process of building parts and materials from the atomic level upwards and arranging matter with atomic precision.
- **Self-Replicating Robots:** Robots that can create copies of themselves indefinitely. These robots could then autonomously assemble into useful parts, tools, or systems through self-replication.

Environmental Omniscience: Pervasive, sensing networks enabling comprehensive awareness of environments and manufactured systems

Sensors are in all equipment, devices, clothing, structures, and the human body. Sensors are wirelessly networked together, so the data is fused and presented to astronauts and ground controllers automatically. Real-time monitoring of an entire outpost or spacecraft enables many applications, such as integrated systems health management.

Supporting Technology Concepts

- **Smart Dust:** A wireless network of tiny sensors.
- **Self-Powered Sensors:** Draw power from the surrounding environment; also called energy-scavenging sensors.
- **Implantable Biosensors:** Tiny sensors implanted in the human body to measure vital signs.
- **Ubiquitous Computing:** Small, networked information processing devices integrated into all objects used in daily activities.
- **Biomimetic Sensors:** Mimic all or portions of a simulated biological sensing system.

Everyday Supercomputing: Supercomputing capabilities available for routine applications in human exploration of space

Advances in supercomputing technologies provide very high processing power and storage for nearly every device and application. Science and vehicle health monitoring capabilities are greatly increased. Huge amounts of data can be processed without having to send it back to Earth.

Supporting Technology Concepts

- **DNA Computing:** A form of molecular computing using DNA and enzymes for computation.
- **Optical Computing:** Computing with light instead of electricity. The properties of light allow these computers to easily parallel process, making them very fast.
- **Quantum Computing:** Quantum bits (qubits) are used to store information. The quantum property of superposition means that *n* qubits may be 2*n* states simultaneously. This exponential growth could offer virtually unlimited processing power.
- **Molecular and Nano Electronics:** There are several technologies that may replace conventional transistors with equivalents built on the molecular scale. Research areas include Carbon Nanotube Field Effect Transistor (CFET), hybrid mono-molecular electronic circuits, organic molecular electronics, and quantum dots.

Seamless Human-Computer Interaction: Virtual, neural, and intelligent interfaces to enable information-rich exploration

Human-computer interfaces enable crew to view data and control machinery in seamless and intuitive ways. Astronauts and mission control personnel enjoy immediate access to data to inform decision-making processes. Complex tasks are negotiated with ease, and vast amounts of data are processed and digested rapidly.

Supporting Technology Concepts

- **Augmented Reality (AR):** The incorporation of virtual elements into a real environment.

- **Virtual Reality (VR):** The creation of a virtual environment for the user.
- **Simulated Reality:** The creation of a completely immersive virtual environment for the user.
- **Brain Machine Interface (BMI):** Monitors the user's neurons and interprets their signals.
- **Intelligent Interface:** Has some level of intelligence in order to assist the user.

Crosscutting Technologies

Throughout the workshops, interviews, and research that supported this report, technologies were consistently mentioned as potential or even necessary components of multiple breakthrough capabilities. Several technology themes emerged time and again as areas of research that cut across all or most of the breakthrough capabilities. These crosscutting technologies are not capability-specific, but have the potential to dramatically impact each of the breakthrough capabilities. Initial research and development for crosscutting technologies are application agnostic. Consequently, breakthroughs in these technologies could affect many different systems. It is also difficult to anticipate the magnitude of these breakthroughs. However, the overall importance of these technologies is apparent in the range of applications they may support.

- **High-Strength Materials:** Includes metals, ceramics, plastics, fibers, cloth, concrete, glass, glues, or other substances that exhibit characteristics such as high specific strength, toughness, hardness, wear-resistance, and durability.
- **High-Temperature Materials:** Materials used for applications that routinely operate at temperatures above 500 degrees C. For space applications 'high temperature' can refer to temperatures within a nuclear reactor, inside of a plasma chamber, during close approaches to the sun, and other extreme thermal environments.
- **Intelligent Systems and ISHM:** Systems that use learning and decision-making capabilities to adapt their behavior to complex, rapidly-changing environments.
- **Low-Temperature Mechanisms:** Mechanisms that can operate reliably and efficiently at temperatures as low as -230 C.
- **Nanotubes:** Hollow, cylindrical structures with small diameters, on the order of a few nanometers, but can have length-to-diameter ratios of more than one hundred million to one; possess a variety of potentially useful characteristics depending on their molecular structure and composition.
- **Plasma Technologies:** Technologies that manipulate, control, and use the fourth state of matter, ionized gases known as plasmas. Plasmas have unique characteristics that enable primary systems, including propulsion, energy generation, shielding, and sensors.
- **Smart Materials:** Includes several different classes of materials that have controllable reactive properties, including conductivity, tension, or volume, and respond to specific stimuli such as electric or magnetic fields, heat, or light.
- **Synthetic Biology**: A young field characterized by the use of DNA engineering for the creation of novel organisms and technologies.

- **Thermal Management**: Systems that transport thermal energy from areas with excess heat or to areas that require additional heat. With thermal management, damaging or dangerous thermal energy can be mitigated by either removing it or scavenging some portion for usable energy.

Next Steps

This report is designed to keep NASA's technology intelligence current, with an alternating two-year cycle for refreshing and updating the technologies in this and the *Game-Changing* report. Continual technology intelligence is critical for NASA's planning, technology investment, and partnering activities. Understanding the trajectories of near-, mid-, and far-term technologies will enable NASA's exploration missions to go further and achieve more with less resources. These reports support NASA in staying current on the technologies that will enable "*people fanning out across the inner solar system, exploring the Moon, asteroids, and Mars nearly simultaneously in a steady stream of 'firsts.'*"'

INTRODUCTION

Background

NASA is transforming the path for space exploration. In October 2009, the Review of U.S. Human Spaceflight Plans Committee, also known as the Augustine Commission, provided recommendations for the future of NASA's human exploration program. One of the core tenets of these recommendations was to move from developing an architecture for one exploration destination, to enabling multiple exploration destinations through a flexible architecture approach. An outcome of this strategy is the need to invest in technologies that advance exploration regardless of the destination. NASA Administrator, Charles Bolden, and the White House are building on the recommendations from the Augustine Commission to transform human exploration of space. In February of 2010, Administrator Bolden summarized NASA's new direction at the NASA Budget Press Conference:

> *Today we are launching a bold and ambitious new space initiative to enable us to explore new worlds, develop more innovative technologies, foster new industries, increase our understanding of the Earth, expand our presence in the solar system, and inspire the next generation of explorers.…the President has laid out a dynamic plan for NASA to invest in critical and transformative technologies. These will enable our path beyond low Earth orbit through development of new launch and space transportation technologies, nimble construction capabilities on orbit, and new operations capabilities. Imagine trips to Mars that take weeks instead of nearly a year; people fanning out across the inner solar system, exploring the Moon, asteroids, and Mars nearly simultaneously in a steady stream of 'firsts'….*

Development of innovative and transformational technologies is fundamental to NASA's new direction. This report was conceived with the goal of identifying technology pathways to a robust, flexible space infrastructure to support human exploration through 2050. This document seeks to investigate areas of technology breakthroughs that will enable the broadening of the horizon for the future of human exploration.

Goals

The goal of this study is to provide NASA with a tool to help identify areas of promising technology advancement, which will help to overcome the biggest challenges in human space exploration. To achieve NASA's ambitious exploration goals, the nation will need better solutions to deliver systems to orbit, enabling more reliable, more frequent, and less expensive access to space. Vehicles will need to quickly move crew and cargo through space and travel long distances on planetary surfaces with ease. Humans will require better protection from the physical and mental tolls of space travel and tools to increase the efficiency of their exploration time. Exploration agencies will need to reduce the logistics tail of space exploration, increasing the sustainability and self-reliance of space missions. Systems will need to collect more data, make sense of that data, and turn data into knowledge. As always, space exploration will require access to more power to support all of these exploration systems. This study addresses all of these challenges and identifies the most promising technology concepts to solve these challenges over the next 40 years.

The results of this study will inform NASA's long-term technology investment planning, as well as identify near- and far-term partnership opportunities. Studying these challenges will illuminate where likely solutions are being developed, helping to identify investments that should be made, research centers where development is already underway, and potential partners in that work. Understanding the technology trajectory, including how the technology is likely to develop and the drivers of its development, will help NASA identify opportune times for technology investment. For example, some technology breakthroughs are likely to be driven by market pull and external innovations, needing only modification prior to use by NASA for exploration. Other technology concepts may require decades of basic research and innovation to advance to a usable technology by 2050. Most technology breakthroughs are impossible to accurately forecast, because the decisions made today and into the future will affect where the technology will be in 2050.

Because breakthroughs are difficult to predict, and because they can have wide-ranging consequences across NASA, continual targeted technology intelligence can keep NASA current on how existing short-, medium-, and long-term technology trajectories stand to augment or disrupt current NASA plans.

The Companion Study

This study is designed as a companion document to an earlier report, *Technology Horizons: Game-Changing Technologies for the Lunar Architecture*. The studies differ in timeline and scope. The *Game-Changing* report, completed in 2009, considered technologies that could have a significant impact on human lunar exploration and could be infused into a lunar architecture in the 2020-2030 timeline. This study expands that scope, looking beyond a lunar architecture to all human exploration activities, consistent with NASA's new approach. The timeframe is also expanded in this study, evaluating technologies that could be used in 2030-2050. These differences necessitate methodological adjustments.

The *Game-Changing* report focused more on external technology developments, to balance against the mission focus of NASA's development efforts. New game-changing technologies that could be infused within a lunar architecture timeline would most likely be unanticipated disruptions or surprises and would be the result of investments and incentives in other, external areas of the economy. These technologies are best identified with a bottom-up approach: starting from a very broad list of technology development areas and identifying those that could have the biggest impact on a lunar architecture.

With the longer timeline of *Technology Frontiers*, and a greater range of possibilities for NASA operations, several methodological changes were appropriate. This study was able to focus more on space-related technologies, because there are multiple exploration options under consideration. The longer lead times allow for the introduction of new technologies and approaches anywhere within an exploration mission. Additionally, a top-down approach to identifying technology concepts was more appropriate to contain the scope of this study. The team used groupings of the biggest challenges for human space exploration to identify the types of technology breakthroughs that would be needed. Related technology concepts were then identified to address those need areas.

Methodology

Because this study looks at a wide variety of exploration activities and has a 40-year time horizon, it was necessary to develop an approach to identify technology concepts that were relevant to a range of exploration activities and would have a significant impact on human exploration.

Easy Access To Space: cheap, reliable, frequent access to space

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Everyday Supercomputing: supercomputing capabilities available for routine applications in human exploration of space

Seamless Human-Computer Interaction: virtual, neural, and intelligent interfaces to enable information-rich exploration

Figure 1. Breakthrough Capabilities

Under the direction of NASA's Exploration Systems Mission Directorate (ESMD), Directorate Integration Office (DIO), The Tauri Group study team developed a strategy to address these methodological challenges: the team identified the biggest challenge areas to all types of human exploration of space.

For example, providing sufficient power and being able to launch frequently and cheaply are challenges that will affect any human exploration mission. These, and many other big challenges, will need to be overcome to push the boundaries of human exploration of space in the next 40 years. The team then envisioned future solutions to these challenges that could be accomplished by 2050. Each of these envisioned future solutions was called a **breakthrough capability**. For this study, a breakthrough capability describes the technological achievements required to overcome significant challenges facing the

A Breakthrough Capability describes the technological achievements required to overcome significant challenges facing the future of human space exploration.

Figure 2. Breakthrough Capability Definition

future of human space exploration. The study team identified thirteen of these breakthrough capabilities addressing a range of exploration challenges. The list of breakthrough capabilities, along with a brief description of the future they describe, is in Figure 1 above. A mapping of all thirteen breakthrough capabilities to likely human exploration targets is included in Figure 3 below.

The breakthrough capability areas were reviewed and prioritized in an initial workshop with a select group of NASA decision makers, external technology experts, futurists, and technologists on March 19, 2010. Participants offered inputs into how the breakthrough capabilities should be defined and what future solutions were realistic in the 2050 timeframe. Additional discussions included recommendations for further research and the identification of subject matter experts to participate in the next phase of the study.

	Lunar	Near Earth Object	In-Space Assembly at L1	Mars	Mars' Moon Phobos
Easy Access To Space	✓	✓	✓	✓	✓
Efficient Interplanetary Travel		✓	✓	✓	✓
Space Oasis	✓	✓	✓	✓	✓
Healthy, Happy Astronauts	✓	✓	✓	✓	✓
Super Humans	✓	✓	✓	✓	✓
Self-Sustaining Habitats	✓			✓	✓
Go-Anywhere Roving	✓	✓		✓	✓
Ubiquitous Access To Abundant Power	✓	✓	✓	✓	✓
Living Off The Land	✓	✓		✓	✓
On-Demand Manufacturing	✓	✓	✓	✓	✓
Environmental Omniscience	✓	✓	✓	✓	✓
Everyday Supercomputing	✓	✓	✓	✓	✓
Seamless Human-Computer Interaction	✓	✓	✓	✓	✓

** Note: this assumes both crewed and uncrewed missions to all destinations*

Figure 3. Mapping of Breakthrough Capabilities to Human Exploration Targets

Once the thirteen breakthrough capabilities were confirmed, the study team began identifying technology concepts that could provide solutions to the challenges and help to make the future described in the breakthrough capability possible. The team started this process by conducting a very thorough literature review, drawing upon academic publications, conference proceedings, space agency studies, and publications by reputable futurist organizations. A few specific examples of resources used in the literature search include:

- A decade of proceedings from the International Aeronautical Congress (IAC), the Space Technology and Applications International Forum (STAIF), and many American Institute of Aeronautics and Astronautics (AIAA) conferences
- Publications produced by the NASA Institute for Advanced Concepts (NIAC), including its annual reports, call for proposals, as well as special publications
- Over three hundred reports and studies published by the European Space Agency's (ESA) Advanced Concepts Team (ACT)

The study team was dedicated to basing the report on realistic possibilities, despite the 40-year time horizon. To ensure the credibility of the study and the reliability of the identified technology concepts, the team developed a set of ground rules for all technology concepts being considered for the study:

- Feasible within the known laws of physics
- Referenced and sourced from academically respected sources
- Realistic and achievable based on current experimental results or demonstrated technologies

The first rule was designed to ensure that no technology concepts that deviate from what we know about physics today were included in the study. As the study team identified technology concepts, several were suggested that stretched the bounds of known laws of physics (for example, gravity wave-induced fusion), and those were excluded from the study. In a few cases, there were borderline areas of physics research that, if successful, could have massive implications for the breakthrough capabilities. The most promising of these research areas are addressed in New Physics, page 27. The second rule is designed to ensure that concepts are recognized by academic research and are not simply popularized references from science fiction or unsubstantiated Internet posts. The study team did not limit sources to those that have gone through a peer review process, but did limit research to conferences, papers, articles in well-respected magazines, and published books. The final rule was designed to ensure that the technology concepts were more than just an idea, speculation, or theory. Each technology concept requires some research behind it, even at a very low technology readiness level (TRL). These guidelines served an important function of filtering out pure science fiction and speculation, while still accommodating substantial creativity in identifying relevant technology concepts.

NASA	External Government	Academia	Industry
HQ – DIO	AFRL	University of Illinois at Urbana-Champaign	Aerojet
HQ - OCT	DARPA	University of Pennsylvania	Bekey Associates
HQ - ACD	FAA	Georgia Tech	SAIC
GRC	DHS	University of Maryland	United Launch Alliance (ULA)
LaRC	Air Force Office of Scientific Research	University of North Dakota, School of Aerospace Studies	Toffler Associates
MSFC		Institute for Human & Machine Cognition	ILC Dover
JSC		Cornell University	Bigelow Aerospace
JPL		University of Houston	Emergent Technology Research Division
ARC		Wayne State University School of Medicine	TechCast
GSFC		Massachusetts Institute of Technology	
KSC		Harvard University	
		University of California, Los Angeles	
		Universities Space Research Association	

Figure 4. Organizations Represented at Breakthrough Capabilities Workshops

The literature search identified as many realistic technology concepts as possible to prepare for the second phase of the project, detailed workshops focused on each of the breakthrough capability areas. In May and June of 2010, NASA DIO hosted a series of eight workshops (some workshops addressed more than one breakthrough capability) in Washington, D.C., pulling together over 120 subject matter experts from across NASA, industry, and academia. (Table 4 details the organizations represented by workshop participants, and APPENDIX A: BREAKTHROUGH SCENARIO WORKSHOP PARTICIPANTS — MARCH 19, 2010 has a list of the participants in each of the workshops.) During the workshops, each of the breakthrough capabilities was reviewed in detail, as were each of the supporting technology concepts. Participants provided feedback on the future described by the breakthrough capability and accepted and rejected technology concepts based on relevance, credibility, and timeframe. Additional technology areas were also recommended and pursued in follow-up research. Additionally, twenty-five interviews were conducted with key experts who were unable to attend the workshops.

This report is the culmination of the workshops and research. It combines detailed information on each of the breakthrough capabilities with a thorough explanation of the challenge faced in each of the breakthrough capability areas. This report is structured around the thirteen breakthrough capabilities. There is a chapter for each, which provides details on all of the supporting technology concepts, information on the technology hurdles faced by each concept, details on the technology trajectory for the capability area, and highlights on potential partnering opportunities. In addition to the thirteen breakthrough capability areas, nine crosscutting technology areas were identified. Each of these is a technology area that touches many or most of the capability areas in a crosscutting way. These are addressed in detail in the Crosscutting Technologies chapter. Although each of the breakthrough capabilities is addressed individually in this study, any future exploration activities will draw on innovations in all of the breakthrough areas.

Breakthroughs in one area will impact innovations in another. Innovations in one area will also trade against those in other areas, for example if advanced on-orbit servicing is available, extremely heavy-lift vehicles may not be needed, instead opting to assemble mission systems on orbit. These trades and cross benefits are addressed in this study, but they will also help define the future of human exploration, as humans begin “fanning across the inner solar system” and beyond.

EASY ACCESS TO SPACE

Cheap, reliable, and frequent access to space

EASY ACCESS TO SPACE

Cheap, reliable, and frequent access to space

All space exploration missions begin with transportation to orbit. The capabilities of vehicles and systems that provide access to space impose constraints on spacecraft mass and volume. Construction in orbit alleviates physical constraints for integrated systems; however, launch constraints still drive individual system components and mission cost. Current commercial launch vehicles cost ~$21,000 per kg to launch a commercial geostationary satellite to orbit.[1] If a future Mars mission requiring 1000 t, based on the 800 t to 1200 t estimates from the *Mars Design Reference Architecture 5.0*, was launched with these commercial vehicles, launch costs alone would be $21 billion.[2] Technologies capable of lifting 1000 t or more to orbit are unlikely to develop within the next 40 years, and technical breakthroughs combined with operational improvements are necessary to increase launch frequency to support human exploration. A higher launch rate historically increases vehicle reliability, although it is likely to result in more launch failures overall. Failures of robotic missions will be costly for NASA and could impact the space industry, but failures during human missions could result in loss of life and end an exploration mission. Ultimately, human exploration will depend on technologies to provide cheap, reliable, and frequent access to space.

BREAKTHROUGH

Systems that provide transportation from planetary surfaces to orbit. These systems provide cheap, reliable, and frequent access to space from Earth, the Moon, Mars, and other exploration targets. Breakthroughs in access to space increase total payload mass and enable larger, more complex exploration missions.

With the Easy Access to Space breakthrough capability, a future is described where access to space is routine, inexpensive, and reliable. Multiple technologies have been developed to provide transportation for crew, cargo, satellites, and robotic explorers. In many cases, these technologies are tailored to specific payloads or types of payloads, increasing efficiency for commonly launched products. Transportation infrastructure is concentrated on Earth, but permanent or semi-permanent infrastructure may exist on frequently visited destinations. For planetary bodies without transportation infrastructure, breakthroughs in reliable rockets provide return capabilities for samples and crew. Some technologies that enable Easy Access to Space will also enable safe and efficient descent to planetary surfaces. With multiple affordable pathways to space, new users in commercial and academic sectors are likely to become integrated in the space economy, pushing demand and innovation. This breakthrough could result in increased launch frequency and streamlined ground operations, leading to “airplane-like” access to space, with commodity pricing and last minute booking. As the number of entities accessing space increases, humanity’s economic sphere of influence will be pushed well beyond Earth.

Space access breakthroughs could be achieved with large, capital-intensive infrastructure projects or a breakthrough in launch vehicle technology and operations, leading to lightweight, more efficient rockets. Breakthroughs in propulsion systems could lead to novel, more powerful rockets that go beyond current chemical or even nuclear capabilities. Breakthroughs in infrastructure investments and technology are likely, but without breakthroughs in manufacturing costs and design reliability that enable cheap, very reliable, expendable rockets, it is unlikely that breakthrough capabilities can be achieved solely with expendable systems. One solution is reusable systems, which are likely to provide reduced cost over multiple missions and could increase design reliability to achieve Easy Access to Space. Reusable systems could include rocket stages, ground launch infrastructure, off-board power systems, or alternative technologies. These systems must enable quick turnaround, require low maintenance, and provide reliable operations. Additionally, astronaut safety will be key in the design of crewed systems. It is possible that a breakthrough in spacecraft operations combined with incremental technical improvements will be sufficient to achieve the Easy Access to Space breakthrough capability.

With this breakthrough capability, the space industry will remove one of the primary economic constraints to solar system exploration—the cost of transporting payloads to orbit. NASA, partnering space agencies, other government entities, and industry will take advantage of cheap, reliable, and frequent access to space. Space infrastructure will increase in size, complexity, and capability, potentially providing staging points to construct and launch large human missions. Combined with advances in inflatable structures and orbital construction, large complex habits can be launched into space with minimal impact from launch constraints on mass and volume. Propellant, consumables, and raw materials may be launched directly from surface-based propulsion systems, further reducing cost for rugged payloads and supporting off-world missions through affordable logistics, refueling, and in-space construction. If we develop launch infrastructure on other planetary bodies, roundtrip missions will become cheaper and easier to plan, resulting in increased mission frequency and, potentially, regular exchange of high-value materials. The emergence of cheap, reliable, and frequent access to space may also result in new space-based economic sectors, providing indirect returns throughout the economic spectrum.

Related Capability Areas

Easy Access to Space provides the initial transportation capability for all other space activities and consequently can impact every breakthrough capability; however, there are three breakthroughs that are more intimately connected with Easy Access to Space.

- **Efficient Interplanetary Travel –** Extends the capability described in Easy Access to Space, providing transportation throughout the solar system. Both access to space and interplanetary travel are necessary to provide transportation for human and robotic exploration. Although the technical challenges are different, there are similarities between in-space propulsion systems and systems designed to escape a planetary surface. Consequently, there are opportunities for technical synergy and commonality between Easy Access to Space and Efficient

Interplanetary Travel. The downside of the close interconnection of these capabilities is that mass and volume constraints of space access systems could influence or limit systems developed for interplanetary travel. For instance, the shroud size on a heavy-lift vehicle could provide restrictive limit on component diameters for an interplanetary vehicle, potentially resulting in a less efficient transportation system. Alternatively, a breakthrough in access to space or interplanetary travel could overcome inefficiencies or limitations associated with the other capability.

- **Space Oasis –** Provides an opportunity to transition from space access infrastructure and operations to interplanetary travel. Oases could provide a range of capabilities for transportation systems, from refueling and refreshing consumables, to long-term, in-space construction. With a network of space oases, propulsion systems can be periodically refueled and reused through all stages of an exploration mission, including launch, interplanetary travel, and surface descent. Alternatively, a space oasis could act as a transition point for transferring crew and cargo from launch infrastructure to optimized interplanetary systems. If space oases, in any form, are included in the exploration architecture, it will be necessary for space access technologies to compatibly interface with space oasis systems. A space oasis designed to refuel launch systems could enable smaller, cheaper launch vehicles.

- **Living Off The Land –** Includes technologies and processes for producing useful resources from exploration sites. Living Off The Land technologies could produce rocket propellant to refuel space access vehicles, reducing the need for long-term storage of propellant and significantly reducing mass delivered by exploration landers. With robust ISRU capabilities, fewer logistic missions from Earth will be necessary, impacting launch vehicle design and markets. Conversely, cheap, reliable, and frequent access to space from Earth reduces the need for self-sufficient exploration outposts.

Supporting Technology Concepts

Space exploration is impossible without technologies to access space. For human exploration and sample return missions, accessing space is not a challenge limited to terrestrial environments. On other planetary bodies, gravitational or atmospheric differences, presence or lack of infrastructure, and surface characteristics may result in different optimal technologies for reaching orbit. For example, electromagnetic launch of lunar material has been studied for several decades[3] and avoids many of the difficulties associated with electromagnetic launch on Earth, such as a deeper gravity well and a dense atmosphere. By 2050, it is possible that multiple space access technologies based on a wide range of physics and engineering will evolve. Some of these concepts may provide a breakthrough in access to space, creating new opportunities for space exploration.

Launch vehicles and alternative concepts represent complex systems. Therefore, solving the challenges of access to space requires more than just physical technologies and engineering design. Operations, ground infrastructure, and the interactions between individual components will be key in transforming a technical improvement into a breakthrough launch concept.[4] In addition, technical advancements in tangentially related technologies can have a tremendous impact on systems as complex as launch vehicles. A breakthrough in high-strength, low-weight materials could lead to large performance gains in access to space with heritage propulsion systems.[5] Similarly, streamlined operations for ground systems and vehicle maintenance could significantly improve cost and frequency of access to space. To accurately evaluate potential breakthrough concepts, comprehensive system studies will be necessary.

The following section highlights several technology concepts that could contribute to a breakthrough in Easy Access to Space. These concepts specifically target breakthroughs in propulsion. Although breakthroughs in propulsion systems could have the largest impact on Access to Space, they do not represent the complete system. Accurately evaluating system-level concepts in operational environments will require additional insight that can only be achieved as breakthrough technologies mature. Where possible, anticipated challenges to implementing a system based on these propulsion technologies are discussed. Enabling technologies that could affect system development are discussed in Crosscutting Technologies, page 216.

These concepts are based on open-source research, workshops with subject matter experts, and individual interviews. The technology concepts do not reflect an exhaustive list, but provide a range of concepts that could be developed prior to 2050.

Supporting Technology Concepts	
Skyhook	Provide access to space through a system of tethers, climbers, and counterweights to lift a payload into orbit.
Air-Breathing Access to Space	Propel launch vehicles using atmospheric gas as reaction mass.
Nuclear Rockets	Heat propellant with nuclear reactors.
Beamed Power Launch Vehicles	Provide energy for propulsion from off-board systems located on the ground or in a stable orbit.
Surface Propulsion Systems	Provide some or most of the energy necessary to reach orbit with ground-based acceleration.
New Physics	May provide breakthrough capabilities that extend well beyond performance of systems based on currently validated physics.

Skyhooks and the Space Elevator

A skyhook is a generalized tether system designed to lift an object into the sky. Original skyhook designs were used in aviation, however, the term was conscripted to describe tether launch and orbit transfer systems.[6] The most famous skyhook design is the space elevator, which has a rotation velocity and orbital period equal to the rotation of the orbited planet and consequently appears to be tied to a single location on the surface of the planet. Other designs include rotating tethers for orbital transfers through momentum exchange and skyhooks that “touch” a planetary surface and “lift” a payload into orbit.[7]

PARTNERING OPPORTUNITES

SKYHOOKS AND THE SPACE ELEVATOR

- Momentum-Exchange / Electrodynamic-Reboost (MXER) Tethers—Tethers Unlimited, Inc.
- Tether Materials—Odysseus Technologies

The skyhook concept has been around for several decades: Arthur C. Clark popularized it, Russian and American engineers developed feasibility studies during the 1960s, and, seventy years earlier, Tsiolkovski made the first steps towards envisioning a skyhook.[8] Several different skyhook designs have been proposed and could enable access to space. It is possible that multiple iterations will develop based on advancements in tether materials and experience operating these systems.

Skyhooks are an advanced technology and are challenging to engineer. Some skyhook designs require material breakthroughs for operation on Earth. Geostationary systems like the space elevator are attractive for continuous access to space and potentially the first stage of interplanetary travel. However, for terrestrial operation, space elevators would require breakthroughs in high-strength materials, space access infrastructure capable of supporting a massive in-space construction project, and space traffic management well beyond current capabilities (see Crosscutting Technologies, “Nanotubes” and “High Strength Materials,” pages 226 and 217). It is unlikely that in 40 years solutions will be developed for the technical and operational challenges of building and launching a space elevator and the ability to protect it from other objects in orbit.[9] For nonterrestrial applications, space elevators may be feasible within 40 years, if a viable return for the infrastructure investment is possible.

For terrestrial use, non-synchronous skyhooks avoid several of the technical and operational limitations of the space elevator concept. Non-synchronous skyhooks have orbital rotational velocities and tether lengths such that periodic contact between the tether and the planetary surface occurs with minimal relative velocities. Payloads that are smaller than the skyhook mass can be captured and lifted into orbit as the hook continues to rotate. Non-synchronous skyhooks can be much shorter than synchronous systems, and consequently tethers can be made from less advanced materials, potentially with currently available materials.[10] In addition, the risk from orbital debris is reduced for skyhooks in low Earth orbit compared to geostationary systems. By carefully choosing the length of the skyhook tether, alignment between the tether tip and the planetary surface can be restricted to a few stationary points. A tether one-third the length of the Earth’s radius would touch six points on the equator, enabling permanent infrastructure to be developed for docking to the tether.[11]

Despite the decades of feasibility studies, considerable research is still needed to develop a skyhook. Advanced material companies are developing long, carbon nanotube fibers that can be woven into a high-strength tether. NASA sponsors prize challenges to promote the development of high-strength tethers and power systems for tether climbers.[12] While component-level development continues, NASA and other organizations conduct system design studies to identify feasible and attractive ideas. If a skyhook is developed in the next 40 years, it will depend on the ongoing basic materials research and the ability to integrate discoveries and ideas into practical solutions.

There are several technical and operational challenges to skyhooks. For terrestrial systems, these challenges make it unlikely that a synchronous skyhook (or a space elevator) will develop within 40 years. Although these problems are reduced for non-synchronous skyhooks, they have similar challenges, including high-strength, low-weight materials and the potential to impact satellites or debris in low Earth orbit. Challenges that are more pronounced for non-synchronous skyhooks in Earth orbit include energy loss from atmospheric drag, heating and damage to the tether due to high atmospheric entry and exit velocities, and corrosive damage from repetitive exposure to atomic oxygen. Systems that combine momentum exchange tethers (traditional skyhooks) with electrodynamic tether propulsions can counteract energy loss and periodically reboost the skyhook.[13] Alternatively, non-synchronous skyhooks could be designed to travel through only the top layers of the atmosphere, reducing drag but requiring a suborbital first stage or hypersonic aircraft to lift payloads.[14] Like the challenges of synchronous skyhooks, these technical challenges are largely reduced or eliminated for planetary systems with thin atmospheres and low gravity.

Whether the use is for Earth or a different planetary system, operational challenges could be the largest difficulty for skyhooks. Although non-synchronous skyhooks are considerably less massive than synchronous ones, they still represent a large infrastructure investment. The cost of transporting skyhook material and building the system around other planetary bodies may be unsustainable without in-situ resources. Maintaining orbital tethers and performing repairs represent an operational and technical challenge to long-term skyhook operations. It is also necessary to consider the impact of terrestrial skyhooks on atmospheric travel, site locations for attaching payloads, and international operations.

If the technical and operational challenges for a skyhook can be overcome, this system can provide access to space with minimal marginal cost. Results from a NASA Institute for Advanced Concepts (NIAC) study indicate one to two orders of magnitude reduction in the marginal cost for a space elevator over current launch systems.[15] With these systems, payloads can be launched cheaply and frequently (multiple times a day), greatly extending human presence in space. Non-synchronous skyhooks could provide testing and demonstration of materials for future synchronous—or space elevator—systems, paving the way for future advances in access to space.

Air-Breathing Access to Space

Air-breathing systems include all vehicles that capture air during transit to provide reaction mass. Some systems use inert gas to provide propulsion and could be used in any atmosphere; others rely on oxygen for combustion and are primarily designed for Earth. By using atmospheric gas to augment thrust, these systems can reduce the amount of propellant necessary to get to orbit, potentially reducing the initial launch mass or increase payload capacity. In addition, most air-breathing concepts are reusable and designed for quick turnaround, aircraft-like access to space.[16]

There are several different air-breathing propulsion concepts. Near-term or current systems include jet, scramjet, and ramjet engines. Several organizations including Defense Advanced Research Project Agency (DARPA), NASA, and other national space agencies are working on combined cycle engines that use a combination of jet, ramjet, scramjet, and rocket propulsion for hypersonic flight and could eventually provide access to space.[17] These combined cycle engines have several technical disadvantages, including increased weight, challenges with supersonic combustion, non-optimized performance, and potentially increased drag.[18] Over the next 40 years, several yet-to-be-matured technologies could reduce these challenges or greatly increase the performance of air-breathing systems. Some example technologies include:

PARTNERING OPPORTUNITES

AIR-BREATHING ACCESS TO SPACE

- DARPA Tactical Technology Program, Falcon Program
- Boeing Phantom Works
- Air Force Research Laboratory, Propulsion Directorate
- Federal Aviation Administration (FAA), Office of Commercial Space Transportation
- Aeroject

- Magneto-hydrodynamic (MHD) propulsion systems use Lorentz force on a conductive fluid to provide thrust. For air-breathing systems, plasma from hypersonic air flow acts as the conductive fluid and is accelerated through a channel.[19] Magnetic fields from the MHD can control plasma flow and compress or cool the air like a scramjet system. Variants of MHD systems can be used with combustion cycles or to accelerate exhaust from rockets.[20] This system requires very powerful superconducting magnets to produce useful levels of thrust. In addition, reaction mass for direct MHD propulsion systems does not have to include oxygen and any conductive fluid could be used.

- Magneto-hydrodynamic bypass systems are a variant of MHD propulsion in which the MHD system controls the airflow for a scramjet rather than providing primary thrust. In this system, an MHD generator is located at the front of the propulsion system to slow hypersonic flow while extracting energy from the plasma. The slowed airflow is easier to combust in a ramjet-style engine, leading to increased engine performance. After combustion, the energy extracted by the MHD generator can be added back to the airflow with a second MHD system or an alternative electric propulsion system, thereby minimizing loss.[21] As an additional advantage, this system can control airflow around airfoils, reducing drag and potentially eliminating shockwaves associated with hypersonic flight.[22]

- Nuclear ramjets provide another way to augment thrust for combined cycle access to space. These systems use nuclear reactors to increase the energy of propulsive mass. Some systems attempt to directly heat the airflow, while others heat liquid hydrogen prior to combustion with oxygen in the supersonic airflow. By heating liquid hydrogen prior to combustion, the system increases mixing and combustion efficiency and directly augments thrust through increased energy.[23] These systems can transition to a nuclear rocket system after leaving the atmosphere.

Most breakthrough technology concepts for air-breathing systems are potentially applicable to interplanetary travel. With sufficient energy, air-breathing systems can increase their flight time in the upper atmosphere, gathering propellant for latter stages of an interplanetary journey. This concept, sometimes called an air collection engine, allows a launch vehicle to have empty propellant tanks that are filled at high altitude, significantly reducing the energy necessary to reach orbit.[24]

Current research that could lead to a breakthrough in air-breathing access to space includes a wide range of technology development activities, from conceptual designs to technology demonstrations. NASA's hypersonic research activities include designing and testing scramjets, which could lead to combined cycle engines. In 2004, NASA successfully tested a scramjet system that achieved powered flight at Mach 9.6.[25] Under the FALCON program, the Department of Defense (DoD) developed technologies for an integrated hypersonic, transatmospheric plane.[26] Outside the United States, several nations have invested in hypersonic flight for atmospheric or transatmospheric systems, including Russia, Australia, and Japan.[27] In addition to basic science on plasma physics, hypersonic control, and propulsion systems, these demonstrations could provide initial steps toward a breakthrough in air-breathing access to space.

Despite the resources invested in air-breathing access to space, there are several challenges facing near-term systems, and technology or engineering breakthroughs are necessary for breakthrough concepts to develop in 40 years. Air-breathing systems have increased dry mass compared to standard rockets, which increases cost and reduces the advantage of scavenging propellant. These systems require high-temperature, low-weight, and strong materials to control flight at hypersonic speeds (see Crosscutting Technologies, "High Temperature Materials" and "Nanotubes," pages 219 and 226. Some concepts require additional understanding of drag reduction as well as plasma generation and flow at hypersonic speed (see Crosscutting Technologies, "Plasma Technologies," page 229).[28] In addition, new ground facilities for testing and evaluating air-breathing rockets will be required, further increasing development cost.[29] Challenges specific to nuclear-augmented systems include potential risks of operating a nuclear reactor in Earth's atmosphere. Nuclear systems may require advances in fusion for safe operation of low neutron reactors.[30] MHD propulsion systems have many engineering challenges. A Russian program, Ajax, investigated MHD air-breathing engines with conventional technology, and the approach proved impractical.[31]

If challenges to breakthrough air-breathing technologies are overcome, these systems could drastically change the approach to accessing space. Breakthroughs in air-breathing systems could lead to single-stage-to-orbit, fully reusable vehicles. Although the capital cost of these systems will be high, improved operations, regular flights, and quick refurbishment could significantly drop the lifecycle cost, enabling cheap and frequent access to space.

Nuclear Rockets

Several existing propulsion concepts utilize sustained nuclear reactions to heat propellant. Two primary designs exist for coupling propellant to a nuclear reactor.[32] Direct thermal conversion systems heat propellant through thermal conduction and radiation directly from the reactor core. This design, a nuclear thermal rocket (NTR), was developed for the NERVA (Nuclear Engine for Rocket Vehicle Application) rocket engine. NERVA used energy from a fission reactor to heat hydrogen propellant, thereby cooling the reactor and generating thrust from hot hydrogen exhaust. NASA preformed twenty tests of the NTR reactors on several reactor designs between 1959 and 1972.[33] The second approach converts the energy released from a reactor to electricity, and then transfers energy into the propellant through an ion beam or through electromagnetic interactions.[34] Indirect energy conversion is less applicable for access to space due to increased mass and reduced thrust-to-weight, however variants of beamed power propulsion (discussed below) could use nuclear reactors for access to space applications. In each case, energy from the reactor is the primary source of power for thrust. In addition, hybrid systems that combine nuclear rockets with air-breathing or combustion systems have been proposed.[35]

PARTNERING OPPORTUNITES

NUCLEAR ROCKETS

- U.S. Department of Energy (DOE) Office of Nuclear Energy
- Argonne National Laboratory Nuclear Engineering Division
- Oak Ridge National Laboratory: U.S. ITER Project Office, Nuclear Technology Program, Nuclear Science and Technology Division, Fusion Energy Sciences Program, and Fusion Energy Division
- Los Alamos National Laboratory: Science, Technology and Engineering, Select offices in Weapons Programs and Nuclear & High Hazard Operations
- Lawrence Livermore National Laboratory: Physical and Life Sciences Directorate, and National Ignition Facility
- University Illinois at Urbana-Champaign, Nuclear Engineering Program

Nuclear rocket designs include both fusion and fission systems. Fission nuclear rockets represent relatively mature technology and could be implemented in the near term. The most mature fission nuclear rocket technology is a solid core system that uses propellant to cool the fission reactor prior to entering the nozzle and generating thrust.[36] If nuclear rocket development continues, it is likely that higher-power-density reactor designs will replace mature solid core designs within the 40-year timeline of this study.[37]

Potential breakthrough fission systems include solid core reactors with high-temperature fuels, liquid core reactors, and gas core reactors. Currently, solid core nuclear thermal reactors are inefficient, compared to proposed reactor designs, with ISP ~900-1000 seconds.[38] However, reactor temperature limits the efficiency of these systems, and fuel elements that operate at higher temperatures will improve rocket performance. Solid core nuclear thermal rockets (NTR) with high-temperature fuels, such as tungsten uranium composites, could provide efficient mid-term access to space with improvement over chemical and heritage nuclear systems.[39] Additional high-temperature materials applicable to nuclear rockets are noted in Crosscutting Technologies, on page 219. Liquid core and gas core rockets have been investigated as alternative NTR designs; however, they are more technically challenging than solid core rockets, and increased reactor mass may prevent access to space applications.[40] Gas core rockets are the most promising technology trajectory for NTR efficiency, and some designs could develop within the next 40 years. These rockets consist of an ionized, hot, dense, fissionable gas contained within magnetic fields, hydrodynamic vortexes (open cycles), or transparent quartz tubes (closed cycle). Propellant is projected around a fission bubble or quartz tube and is heated through radiant energy.[41] Gas core reactors can reach much higher temperatures than solid core reactors, since they are not limited by the melting point of the fuel elements, and specific impulse rates (ISPs) of several thousand seconds are possible.[42] However, projected designs for gas core rockets have relatively low thrust to weight and are only applicable for access to space from low-gravity planetary bodies or with extremely powerful reactors (tens of gigawatts).[43]

In addition to fission systems, fusion reactors can power nuclear rockets. Fusion reactors are more challenging than fission systems, requiring additional energy and specialized reactor designs to generate the high temperature, pressure, and confinement time necessary for sustained fusion.[44] However, fusion reactors can enable high-power propulsion systems that are safer and less polluting than fission reactors. In addition, the development path for fusion propulsion could lead to reactors that use low-neutron fuels, further increasing safety and reducing the need for shielding. There are several different fusion reactor designs that may be applicable to a nuclear rocket, including inertial electrostatic confinement reactors, electrodynamic confinement systems, and pulsed fusion reactors. Further research is necessary to validate these designs and determine their applicability to nuclear rockets.

Nuclear rockets received considerable technology development during the NERVA program in the 1960s and early 1970s.[45] This research focused on a solid core design that was matured through a series of ground tests. Although breakthrough nuclear rocket concepts are likely to advance well beyond NERVA's demonstrated capability, this program provides a basis for current and future research. Ongoing research has lead to better reactor and fuel designs for solid core systems and paved the way for more advanced reactor designs.[46] NASA has conducted several studies of nuclear propulsion concepts, which could inform development of future launch systems. However, NASA's most recent and planned efforts focus on in-space propulsion, and additional development will be necessary for space access systems. For operations in the Earth's atmosphere, non-polluting, low-neutron fusion systems may be the most attractive solution. Several private companies, the Department of Energy (DOE), and international partnerships are working to advance fusion reactors.[47] Fusion research is primarily focused on terrestrial markets and additional development, potentially including breakthrough, compact designs, will be necessary for systems applicable to launch vehicles.

There are several challenges to building and operating a nuclear rocket. Nuclear rocket systems are likely to be heavier and cost more to manufacture than conventional rockets made from similar materials. Additional, and potentially heavy, shielding may be necessary for crewed launch vehicles operating in an atmosphere to prevent scattering towards the crew compartment.[48] To be economical, these systems may need to be packaged into a reusable rocket system that is easy to refurbish and refuel. This could prove to be challenging for rockets with fission cores that have high levels of latent radiation in the reactor chamber. Alternatively, the cost of a nuclear rocket could be spread over a long mission, by providing launch and interplanetary propulsion with one reactor system. A variant of this approach is the nuclear space tug, which spreads cost over several orbital transfer missions outside of a planetary atmosphere.[49]

Design challenges currently face the more advanced reactors, including the gas core and fusion breakthrough technology concepts. Research in plasma dynamics and fuel containment has improved conceptual designs for gas core reactors, however, fuel loss from open cycle reactors is still an issue.[50] A small amount of fuel loss may be acceptable for interplanetary travel, but completely contained systems will likely be required for operation in the Earth's atmosphere. For other planetary bodies, containment requirements will depend on the potential for surface contamination and associated planetary protection regulations. In fusion systems, fuel loss is not an issue for environmental safety, however, containment is vital for sustained energy generation. Confinement time, temperature, and pressure are significant hurdles to fusion systems that may prevent small, launch-vehicle-scale, reactors.[51] In addition, fusion fuels that result in high-neutron flux can damage the materials of the reactor chamber, leading to structural failure.[52] Reactors for low-neutron fuels are more technically challenging and require more high ion energies than conventional fuels with high-neutron flux. After proving gas core and fusion reactor technologies, new designs and further development may be necessary to increase reactor performance and thrust-to-weight for economical access to space. Due to these challenges, feasible gas core or fusion launch vehicles are long-term technologies, and development prior to 2050 will be challenging.

Development of nuclear rockets may face constraints related to scrutiny and documentation required by regulating agencies. This documentation is designed to mitigate any risks due to political acceptance and public perceptions of using nuclear materials on space missions. To date, this added scrutiny has not impacted mission success, however, future development will need to consider these constraints as well as technical challenges. In addition, designs that leak radioactive fuel or have a potential for releasing radioactive fuel on impact are unlikely to be accepted by the U.S. for use in the Earth's atmosphere. Because social opinions about technology change drastically over time and from culture to culture, forecasting the future regulatory and social environment is outside the scope of this study; consequently, this report does not provide detail on social challenges to nuclear or other technologies.

Nuclear reactors can easily provide sufficient power to launch large payloads to space. With sufficiently large propellant tanks, these systems could enable single-stage-to-orbit, reusable rockets. Unlike air-breathing systems, nuclear rockets operate through all stages of transatmospheric propulsion, providing an opportunity for commonality in access to space and interplanetary propulsion systems. If successfully developed, a low-neutron, fusion rocket system could provide a safe, reusable, non-polluting and potentially cost-effective propulsion system that is the basis for cheap, reliable, frequent access to and travel through space.

Beamed Power Launch Vehicles

To reduce the weight of launch vehicles, several concepts remove power generation systems from the rocket. By locating power sources on a planetary surface or in a stable orbit, the dry mass of a launch vehicle can be significantly reduced. In addition, ground-based power systems can be easily maintained, enabling frequent launch opportunities with reusable infrastructure. For launch from Earth, energy powering these systems can be generated from mature terrestrial technology at 10 cents per kilowatt and can be used to support the terrestrial energy market between launch events.[53] With beamed power, terrestrial nuclear power plants that are too large or heavy for launch vehicles, potentially including mid-term fusion plants, could provide an alternative to developing onboard reactors. On other planetary bodies, new infrastructure will be necessary to provide beam energy, however, power plants built for transportation could serve outpost or permanent settlements between launches. Beamed power has been identified as one of the most promising technologies to lower the cost of access to space to tens of dollars per pound.[54]

PARTNERING OPPORTUNITES

BEAMED POWER LAUNCH VEHICLES

- Lightcraft Technologies, Inc.
- Solaren Corp.
- Princeton University, Beam Dynamics and Nonneutral Plasma Division
- University of Maryland, Particle Beam Dynamics Group
- Air Force Research Laboratory, Directed Energy Directorate
- Los Alamos National Laboratory, Threat Reduction Directorate
- California Institute of Technology, Department of Astrophysics

Two methods of beaming power to launch vehicles have been investigated: near visible lasers and microwave radiation.[55] These wavelengths were selected in part due to transmission properties through the Earth's atmosphere; different approaches may be necessary for optimal performance on other planetary bodies. In addition to beam types, there is also variation in the approaches to using beamed energy. Beamed power can be directly converted into thrust or into electricity. Some vehicle concepts use a heat exchanger to convert energy from microwaves to thermal energy, which is used to heat onboard propellant for propulsion.[56] Other systems focus beamed energy, in the form of laser pulses, to super heat atmosphere below the craft then ride the resulting shock waves. This design can include an ablative solid as an onboard propellant for propulsion above the atmosphere.[57] Indirect systems use retinas or photovoltaics with specific bandgaps to convert the beamed energy into electricity for high-thrust electric propulsion, potentially including an MHD system.[58] Hybrid systems that use beamed energy to augment conventional rockets can include a heat exchanger that transfers additional energy to rocket exhaust prior to entering the nozzle; direct coupling of microwaves to alumina particles in solid rocket exhaust; or powering a plasma accelerator for acceleration of rocket exhaust.[59] There are also complex concepts that use several of these approaches, including the microwave lightcraft, which focuses microwave energy into an airspike for ionization and drag reduction, captures some energy in a retina, and uses MHD propulsion to provide thrust with the ionized air.[60] Development over the next 40 years will determine which concepts are practical and how beamed power systems can be designed for various access to space applications.

There is considerable research in academia and government, as well as some research by private industry, on technologies that could support beamed power launch vehicles. Beamed power research was well under way in the early 1960s and resulted in a demonstration of a microwave-powered helicopter in 1964.[61] More recently, NASA and the Air Force Research Laboratory's (AFRL) advanced concepts division developed and tested a laser-propelled, spin-stabilized lightcraft.[62] A private company eventually developed this concept.[63] Marshall Space Flight Center developed a test system for assessing rocket performance augmented by an MHD accelerator. This system has the potential to evolve into a beamed power technology.[64] Related work in academic laboratories include nuclear pumped lasers that may enable efficient power beaming from specialized reactors.[65] In addition, several studies and papers have continued to refine beamed power launch vehicle concepts and designs.

Tangential to research for beamed power vehicles, the energy industry is actively evaluating technologies for energy transmission through microwaves or lasers. U.S. companies and other governments, such as Japan, are working on business models and technologies for space-based solar power, which requires a power-beaming component.[66] In May 2008, power beaming was demonstrated over 148 kilometers between two Hawaiian islands.[67] While the focus of this research is the terrestrial energy market, it could directly enable development of beaming technology for access to space.

There are several challenges to power beamers. Some difficult technical challenges include accurate pointing and tracking as well as limiting energy loss as beams spread and interact with the atmosphere. Advances in diffraction-free optics for high-power beams or metamaterials for focusing and controlling beam dispersion may be necessary. Alternative solutions include a dual-beamer system with power sources on the ground and in space. The ground power source provides energy for the initial stages of the launch, and the orbital system takes over during flight, minimizing the effects of the atmosphere and dispersion.[68] Also, it is potentially possible to use nonlinear effects of the atmosphere to mitigate dispersion by propagating soliton waves, which travel in a self-reinforcing wave packet.[69]

In addition to technical challenges, there are several infrastructural and operational challenges. Beamed systems require very large power levels, on the order of 0.1 to 1 MW of power per kilogram of vehicle, propellant, or payload mass.[70] To launch a 9 t capsule (roughly the mass of Soyuz or the projected mass of Orion) would require a power plant capable of producing 900MW to 9GW. For comparison in the U.S., the average capacity for a nuclear power plant is just over a gigawatt, and coal power plants have an average capacity of around 230 MW. Although, in both cases, plants can be designed to exceed the national average.[71] In addition to the power plant, specialized launch infrastructure, including the beamer system, will need to be developed and built. Technical advancements may reduce the required power plant size and associated cost, but a high initial investment in infrastructure likely will be required. Further operational challenges could exist due to nearby air traffic and overflying satellites. Current overflight restrictions with minor modifications are probably sufficient for controlling the airspace around beam-powered launch vehicles; however, technical or operational solutions will be necessary to ensure power beams do not damage satellites or facilities on the ground.

Given current research, beamed power systems are mostly likely for Earth-to-orbit transportation systems, but if the investment is considered worthwhile, these systems could be developed for other planetary bodies. Beamed power designs promise that significant cost savings over current chemical launch vehicles is possible.[72] The infrastructure necessary for beamed power can support frequent launches or could provide energy for ground or orbital facilities. Technology development and testing will be necessary to determine the reliability and safety of these systems. If successful, beamed power could provide efficient, low-cost access to space and may lead to interplanetary travel systems. (See Efficient Interplanetary Travel, page 34 .) Beamed power technologies may also overlap with power beaming for other energy applications. (See Ubiquitous Access to Abundant Energy, page 130.)

Surface Propulsion Systems

Most breakthrough technology concepts for access to space use continuous, or quasi-continuous, acceleration from the planetary surface to orbit. A few concepts are designed to provide a portion of the necessary orbital velocity via ground-based accelerators. These concepts, collectively referenced as surface propulsion systems, can accelerate a payload to escape velocities or, more likely for near-term development, provide launch assist for launch vehicles.[73] Like power beamers, surface propulsion systems can use terrestrial energy sources to increase payload mass while reducing cost, and most designs provide acceleration without propellant expenditure from the vehicle tanks.[74]

PARTNERING OPPORTUNITES

SURFACE PROPULSION SYSTEMS

- Rail Gun—Office of Naval Research
- Magnetic Launch Assist—Naval Air Systems Command, Aircraft Launch and Recovery Systems Program; General Atomics Electromagnetic Systems Division

There are several surface propulsion system designs, however, most fall into one of three categories: chemical, mechanical, and electromagnetic. Chemical systems include cannons with explosive charges, light-gas guns that use expanding hot gas, and blast wave accelerators that use successive rings of explosives to accelerate a payload.[75] Chemical systems are limited to high-acceleration applications, and several of these systems can only achieve velocities equal to the speed of sound in the expansion gas.[76] Mechanical systems include the slingatron, which accelerates payloads in a gyrating ring or spiral to achieve orbital velocity. Payload acceleration occurs as the gyration frequency is increased, and acceleration is dependent on the radius of the ring. Evacuating the tube and ablative, low-friction surfaces can be used to mitigate drag and friction forces.[77] Electromagnetic (EM) systems, such as coil guns, rail guns, and linear induction motors, use electrodynamic forces to accelerate a payload. EM systems are potentially the most promising surface propulsion technologies, since they are easier to control, designs can be tailored to specific capabilities, and they do not have the same high-strength material challenges of mechanical and gas systems.

Subscale and proof-of-concept demonstrations have occurred for each of these technologies. Chemical systems were demonstrated in the 1960s with the High Altitude Research Project, which fired a suborbital projectile to an altitude of almost 100 miles.[78] Laboratory experiments have tested some of the physics behind the slingatron with small particles and velocities up to 4 km/s.[79] In addition, the DoD spent several million investigating the slingatron concept.[80] Electromagnetic launchers have a long history, and initial attempts at building an EM accelerator date back to 1901.[81] More recently, the U.S. Navy has invested in developing electromagnetic rail guns that reach mach 7, to launch conventional weapons over 290 miles.[82] NASA has also looked at electromagnetic systems for launch assist, including a Goddard project that uses linear induction motors to assist a two-stage-to-orbit reusable vehicle. This system has also been proposed for ground launch on the lunar surface.[83] In addition to government development, maglev and linear induction motor systems have attracted commercial development for high-speed surface transportation.

Given the long history of development for surface launch systems and the lack of currently viable technologies, it is unsurprising there are several challenges to implementing these systems. All surface launch systems require a large investment in infrastructure. This investment might be comparable to developing a new launch vehicle and supporting ground infrastructure, but further studies are necessary to accurately compare these costs as well as the utility of each system.[84] Many surface launch system designs significantly restrict potential missions and, once built, lack the flexibility to accommodate evolving requirements. Gun or tubular systems restrict payload size and shape, while immobile rail or gun systems restrict launch trajectories and subsequent orbital planes.[85] Trajectory constraints can be mitigated at the expense of additional propulsive energy by subsequent launcher stages with controlled propulsion. Also, the location of a surface launch system will have to be carefully chosen. Surface features or position on the globe can affect flight characteristics and infrastructure requirements, and the effects of sonic booms on local population may restrict some locations or launch windows.[86]

In addition to operational challenges, surface launch technologies have several technical challenges. Slingatrons with sliding payloads, chemical guns, and EM launchers that have contact between the launch vehicle and the rail require low-friction surfaces to extend barrel or rail lifetimes.[87] All chemical systems require physical reloading procedures, and some of these systems may need refurbishment between launches due to damage caused by high-pressure shock waves. Surface launch systems with high muzzle velocities in dense atmospheres may require drag reduction technologies as well as airframes that can take increased loads.[88] Electromagnetic systems designed to reach hypersonic velocities require high-pulse power systems with precise timing. Advances in flywheels, superconducting magnetic energy storage, or ultracapacitor banks may be necessary to meet these power requirements. Many of these challenges can be mitigated with new technologies. However, each of these designs is dependent on either long (i.e., thousands of kilometers) barrels or tracks or very high accelerations (i.e., several thousand times gravity for orbital muzzle velocities from the Earth's surface).

Given the challenges and physical constraints of surface launch systems, applications for these technologies will be limited to specific missions at a few locations. Currently, electromagnetic systems appear to have the most flexibility and may provide a pathway to practical surface launch systems. Orbital systems could provide high mass throughput for ISRU materials from the surface of the Moon, or another planetary body with a thin atmosphere, to an orbital staging point. This approach may be practical if valuable, rugged ISRU materials, such as water, propellant, or building materials are available in large quantities and an apogee boost motor that can survive high accelerations is developed. For low-acceleration applications, like crew launch, linear induction motors can provide stage assist for a launch vehicle, potentially providing an initial launch velocity of several hundred feet per second and doubling or tripling payload mass.[89] Launch assist systems could build on technologies that assist aircraft launch and high-speed trains, potentially decreasing infrastructure development costs. In the next 40 years, it is unlikely that surface launch systems will provide a breakthrough for all aspects of access to space; however, they may supplement other breakthroughs, providing an important addition to the breakthrough capability.

New Physics

There are several potential systems for accessing space that rely on unverified physical principles. Although these principles are not fully explained, there is experimental and computational evidence to indicate that a breakthrough is possible. In general, breakthrough concepts that rely on new physics consist of methods for generating and storing energy. It could be possible to create a system that uses this energy to propel a payload to space. Alternatively, these new physics concepts could result in interplanetary travel technologies or power generation systems. At the current stage of research, it is impossible to know if or when these concepts will develop into a technology or how they will manifest. However, if they are successfully developed, these technologies will provide a breakthrough potentially representing several orders of magnitude improvement over the current state-of-the-art in propulsion or power generation.

New physics technologies are on the edge of scientific acceptance and the scope of this report. They are also crosscutting between several breakthrough capabilities, including Easy Access to Space, Efficient Interplanetary Travel, and Ubiquitous Access to

Abundant Power. More information on these concepts and their potential applications can be found in the New Physics excerpt, on page 27.

Technology Trajectory

Current space access technologies are the result of incremental improvements on historic rocket technologies. These technologies use chemical propellant in various forms, including solid rockets, bi-propellant, and mono-propellants, with the most advanced systems consisting of cryogenic liquid oxygen and liquid hydrogen rockets. These improvements have not resulted in a significant decrease of cost to access space and, according to an unofficial log, launch frequency has decreased in the last 40 years with relatively constant launch success rates.[90] Current commercial development activities have the potential to reduce launch costs by a factor of 2 or more, in part through improved manufacturing techniques and operations, and further improvement may be possible with increased launch rates. However, these next generation commercial systems will not achieve an order-of-magnitude reduction in cost or improvement in frequency and safety. To achieve Easy Access to Space, current incremental development will have to shift to breakthrough technologies and new operational concepts, such as fully reusable, low-cost launch systems, and processes may be required.

Current and historic space access systems are primarily designed for operation from Earth to orbit; however, both the U.S. and former Soviet Union have experience with launching from other planetary bodies. During the Apollo program, NASA managed six Moon landings and subsequent returns from the lunar surface.[91] The Soviet Union successfully launched and retrieved three lunar robotic sample return missions between 1970 and 1974.[92] In the next 40 years, access to space from other planetary bodies may continue to rely on a subset of terrestrial technologies. Alternatively, it may become desirable to develop an optimized launch system for a frequently visited planetary system or one with a permanent human presence.[93] Additional research and development will be necessary to design, select, and develop breakthrough concepts optimized for non-terrestrial environments.

Based on current activities, there is a foreseeable technology trajectory to developing breakthrough technologies that will significantly alter how humanity accesses space. Breakthrough technology concepts for access to space have been proposed since the 1960s, and new or modified ideas are common in academic literature. Current research indicates that several near-term technologies may be viable and could begin a new technology development path. Some of these technologies were highlighted in the *Technology Horizons: Game-Changing Technologies for the Lunar Architecture* report:

- Advanced Cryogenic and Liquid Oxygen (LOX)-based Propulsion Systems: A simplified propulsion stage that includes self-pressurized tanks, a low-pressure engine, elimination of the chilldown sequence, and multiple restarts.

- High Energy Density Matter Cryogenic Solids: Freezes a propellant that is normally a gas or liquid at room temperature into a solid propellant grain.

- Air-Augmented Rocket: Combines a conventional rocket with an ejector that ingests, compresses, and mixes atmospheric air with additional fuel and the hot rocket exhaust.

- Electrically Controlled Solid Propellant (ESP): A solid propellant for thruster and ignition systems that is throttlable, re-startable, and environmentally sound.

- Nanoenergetics: Metastable Intermolecular Composites (MIC): Mixtures of nanoscale powders of reactants that exhibit high exothermic behavior.

- Pulse Detonated Wave (PDW) Rocket: Operates by injecting propellants into long cylinders that are open on one end. An igniter activates the propellant, causing a detonation, from which the pressure pushes the exhaust out the open end of the cylinder, providing thrust to the vehicle.

Research communities for most of the technologies listed in this report remain fairly small with a limited number of potential users. Beamed power technologies may be an exception due to potential overlap between beamed power for propulsion and energy distribution, including the space-based solar power community. Air-breathing rockets have a relatively large research community within the DoD and other governments outside the U.S. These research activities could lead near- and mid-term technology development. Skyhooks and surface propulsion systems are longer-term concepts and currently have less investment than air-breathing rockets. Material breakthroughs that enable skyhooks and surface propulsion systems may develop in the broader economy; however, the space industry will need to invest in system technologies to develop and validate these capabilities. Nuclear rockets may also be a farther term technology, especially for systems that are approved for operation in the Earth's atmosphere. Interplanetary nuclear systems may develop first, allowing proven technology to be incorporated into the first generation of space access nuclear systems. Unlike other breakthrough capabilities, technologies for access to space will predominately be developed by the space industry. Consequently, development trajectories for these technologies will depend on investment from NASA and other space-oriented organizations.

Development for new space access systems can take years or decades and often represents a large capital investment. It is possible space transportation systems in 2050 will be composed of rockets based on relatively minor incremental improvements over current systems. If a breakthrough in access to space occurs, it will likely require development of precursor systems in the next decade. Technologies highlighted in the *Technology Horizons* report may provide an initial step to a breakthrough capability. Current research efforts for these and other next generation space access systems are ongoing at NASA, the DoD, academia, and international organizations. In addition, several terrestrial markets are developing technologies that could evolve to support space access systems. NASA may find potential partnerships from these communities leading to technology co-evolution.

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In several of the breakthrough capabilities, there is a possibility of new technologies arising from a breakthrough in physics. These technologies lie on the edge of this report's scope, specifically the requirement that included technologies "feasible within the known laws of physics" and "be realistic and achievable based on current experimental results or demonstrated technologies." These breakthrough technology concepts, collectively referenced as 'New Physics,' derive from some kernel of experimental or computational evidence, but the theories that tie this evidence to the body of scientific knowledge are unverified or have yet to be developed. Consequently, technologies based on these unverified physical principles cannot be confidently predicted, and estimates of when or if they will develop remain conjecture. However, envisioned technologies that may develop from new physics would have a substantial impact on space exploration, in addition to all other human activities. Moreover, it is possible that technologies built on new physics will arise within the 40-year timeline of this report.

New Physics technologies identified during the research for this report primarily support Ubiquitous Access to Abundant Power, Efficient Interplanetary Travel, and Easy Access to Space. Although it is possible to envision New Physics breakthroughs for any engineering application, workshop participants, interviewees, and third party research primarily identified new physics technologies based on energy systems with applications in energy generation and propulsion. Breakthroughs in these areas could have the largest impact on space exploration. With a breakthrough in New Physics, human and robotic explorers may be able to travel rapidly to any point in the solar system, and interstellar robotic probes might be possible. Lightweight, fully reusable launch vehicles could have substantially larger payload mass fractions. Small, lightweight, and portable power sources will provide sufficient energy for complex, power-intensive applications like ISRU, greenhouses, large environmentally controlled habitats, and in-space manufacturing. This section cannot provide an exhaustive list of potential New Physics breakthroughs, but some of the most promising areas of research, recommended by subject matter experts, are briefly highlighted below.

Low Energy Nuclear Reactions

Low energy nuclear reactions (LENR) is field of scientific study to explain anomalous energy readings from experiments on specially prepared surfaces. Current hypotheses suggest that these energy readings result from nuclear binding energy released when light elements capture neutrons. Moreover, these reactions are catalyzed by the metal hydride surface, significantly increasing their frequency. One theory, which is in the process of being tested, suggests that heavy electrons are captured by protons on the surface of the metal hydride, resulting in a neutrino and low-momentum neutron. Secondary reactions from neutron capture by light elements, such as lithium, release energy in the form of heat. Research into LENR faded after initial theories were disputed, however, in recent years there has been a resurgence of interest at NASA, Army Research Laboratory, and respected academic institutes and physics communities. Experiments within this field still yield unpredictable results, and proposed theories remain controversial. Significantly more research is necessary before a theory for LENR can be validated, or the phenomena can be dismissed. However, if a validated theory leads to a functional, efficient, flow-through device, then LENR systems may enable future launch systems, interplanetary travel, and scalable, portable power systems.

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Positronium and Other Positron Storage Systems

Antimatter-matter reactor concepts that rely on positrons require new techniques for long-term storage of positrons. Experimental results show that electrons and positrons can bind to form a positronium atom, however, average lifetimes of these exotic particles are around a hundred nanoseconds. Experimental evidence for molecular positronium suggests that macroscopic assemblies of positrons and electrons are possible, however, lifetimes remain very short. New hypotheses suggest stable states of positronium can be prepared, which separate the electric and positron from their normal orbital radius of about 1 angstrom to a radius over 1000 angstroms. Electromagnetic fields are used to create potential wells that separate the particles, and various techniques may enable a transition from normal positronium states to the stable configuration. Methods for achieving stable positronium are under investigation in domestic and international academic institutions and small research firms. Currently, experiments have not verified these hypotheses, however, if successful, this work may enable long-term storage of positronium for multiple years, enabling cheap antimatter fuel.

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Metastable Innershell Molecular States

Metastable Innershell Molecular States (MIMS) are proposed molecules that may form from quickly compressing atoms with pressures greater than 100Mbar, roughly 100 million times Earth's atmospheric pressure at sea level. In a typical molecule, bonds form between the outer electron shells of the atoms. Theories for MIMS molecules suggest bonds can form between inner electron shells under precise conditions. These innershell bonds have much higher bond energy than outer shell bonds, and consequently far more energy is released when these bonds are broken. Current hypotheses suggest that MIMS can be formed if two atoms are compressed at very high pressures in a time scale smaller then the thermal ionization time of the outer electrons. In practice this may occur from high-speed collisions of nanoparticles. Under these conditions, the outer electrons cannot ionize and carry away the excess collision energy, and instead the inner electrons form a molecular bond storing this energy. Interest in new physical properties for high-energy-density states is expanding in the physics community, however, research into MIMS is limited to a few institutions. Published data suggests MIMS can be formed with current experimental capabilities, however, further research is necessary. If the theory can be refined and MIMS can be efficiently produced, a high-energy-density rocket fuel exceeding current chemical performance a factor of 1000 may be possible.

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Metallic Hydrogen

Metallic hydrogen—hydrogen atoms in a solid crystalline lattice—is a theoretical form of matter, which may be produced at very high pressures. Current theory suggests metallic hydrogen can form from molecular liquid hydrogen at constant pressures in excess of 400 GPa, almost 4 million times the Earth's atmospheric pressure, and may be proceeded by a liquid metallic hydrogen phase. Computational evidence also suggests that, once formed, metallic hydrogen remains in a metastable state if pressure is reduced to ambient conditions, enabling a stable, high-energy-density fuel. This metastable state should have a critical temperature above which the hydrogen atoms recombine into molecular hydrogen, releasing 20 times more energy than liquid oxygen and liquid hydrogen rocket fuel. Currently this critical temperature is unknown, and metallic hydrogen may require significant thermal energy to trigger a reaction. In addition, related theories suggest that metallic hydrogen in a metastable state may be a room temperature superconductor, a significant breakthrough that directly affects power systems and potentially other exploration systems. Current research into metallic hydrogen remains theoretical, because steady-state pressures of 400 GPa have not been achieved on Earth. Moreover, estimates of the phase transition are not consistent, and metallic hydrogen may form at pressures in excess of 600 GPa, if at all. Current equipment, specifically diamond anvil cells, have achieved pressures up to 320 GPa with continuing improvement, providing some hope that experimental evidence may develop in the near term. Envisioned applications of metallic hydrogen commonly include efficient, high power monopropellant for rockets; depending on physical characteristics of metallic hydrogen, other applications may be possible.

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Structural Bond Energy Release (SBER)

Structural bond energy release is a theoretical mechanism for storing and violently releasing energy in solid-to-solid phase transitions. An example of a solid-to-solid phase transition is graphite to diamond. Both graphite and diamond are crystalline forms of pure carbon, however, they have different bond structures, and diamonds store a little more bond energy per atom than graphite. Some hypotheses suggest that considerable energy can be stored in specially prepared metastable solids that undergo a high-energy solid-to-sold phase transition. A commonly referenced example is a composite carbon particle with a nanodiamond core constrained by a surface of hexagonally bound carbon, similar to a nanotube or buckyball. Other potential materials for SBER include polymeric carbon monoxide (a solid polymer formed from carbon monoxide molecules), polynitrogen solids, and boron crystal structures. Initial research with polymeric carbon monoxide suggests energy storage in SBER materials is very dependent on the formation process, and in some experiments exceeded energy densities of high performance explosives. New phases of solid matter and methods to ensure stability at ambient conditions may be necessary to achieve high-energy-density storage with SBER, potentially exceeding performance of other energetic materials by more than an order of magnitude. Even without new phases of matter, SBER may enable high-power-density storage for rocket propellant. In several candidate SBER materials, including the nanodiamond example, high-velocity impacts or other triggering mechanisms can very quickly and violently release stored energy, resulting in a cloud of hyper-velocity molecules, potentially including reactive products that quickly combust with oxygen. If successfully developed the products from these reactions would include combustion energy and high velocity gas, indicating SBER materials could be ideal candidates for rocket propellant. Other potential applications include explosives for ISRU, nano-scalpels using laser triggered nanodiamonds, and shape changing materials through controlled solid-to-solid phase transitions.

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Quantum Vacuum Energy Conversion

Currently accepted theories of physics describe constant fluctuations between electrodynamic fields and subatomic particles on the quantum level. Even in a perfect vacuum with zero thermal energy (0 K), virtual particles can pop in and out of existence. According to developing hypotheses, energy and mass fluctuations in the quantum vacuum may represent an untapped power source. Observed phenomena such as the Casimir Force, an observed attractive force between two conducting plates separated by a vacuum, lend credence to these hypotheses. Proposed methods for extracting energy from the quantum vacuum vary. Conceptually simple methods include parallel plates capable of switching electrical properties between conducting and non-conducting states to enable a Casimir-driven motor. Recent advancements by MIT in modeling the Casimir Force may enable future development of a Casimir motor. Other methods can be very complex and may border on concepts proposed in science fiction. Currently, functioning technologies to extract energy from the quantum vacuum have not been designed, and the capability to extract energy, much less the magnitude of accessible energy, remains conjecture. However, if technologies do develop, there is some possibility that future space exploration systems will incorporate power and propulsion systems with capabilities many orders of magnitude beyond current state-of-the-art.

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EFFICIENT INTERPLANETARY TRAVEL

Lightweight, highly-maneuverable, and rapid transportation to and around locations in space

EFFICIENT INTERPLANETARY TRAVEL

Lightweight, highly maneuverable, and rapid transportation to and around locations in space

BREAKTHROUGH

Systems that provide transportation between and around locations in space. New technologies enable flexible interplanetary transportation. Inexpensive, very efficient systems to preposition cargo. Low-mass, highly-maneuverable, rapid transportation reduces travel time for crew.

Long travel times associated with interplanetary exploration missions negatively impact crewed and robotic exploration. Missions to other planetary bodies are limited by current propulsion systems and can take months or years. *Spirit* and *Opportunity* both took over 200 days to reach Mars, whereas an optimized "fast transfer trajectory," highlighted in a 1997 Mars reference mission, requires 180 days to reach Mars.[94] Missions to the outer planets can take much longer, like the Cassini Mission, which traveled for almost seven years.[95] These long transit times expose human crew to increased levels of radiation and can impact crew health, physical fitness, and mental stability. Robotic missions do not have the same constraints as human missions; however, long transit times require advanced planning and increase the potential for mission-ending equipment faults or other unpredictable events. In addition, current propulsion systems limit orbital transfer windows, increasing the risk of cost overruns and significant delays.

Long interplanetary transit time and restricted mission windows are the direct results of current propulsion system limitations. Chemical systems are inefficient, requiring large amounts of propellant, heavy engines, and significant cost to achieve quick transit. Current electric propulsion technologies enable complex, customized trajectories that minimize propellant, however, these systems have limited thrust and require very long burn times. To support human exploration, high-power propulsion systems would have to be coupled with very-high-power energy sources that have low mass.[96]

With a future breakthrough in Efficient Interplanetary Travel, transportation systems will transcend current capabilities, providing lightweight, highly-maneuverable, and rapid transport to exploration locations of interest. Onboard propellant will last longer, and mission transport times may cease to be a challenge for interplanetary travel. Spacecraft propulsion will be flexible, enabling customized trajectories to save fuel, continuous propulsion for rapid transit, and high thrust for key orbital maneuvers around gravity wells. High-thrust propulsion systems with thousands, or even hundreds of thousands, of seconds of Isp may enable large exploration missions that are both efficient and timely. Near-term technologies, such as aero braking and complex orbital trajectories, will continue to complement breakthrough technology concepts, improving performance around planetary bodies. Some interplanetary propulsion systems will scavenge propellant or use energy from the environment to reduce propellant mass. Technology breakthroughs could eventually lead to transportation systems that haul thousands of tons of cargo and rapidly transport crew, potentially shortening transit time to Mars from months to weeks or even days.

A breakthrough in Efficient Interplanetary Travel will open every corner of the solar system for human and robotic exploration. Humans and robots will be able to travel to more locations and will no longer be constrained by planetary alignment for launch windows. Direct transit to the outer planets or toward Mercury will be possible. Rapid transport by the quickest route will increase crew health and safety while maximizing time for exploration. Complex trajectories that exploit gravity wells, Lagrange points, and chaotic transfers will enable transportation with minimal or no propellant. In the future, it is also possible that regular trade will occur between locations of economic value, prompting the construction of a permanent transportation infrastructure.

Related Capability Areas

Transportation is a critical element of exploration and could impact each of the breakthrough capability areas. In most cases, interplanetary travel technologies affect other capability needs through constraints on what can and cannot be included in a mission. In some cases, rapid transit or high maneuverability will enable new approaches for other capability needs, for instance, minimizing crew exposure to radiation rather than developing new shielding. There are three capability needs in particular that are closely tied to and trade against Efficient Interplanetary Travel when planning exploration missions.

- **Ubiquitous Access to Abundant Power** – Details several breakthrough concepts that can provide high power with a low ratio of power plant mass to power output, known as alpha (kg/kW). Many interplanetary propulsion concepts rely on an internal power source to power electric thrusters. The performance of these concepts will be directly dependent on the alpha of the power plant.

- **Easy Access to Space –** Provides the first step for Efficient Interplanetary Travel. Opportunities exist for synergies or shared technologies between these breakthrough capabilities. Variable thrust systems may be used for various stages of space transportation, including planetary launch, escape from a gravity well, and interplanetary costs. In addition, realized capabilities for Easy Access to Space will directly affect potential interplanetary propulsion systems. Constraints on launch mass and volume will impact the size and design of interplanetary spacecraft and associated propulsion systems. Launch systems with high mass throughput can lift more propellant, reducing the need for efficient interplanetary propulsion systems.

- **Space Oasis –** Represents a staging point between access to space and interplanetary travel. Oases can provide facilities and resources for constructing interplanetary systems or refueling and refreshing consumables. Interplanetary spacecraft could use multiple space oases along a transit path to refuel and provide additional resources for the crew. Like cars and gas stations, spacecraft and space oases will require standardized interfaces for transferring propellant and resources. Developments and breakthroughs in the area of space oasis will impact system design for breakthrough interplanetary concepts and may influence propulsion system selection. In an interplanetary transportation network, space oases will likely become high-traffic nodes, providing repair and refueling services.

Supporting Technology Concepts

Multiple application-specific technology solutions may together provide a breakthrough capability in Efficient Interplanetary Travel. Cargo missions and equipment prepositioning that do not require rapid transport may use propulsion systems optimized for efficiency to minimize propellant expenditures. Prepositioned equipment may include robotic explorers or automated ISRU systems that prepare the way for human exploration and provide propellant for later missions. Time-sensitive transportation, including crewed missions, may use breakthrough technology concepts optimized for high thrust and rapid transit. If supported by prepositioned depots or ISRU, these systems could refuel at key locations and further reduce transport times. Eventually, these transportation options may develop into a network of interplanetary transport routes.

This section highlights several technology concepts that could contribute to a breakthrough in Efficient Interplanetary Travel. These concepts specifically target breakthroughs in interplanetary propulsion, while elements of vehicle design, life support, and habitability are addressed in other breakthrough capability chapters. Several propulsion systems include power plants and are closely related to some power generation technologies. This section discusses the propulsion aspect of these technologies; further information on potential breakthrough power technologies is included in the Ubiquitous Access to Abundant Power chapter. Other technologies that could affect interplanetary propulsion systems, including carbon nanotubes, plasma technologies, high-strength materials, integrated systems health management, thermal management, and high-temperature materials are discussed in Crosscutting Technologies, page 216.

The information included below is based on open-source research, workshops with subject matter experts, and individual interviews. Several breakthrough concepts are grouped into technology areas, such as nuclear reactor propulsion systems. Multiple breakthrough technologies could arise from these technology areas, and specific examples of these technologies are highlighted. However, the discussion emphasizes the range of capabilities these technologies can provide. The technology concepts do not reflect an exhaustive list, but provide a range of concepts that could be developed prior to 2050.

Supporting Technology Concepts	
Nuclear Reactor Propulsion Systems	Provide power for propulsion with nuclear reactors.
Nuclear Pulse Propulsion	Propulsion with controlled explosions of nuclear fuel.
Solar-Powered Propulsion	Propulsion with power from the Sun.
High-Thrust, High-Isp Electric Propulsion Systems	Provide propulsive force through electrically-powered thrusters.
Beamed Power Propulsion	Provide energy for propulsion from off-board systems.
Matter-Antimatter Propulsion	Use stored antimatter to provide high energy for propulsion.
Tethers	Use momentum exchange tethers to propel payload between orbits.

Nuclear Reactor Propulsion Systems

Propulsion systems built around nuclear reactors are common in conceptual space exploration architectures. In 1961, in a letter to the U.S. Vice President, Wernher von Braun highlighted the potential for using nuclear rockets for deep space propulsion.[97] Many studies and conceptual architectures of interplanetary nuclear propulsion have been proposed since Apollo. The 1989 "90-day" study identified nuclear propulsion as a promising approach for a human mission to Mars, as did several NASA Mars Design Reference Missions. These studies specifically identify nuclear thermal propulsion because of its performance advantages, relatively mature technology, and operational flexibility.[98] The 2002 Human Outer Planet Exploration (HOPE) study discusses several nuclear propulsion concepts in the context of a crewed mission to Callisto.[99] Currently, advanced nuclear rockets potentially represent a development pathway to a breakthrough capability.

Nuclear reactor propulsion is a broad technology area covering any breakthrough technology concept that uses a nuclear reactor to provide energy for propulsion. Specific technologies in this area include variations of nuclear thermal propulsion (NTP), nuclear electric propulsion (NEP), and hybrid systems.

PARTNERING OPPORTUNITES

NUCLEAR REACTOR PROPULSION SYSTEMS

- U.S. Department of Energy (DOE) Office of Nuclear Energy
- Argonne National Laboratory, Nuclear Engineering Division
- Oak Ridge National Laboratory: U.S. ITER Project Office, Nuclear Technology Program, Nuclear Science and Technology Division, Fusion Energy Sciences Program, and Fusion Energy Division
- Los Alamos National Laboratory: Science, Technology and Engineering, Select offices in Weapons Programs and Nuclear & High Hazard Operations
- Lawrence Livermore National Laboratory: Physical and Life Sciences Directorate, and National Ignition Facility

NTP systems are introduced in the Easy Access to Space breakthrough (see page 16) and include near-term solid core rockets as well as longer-term technology concepts, such as gas core nuclear rockets. Some of the challenges that affect long-term NTP systems, such as low thrust-to-weight ratios, are less prevalent for interplanetary travel. Gas core nuclear thermal propulsion has been studied for Martian missions. This technology potentially enables transit times of a few months and, by optimizing overall system mass, gas core reactors could increase the ratio of dry mass including payload to 20%.[100] Viable indirect nuclear systems, briefly highlighted in Easy Access to Space, can be expanded here to include a wider range of nuclear-electric concepts, because interplanetary travel requires less thrust than escaping a planetary surface. NEP systems can use any electric thruster and have the potential to achieve very high exhaust velocities (up to 100km/s), leading to specific impulse as high as 10,000 seconds.[101] Consequently, NEP systems require significantly less propellant than NTP systems for similar trips. However, NEP systems tend to have less thrust than comparable NTP systems and could have maintenance and thruster lifetime challenges due to extended burn times.[102] To compete with other transportation systems, NEP concepts will require low-alpha (kg/kW) power systems, including radiators and other external components.[103] A third path for nuclear reactor propulsion systems combines NTP and NEP for a potentially breakthrough concept. This hybrid solution uses a single reactor to provide high-thrust NTP to transfer out of gravity wells and NEP for long-duration acceleration during interplanetary travel. This approach enables quick transit times while minimizing propellant mass and volume and eliminating the spiraling trajectories necessary for traditional NEP.[104]

Interplanetary nuclear reactor propulsion can include both fission and fusion propulsion. Near-term designs are based on fission technology, however, fusion may provide a significant increase in propulsion performance. As noted in the Easy Access to Space chapter, technology pathways to low-neutron fusion fuels exist, which could result in rockets that are safer for crew and do not require large reactor shields. Fusion reactors can power electric propulsion systems or provide high-thrust propulsion by diverting plasma from the reactor to a magnetic nozzle (for more information on “Plasma Technologies,” see Crosscutting Technologies, page 229). These concepts could enable very high Isp, with thrust sufficient enough to accelerate directly to the outer planets. One concept projected Isp of 30,000-40,000 seconds and rapid transit, resulting in a trip of about 150 days to Jupiter.[105] Actual mission designs and performance will depend on technology development for fusion systems but will likely exceed fission performance.

NASA and other organizations have studied interplanetary nuclear propulsion. Human and robotic missions using nuclear propulsion have been proposed for a wide range of destinations, including Mars, Jupiter, Saturn, and the Moon. NASA began technology development on a robotic, NEP mission to explore Jupiter’s moons. Reactor and thruster technologies were advanced under project Prometheus, and a contractor for the Jupiter Icy Moons Orbiter (JIMO) spacecraft was selected prior to cancellation in 2005.[106] Both the U.S. and former Soviet Union have developed and flown nuclear reactors in space. The U.S. flew a SNAP-10A reactor in 1965, and the former Soviet Union launched 34 reactors between 1970 and 1989.[107] These systems are relatively low-power but provide a stepping stone to future NEP systems. Currently, NASA is researching NTP technologies to prepare for a potential crew mission to Mars.[108] The agency is planning on developing NTP technology through the Enabling Technology Development and Demonstration (ETDD) program to support a potential human Mars mission around 2033.[109] NASA has identified several technology areas that require further investment, including maturing composite fuels, reactor design, and building ground test facilities.[110] If developed, this NTP system could provide a 100% increase in efficiency over chemical rockets and may evolve into a breakthrough nuclear hybrid rocket for solar system exploration.[111]

Nuclear reactor propulsion systems have similar challenges as nuclear launch systems. Many technology concepts require, or at least would benefit from, high-temperature materials (see Crosscutting Technologies, "High Temperature Materials," page 219). While leakage of fissionable fuel from gas core reactors on interplanetary vehicles does not pose the same health risk as leaking reactors in the Earth's atmosphere, fuel loss may increase required onboard fuel and impact long-term missions with long burn times. NEP systems require low-alpha (kg/kw) power systems to increase performance.[112] Most nuclear reactor systems will require heavy shielding between the reactor and the rest of the spacecraft, and some designs may require additional plume shielding to protect the spacecraft from energetic propellant plumes.[113] NEP, hybrid, and potential fusion systems require large radiators to remove waste heat, increasing power plant mass. The power system, waste heat, and materials available will determine radiator size and mass and impact spacecraft performance. Breakthroughs in thermal management and heat rejection could reduce the size of these radiators and the impact on performance (see Crosscutting Technologies, "Thermal Management," page 237).[114]

Nuclear reactor propulsion represents a technology development pathway that could lead to breakthrough Efficient Interplanetary Travel technology concepts. Near-term technologies could enable quicker transits to Mars with added benefits of abundant power. Technologies that could develop in the next 40 years, including gas core reactors and fusion systems, could lead to rapid, high-energy trajectories to Mars or the outer planets. These systems are capable of providing high-velocity changes, enabling flexible mobility throughout the solar system.

Nuclear Pulse Propulsion

Nuclear pulse provides a different technical approach to nuclear propulsion. Instead of a stable reactor providing energy for a rocket, a series of supercritical, explosive events provide energy or momentum. A historic, and relatively famous, example of this technique is the Orion Project from the late 1950s to early 1960s. The Orion propulsion concept relied on low-yield (1KT to 1.2 MT) nuclear explosions that were dampened by a large spring-mounted pusher plate to provide interstellar, and potentially, Earth to orbit transportation.[115] Variants of this design include magnetic pusher plants and large sails that capture fission products.[116] This concept has several engineering challenges as well as social and political hurdles, including international law prohibiting tests of nuclear weapons in space.[117] These challenges led to the cancellation of the Orion Project and currently prevent development of similar vehicles. In the next 40 years, it is unlikely that

PARTNERING OPPORTUNITES

NUCLEAR PULSE PROPULSION

- U.S Department of Energy (DOE) Office of Nuclear Energy
- Lawrence Livermore National Laboratory, National Ignition Facility
- Fermi National Accelerator Laboratory, Antiproton Source
- Pennsylvania State University, Department of Physics
- University of Michigan, College of Engineering: Nuclear Engineering and Radiological Sciences

an Orion-type vehicle will be feasible; however, recent papers propose a variant of nuclear pulse propulsion that mitigates some of the engineering challenges and may eliminate the social and political hurdles. This concept uses micro-fusion pulses to potentially enable a breakthrough interplanetary nuclear pulse propulsion system.

Micro-fusion pulse propulsion relies on small pellets of fusion fuel, ignited within a rocket combustion chamber. The resulting explosive pulses are much smaller than the nuclear pulses required for the Orion concept. For comparison, one pellet design is based on a fuel pellet yielding roughly 1800MJ of energy or the rough equivalent of 0.5 tons of TNT, or 0.0005 the strength of the smallest proposed pulse for Orion.[118] A common design for these pellets includes fusion fuel surrounded by a hard metal casing. Deuterium and tritium are considered as fuel sources; low-neutron fuels are also possible albeit more challenging. High-power lasers or antiproton beams are used to ignite the fuel through a pinhole in the casing. Antiproton beams are particularly attractive, since they eliminate the need for massive optics and high-powered laser sources. In the case of the antiproton beam, a subcritical fission target is used to react with the antiprotons and produce high-energy fission products that ignite the fusion fuel.[119] The energy from these reactions could be used to heat a propellant or provide thrust through magnetic confinement and a magnetic nozzle. With a magnetic nozzle, Isp of 100,000 seconds is possible, and system thrust is dependent on the rate of explosions (35,000N for 10 pulses per second).[120] Higher pulse rates for increased thrust are conceivable. Project Daedalus, a concept study by the British Interplanetary Society, baselined another nuclear pulse variant for interstellar travel using inertial confinement fusion and 250 pulses per second.[121] As the pulse rate increases, so do the technical challenges associated with confining and capturing the energy released, and eventually these systems overlap with quasi-steady-state reactors.

Micro-nuclear pulse concepts for in-space propulsion received renewed attention in the 1990s through several conceptual studies.[122] These theoretical efforts focused on pellet and trigger designs to optimize nuclear pulse systems. More recently, fusion research has been advanced for terrestrial applications. Some of these systems utilize a quasi-steady-state reactor with pellet fuel and could be relevant to nuclear pulse propulsion. The National Ignition Facility at Lawrence Livermore National Lab is currently running experiments leading to inertial confinement fusion with laser-ignited fuel pellets.[123] These experiments could support future development of laser-driven micro-nuclear pulse systems. Research at Fermi National Accelerator Laboratory (Fermilab) and other organizations is advancing the production of antiprotons. Current antiproton production capability at Fermilab peaks at about 30×10^{10} antiprotons per hour, or a maximum possible yearly production of approximately 4.5 ng.[124] A conceptual micro-fusion pulse mission to Jupiter would require 1.16 billion ng of antiprotons (or 1.16 grams).[125]

Current designs for micro-nuclear pulse systems are conceptual and several hurdles still block development of practical systems. Laser-driven systems require high-power lasers with mass and volume penalties. For example, the National Ignition Facility requires 192 lasers, which are housed in a building the size of three football fields.[126] New designs, systems, or breakthrough technologies will be necessary to scale this technical approach down to a system applicable to spacecraft propulsion. Antiproton-driven fusion avoids some of these mass and size constraints, however, production of antiprotons is limited and costly. In addition to the fusion-driving system, further research on pellet design, energy coupling, and control of plasma in the reaction chamber may be necessary.

Nuclear pulse propulsion offers a possibility for high-thrust, high-Isp interplanetary travel. Direct flights to Jupiter in four months are conceivable with this technology, opening the possibility of crewed exploration of the outer planets.[127] Thrust to weight of these propulsion systems scale well. For larger missions, thrust can be increased through an increased pulse rate and the marginal mass of additional propellant pellets. Improvements in propellant design could increase the mass efficiency of the fusion reaction, providing additional energy and improving rocket performance. However, nuclear pulse propulsion concepts have several significant technical and operational challenges that will have to be met before these concepts can provide a breakthrough capability for space exploration.

Solar-Powered Propulsion

Solar-powered propulsion includes all technology concepts that use the Sun to provide propulsive energy. Solar-powered technology concepts are designed to minimize or completely eliminate onboard propellant and increase the payload mass fraction. Some solar propulsion systems have less weight than chemical or nuclear systems, but they are dependent on the Sun for acceleration, and propulsive efficiency rapidly drops with distance from the Sun.[128] There are two primary technology approaches for solar-powered propulsion: electric thrusters powered by solar photovoltaic systems and zero-propellant systems that rely on solar wind to provide acceleration. Both these approaches have near-term applications. However, evolutionary pathways could lead to breakthrough technology concepts.

PARTNERING OPPORTUNITES

SOLAR-POWERED PROPULSION

- U.S. Department of Energy Solar Technologies Program
- DARPA Tactical Technology Office
- QinetiQ, Electric Propulsion Division
- JAXA, IKAROS Project
- Arizona State University, Solar Power Lab
- Solar @ MIT
- The Planetary Society
- Various commercial companies producing solar cells

Solar electric propulsion (SEP) is a rapidly maturing technology with potential application to efficient interplanetary travel. For near-term applications, SEP is a mature, and potentially the most practical, electric propulsion technology.[129] Current scientific missions, including Dawn, use SEP systems that consist of relatively small solar arrays (10s of kilowatts) and low-power ion thrusters.[130] For crewed-mission applications, SEP systems will require scaling up with high-power thrusters and megawatt-capable solar arrays (two orders of magnitude above current interplanetary spacecraft capabilities).[131] Breakthroughs in photovoltaic systems, power management and distribution, and potentially rugged or self-repairing solar cells may be necessary to achieve a breakthrough SEP concept.

Solar sails and solar magnetic sails are less mature than SEP, but these systems could enable propellantless exploration missions with decreased transit times. Near-term technologies could enable reduced transit times for planetary flyby missions, where the majority of velocity change is achieved early in the mission.[132] A material breakthrough that reduces the mass of solar sails would further reduce flyby transits, and it may make solar sails competitive with other technologies for planetary orbiters or other missions with high-velocity change requirements. Technologies such as metalized thin films, perforated materials, and carbon nanotube materials could enable large solar sails with radii of several kilometers and aerial densities of < 1 g/m^2.[133] An alternative approach, often referred to as a magnetic sail, employs a superconducting loop to reduce mass. With improvements in high-temperature superconductors, solar magnetic sails could provide propulsive forces comparable to a solar sail.[134] However, to extract sufficient force from charged particles in solar wind, solar magnetic sails need superconducting rings that are tens or hundreds of kilometers in diameter.[135] Solar sails and solar magnetic sails can also be used with beamed energy propulsion systems for increased acceleration over that provided by solar wind alone.

NASA, DoD, other space agencies, and private industry are currently developing technologies that could benefit solar-powered propulsion. DARPA developed a power system for SEP under the Fast Access Spacecraft Testbed (FAST) project. This project was designed to create 30kW array with a power density of 130 W/kg.[136] NASA's proposed 2011 budget includes funding for advanced SEP propulsion. This project is focused on near-term technology demonstrations with 30kWe, based on DARPA's FAST systems and NASA's Evolutionary Xenon Thruster (NEXT) ion propulsion. Future plans include technology trajectories to greatly increase power.[137] Private industry also supports technology development of SEP. Some companies, such as QinetiQ, are developing propulsion systems for space agency partners.[138] Space-based solar power companies are investigating technologies to reduce the weight of power management and distribution systems.[139] Other companies are focused on developing high-efficiency, affordable solar cells for terrestrial markets, and these technologies may impact spacecraft development.

Technologies for solar sails are also advancing. In 2010, Japan's IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) mission successfully demonstrated deployment of an integrated solar sail and thin-film photovoltaic.[140] Concurrent with technology demonstrations, research into lightweight solar sail materials continues. Several conceptual studies have identified missions for solar sails, including a

NASA Institute for Advanced Concepts (NIAC) study that considers the possibility of high-temperature solar sail materials capable of trajectories with close approaches to the Sun. Materials that can withstand the thermal and radiation environment near the solar surface could enable solar sails with velocities up to 4% the speed of light.[141] Carbon nanotube sheets, which have already been produced in single sheets of 4’ x 32’, may provide a precursor to lightweight, high-temperature materials for solar sails. (See “High-Temperature Materials,” in Crosscutting Technologies, for other potentially applicable materials, page 219).[142] For solar magnetic sails, research in high-temperature superconductors with high critical current could support future technology development.[143] Academic labs and companies in the power industry are providing initial research that could be leveraged in a future solar magnetic sail.

There are several challenges with solar-powered propulsion. SEP systems require lightweight, high-power solar arrays. To achieve acceptable accelerations for high-mass, crewed missions, a breakthrough in solar array design may be necessary.[144] Technologies for distributed solar arrays, solar concentrators, and wireless power distribution are needed to enable low-mass, multi-megawatt arrays. Engineering challenges may require new propulsion methods that distribute thrust across the array and the spacecraft. Solar sails require breakthroughs in lightweight materials for high acceleration. Most high-speed trajectories using solar sails require a close pass to the Sun. In addition to needing high-temperature solar sail materials, these trajectories will require advanced thermal protection for sensitive instruments on the spacecraft.

Solar magnetic sails are the least mature of these technologies and will need considerable material research prior to a technology demonstrator. Solar magnetic sails, in their most advanced state, will only extract a fraction of the thrust from solar wind and are several orders of magnitude less efficient than solar sails of the same size. Consequently, larger sails are necessary for increased forces.[145] In addition, deployment of the superconducting magnetic ring will be a major challenge for large-scale systems.[146]

In addition to all the technical challenges, there is a significant challenge to mission operations that will limit solar power propulsion for exploration. All of these systems require proximity to the Sun for acceleration. Several concepts can reach very high velocities with solar flybys, but secondary systems are necessary to provide velocity changes during latter stages of the mission that may occur beyond Mars or the asteroids. Consequently, solar-powered propulsion for the outer planets will be limited to flybys and potentially prepositioning of supplies through solar sail propulsion and aero capture for deceleration. Orbital systems or missions requiring additional velocity changes will need a secondary, high-thrust propulsion system.

Solar-powered propulsion provides an attractive option to reduce propellant in interplanetary exploration missions, however, the limitation of these propulsion systems will restrict their use to the inner solar systems or niche, one-way missions. Solar-powered propulsion could be an important element of Efficient Interplanetary Travel, but it is unlikely to provide sufficient capability to be a primary propulsion system for crewed missions.

High-Thrust, High-Isp Electric Propulsion Systems

Both nuclear and solar electric propulsion systems require electric thrusters. In principle, electric thrusters can be designed to have arbitrarily high specific impulses, however, the thrust provided by these technologies is closely tied to the weight of the propulsion system.[147] For breakthrough electric propulsion capabilities, advancements in thruster power density, efficient energy coupling, and maximum thrust are equally as important as low-alpha power systems. Current electric propulsion systems show promise for technology development pathways for high-thrust electric propulsion systems.

PARTNERING OPPORTUNITES

HIGH-THRUST, HIGH-ISP PROPULSION SYSTEMS

- QinetiQ, Electric Propulsion Division
- Boeing, Xeon Ion Propulsion Center
- Air Force Research Laboratory, Propulsion Directorate
- European Space Agency, Propulsion Laboratory
- University of Michigan, Department of Aerospace Engineering: Plasmadynamics and Electric Propulsion Lab
- Michigan Technological University, Ion Space Propulsion Laboratory
- MIT, Space Propulsion Laboratory

Several near-term electric propulsion technologies could evolve into high-thrust, high-Isp systems. High-power electric concepts include radio-frequency-driven plasma propulsion, magneto-hydrodynamic propulsion, pulsed inductive plasma systems, and nanoparticle or nanodroplet electric propulsion.[148] Many of these systems are currently under development, and some were highlighted in the report, *Technology Horizons*. However, continued development could increase the power density and thrust-to-weight ratio of these systems, leading to potential applications for large crewed missions.

Radio-frequency-driven propulsion is the basis for several high-power plasma thrusters. These systems use radio waves to ionize and sometimes further heat a propellant. Technology variations use electrostatic grids to accelerate ions or magnetic nozzles to direct propellant.[149] Commercial organizations are developing and demonstrating technologies for subscale systems, and megawatt systems could be achievable within 40 years.[150] However, power density is a challenge with radio frequency propulsion, and high-power systems for crewed missions may be too massive for practical space application.[151]

Magneto-hydrodynamic propulsion (MHD) can provide high-thrust propulsion through Lorentz force on currents in conductive plasma propellant. As noted in Easy Access to Space, MHD systems have the potential to create high thrust at relatively high specific impulse. Several different conceptual designs exist, but ground testing can be difficult due to insufficient testing facilities.[152] Like many ion propulsion systems, MHD thrusters have challenges with life-limiting erosion at the electrodes.[153] Both NASA and the Air Force have investigated high-power MHD propulsion systems.[154]

Pulsed inductive plasma systems work similarly to MHD propulsion systems. However, this technology eliminates the electrodes and associated challenges. Pulsed inductive plasma thrusters collect a 'pulse' of propellant on a plate. Strong magnetic fields ionize the propellant and establish an induced current. Lorentz force on the plasma provides micro pulses of thrust.[155] This technology could be used for high-thrust, crewed exploration missions, if the thruster can be pulsed for long durations at 100-1000 times per second. However, current precursors have not indicated potential for this lifetime.[156]

Nanoparticle and nanodroplet thrusters have the potential to provide high thrust-to-weight through large arrays of micro-fabricated thrusters. These thrusters accelerate charged nanoparticles or small droplets of an ionic liquid with electrostatic fields.[157] The size, and potentially the charge density, of these particles can be tailored for a variable range of Isp and thrust. For nanoparticles, theoretical calculations suggest thrusters can be designed for high thrust, ~1N/kW, or high Isp, 1 mN/kW, at 10,000 seconds.[158] Thrusters that can change the size of propellant droplets or particles can enable variable thrust for different propulsion missions. However, current material and design challenges limit further development, including electric shorts from conductive particles, extraction of the nanoparticles, and control of transfer fluids.

High-thrust, high-Isp electric thrusters will enable breakthrough SEP and NEP propulsion systems. Breakthrough electric propulsion technology will likely be based on current electric thruster concepts. However, material improvements, advanced designs, and improved power systems will be necessary to create high-power-density electric thrusters. The impact of electric propulsion on efficient, interplanetary propulsion will depend on the technical evolution of these concepts.

Beamed Power Propulsion

Beamed power propulsion, similar to the systems discussed in Easy Access to Space, can support interplanetary spacecraft. For interplanetary travel, beam sources are likely to be located in stable orbits or on planetary bodies with no atmosphere, to avoid atmospheric attenuation. These systems could be smaller than space access systems with a total power output of ~0.1 to 10 MWs instead of the hundreds of MW to GW required for terrestrial launch applications.[159] With additional power beamers located in space, interplanetary beamed power propulsion could build on launch system capabilities, enabling a single system to provide space access and interplanetary transportation. Potentially, multiple power beamers throughout the solar system could work together to provide acceleration and braking for an interplanetary transportation network.[160]

PARTNERING OPPORTUNITES

BEAMED POWER PROPULSION

- Lightcraft Technologies, Inc.
- Solaren Corp.
- Princeton University, Beam Dynamics and Nonneutral Plasma Division
- University of Maryland, Particle Beam Dynamics Group
- Air Force Research Laboratory, Directed Energy Directorate
- Los Alamos National Laboratory, Threat Reduction Directorate

Like Easy Access to Space concepts, there are two primary approaches to interplanetary propulsion through power beaming: direct and indirect systems. Indirect systems convert beamed energy into electricity to power electric thrusters, providing an alternative to SEP and NEP concepts. Direct systems can include laser and microwave thermal propulsion systems, similar to high-thrust space access concepts that heat onboard propellant. However, for low thrust in space applications, more efficient systems, including direct momentum transfer from the power beam to the spacecraft, are possible.[161] There are several technology variations under direct momentum beam propulsion. Laser-propelled light sails are modified solar sails that reflect directed laser light instead of, or in addition to, sunlight. This concept requires a high-powered laser that can focus on the light sail for several days or longer, depending on the power of the laser and the required velocity change. A second laser at the spacecraft's destination or an alternative propulsion system is necessary to decelerate the light sail.[162]

Interplanetary missions can also use particle beams, in the form of neutral plasma, to provide acceleration through momentum transfer. In these systems, a magnetic sail or electrostatic field deflects particle beams to provide thrust.[163] Cold, neutral plasmas have a self-focusing effect and are used to minimize beam divergence due to thermal variations.[164] Particle beam systems can provide more force than laser-powered light sails. However, interference from the Sun's magnetic field, collisions with interplanetary gas, and beam instabilities limit transmission to relatively short distances, around 100,000 km.[165] More complex hybrid solutions use laser light to propel low-mass sails to high velocities, then ionize these masses before impact with the spacecraft. This technique is primarily proposed for very long missions.[166]

Research into beamed power propulsion includes both conceptual and experimental work and overlaps with other propulsion concepts. Much of the beamed power research discussed in Easy Access to Space also applies to interplanetary travel. In addition, technologies for solar sails, or solar magnetic sails, directly apply to some beamed power system concepts. Conceptual studies incorporate a wide range of proposed missions, including interstellar probes. Several universities have research laboratories specializing in particle beams, plasma propagation, and high-energy lasers.[167] Experimental research into neutral plasma beams includes activities by the Air Force and Los Alamos National Laboratory to characterize beam propagation in magnetic fields.[168] Development of high-energy lasers and particle beams for propulsion could overlap with future weapon systems, power transmission, and fusion technologies.

There are several technical challenges for practical interplanetary beamed power transportation systems. Beam divergence is a major challenge for both laser and particle beams over interplanetary distances. The development of large optics capable of low divergence or divergence-free propagation over millions of kilometers is necessary for laser systems.[169] For particle beams divergence, interference from magnetic fields and collisions could limit acceleration periods to relatively short distances, such as cislunar orbit, requiring high-power beams for quick acceleration.[170] Momentum transfer systems require a secondary power beam, or an alternative propulsion system, at the target exploration site to decelerate and provide propulsion for return trips. Indirect systems may also require a secondary power beam, if beam technical challenges for divergence cannot be overcome. To improve transmission efficiency, optical and particle beam systems will have to be built in orbit or on planetary bodies without atmosphere, thereby avoiding atmospheric scattering and attenuation.

Beamed power systems for interplanetary propulsion could enable efficient and rapid transport to any point in the solar system but are limited by beam power and propagation distance. Spacecraft propulsion systems are likely to be lighter, with this technology requiring thrust components but not power generation systems. Stationary power systems can be maintained and reused for several missions, reducing mission cost. Electric thrusters, momentum transfer, or thermal systems can be chosen on performance characteristics and mass for specific missions. Beamed power propulsion may support both human and robotic exploration throughout the solar system.

Matter-Antimatter Propulsion

Matter-antimatter propulsion has the highest energy density of any conventional physics approach to propulsion. Antimatter, in the form of positrons, has an energy density of 10 billion times current chemical rockets.[171] With appropriate facilities and sufficient energy, antimatter can be manufactured on Earth in a variety of particle types. Concepts, and some functional designs, for long-term storage of antimatter potentially enable an energy storage system equivalent to extremely powerful batteries. Consequently, antimatter represents an ideal power technology for interplanetary propulsion.

Several different propulsion technology concepts are based on antimatter. Antimatter can be manufactured in as many varieties as normal matter, including atoms, positron (antielectrons), antiprotons, and all other varieties of bosons and fermions. Rockets that use antiproton fuel are particularly attractive, since the reaction between a proton and antiproton produces high-energy charge carriers. Thrust can be directly harvested from these charge carriers with magnetic nozzles, like systems designed for fusion or plasma rockets.[172] Positron reactions produce gamma rays, which can be harder to harvest for thrust. Positron rocket concepts include solid and gas core positron thermal rockets, which are similar to nuclear thermal systems and have the same technical challenges except for residual radiation.[173] In addition, both positrons and antiprotons can be used for ablative propulsion with pusher plates or large sails.[174] Most antimatter propulsion concepts are designed for interplanetary or interstellar transportation; however, it is conceivable that

PARTNERING OPPORTUNITES

MATTER-ANTIMATTER PROPULSION

- Lawrence Livermore National Laboratory, Physical and Life Sciences Directorate
- Fermi National Accelerator Laboratory, Antiproton Source
- Brookhaven National Laboratory, Collider-Accelerator Dept.
- CERN, Physics Department
- Positronics Research LLC
- Australian Research Council Center of Excellence, Center for Antimatter-Matter Studies

high-thrust systems could be developed for launch, potentially including launch in a dense atmosphere.

Due in part to the scarcity of antimatter, experimental research into antimatter propulsion technologies is limited. However, related research is ongoing. Basic research programs for the creation, use, and storage of antimatter can be found at national laboratories, including Lawrence Livermore and Fermilab; international organizations, such as CERN (Conseil Européen pour la Recherche Nucléaire—European Council for Nuclear Research); domestic and foreign universities; and even a few private companies. [175] These facilities have matured long-term storage techniques for small amounts of antiprotons in Penning Traps. In addition, methods for storing large quantities of antimatter, both as non-neutral plasmas and antihydrogen, are being investigated.[176] Research activities specific to interplanetary spaceflight include concept development and mission design. Related conceptual studies also exist, including harvesting antimatter from free space or within magnetic field lines around a planet.[177]

There are several challenges associated with antimatter propulsion, and they differ depending on the type of antimatter. For antiprotons, cost is the main challenge. As of 1999, the projected production cost of antiprotons was around $62.5 trillion dollars per gram and was primarily dependent on production efficiencies.[178] However, antiprotons are relatively easy to store and can be easily coupled to a propulsion system. Positrons, on the other hand, are relatively inexpensive to make, but there is no proven technique for long-term storage. Current concepts for developing this technology require new and unverified physics.[179] Other antiparticles receive less attention, but they have similar issues with production and storage. In addition to these main challenges, there are engineering challenges to developing antimatter rocket technologies, and significant near-term research and development will be necessary for this concept to develop by 2050.

Antimatter rockets are based on the most efficient fuel possible, given our current understanding of physics. These systems could provide high thrust with a fraction of the propellant necessary for other rocket concepts. Antimatter rockets could enable very large, crewed missions with trajectories that require high-velocity changes, leading to rapid transit to any point in our solar system. However, these rockets will require a large supply of relatively inexpensive, stable antimatter. Consequently, basic research is still necessary to validate these breakthrough concepts.

Tethers

Momentum exchange tethers for interplanetary transfer build on the skyhook and space elevator concepts, discussed in Easy Access to Space, to provide an interplanetary propulsion system. In addition to providing access to space, rotating orbital tethers can be used for a number of other propellantless momentum transfer applications, including reboosting or deorbiting payloads, providing changes to orbital inclination, and interplanetary travel.[180] Momentum exchange, tether-based interplanetary travel systems have been evaluated for the Moon, Mars, and other planetary bodies.[181]

PARTNERING OPPORTUNITES

TETHERS

- European Space Agency, Young Engineers Satellite (YES2) Project
- Tethers Unlimited, Inc.

Interplanetary tether systems involve complex orbital rendezvous and multiple tether systems to provide propellantless, roundtrip interplanetary propulsion. A single transport leg usually consists of at least two tethers orbiting respective planetary bodies, although the catching tether can be eliminated with aerocapture. Each tether includes a counterweight and has a large center of mass, relative to the payload. Multiple sets of tethers can provide additional transfer opportunities for planetary bodies in different orbital planes.[182] After launch from the planetary surface, the first tether captures the payload and releases it further from the planetary body, increasing the payload's orbital velocity and sending it on a rendezvous trajectory to the second planetary tether system, like an acrobat on a trapeze. The second tether captures the incoming payload and releases it in a suborbital trajectory to the planetary surface.[183] Unless the exploration architecture is designed for equal outbound and inbound mass transfer, these tethers have to be periodically reboosted. Reboosting can be accomplished with a near-term propulsion concept, using a conductive tether and Lorentz force to enable propellantless propulsion in a magnetic field.[184]

NASA and other space agencies have launched and tested technology demonstration missions that could lead to interplanetary momentum exchange tethers. In 2007, the Young Engineers Satellite (YES2) experiment, sponsored by ESA, demonstrated reentry of a capsule using a 31.7 km tether.[185] In 1996, an electrodynamic tether experiment was conducted from the Space Shuttle. Flaws in the tether led to excess electrical current and destroyed the tether, but the initial results verified the concept.[186] NASA also developed a combined momentum exchange and electrodynamic tether experiment prior to the Columbia accident. However, the experiment was canceled, citing potential risk to the International Space Station.[187] In addition to technology demonstrations, several studies have assessed interplanetary tether systems and identified potential designs, optimal trajectories, and material requirements.

There are several challenges associated with interplanetary tether systems. The material challenges associated with momentum exchange tethers are not as severe as those associated with the space elevator. However, high-strength, rugged, multi-kilometer-long tethers have to be developed and tested (see Crosscutting Technologies, "High-Strength Materials," page 217). Tether capture can also be a significant challenge. A Mars transport vehicle would have a rendezvous velocity around 12-13 km/s. Although tether rotational velocity is relatively low, conjunction between the spacecraft and the tether is limited.[188] Techniques for prolonging rendezvous up to a few minutes are possible, but capture could still be a challenge, and there are no second attempts.[189] Depending on the local orbital environment, the tether high tip speeds could increase the risk of tether malfunctions due to debris impact. Capturing and releasing payloads could result in shock waves through the tether, impacting performance or potentially damaging the tether. Some systems may require vibration-damping systems to compensate.[190]

In addition to these technical challenges, there are several operational challenges without easy technical solutions. Interplanetary momentum exchange tethers require preplaced infrastructure. These systems are unlikely to be cost-effective, unless frequent travel occurs between the planetary bodies. Each throwing-catching pair provides a limited number of launch windows dependent on the harmonics of the planetary bodies and tether systems.[191] To increase the number of launch windows, multiple tether systems will be required, further increasing the necessary infrastructure. Finally, propellantless reboosting through electrodynamic tethers only works around planetary bodies with strong magnetic fields. For other systems, reboosting may be dependent on propellant, effectively limiting the maximum amount of mass that can be transferred.

Momentum exchange tethers provide a rapid, propellantless option for interplanetary transfer. A tether system with a tip speed around 2.5 km/s could enable Mars transit in 130-160 days or as little as 90 days with aerocapture.[192] This system is attractive for rapid transit of frequent cargo missions between two planetary bodies. Momentum exchange tethers could contribute to a breakthrough in Efficient Interplanetary Travel, but this system is not sufficient to enable a breakthrough as a standalone technology. The identified challenges may prevent crew transfers via momentum exchange tethers. Even if tethers are large enough and deemed safe enough for crew missions, the required infrastructure and limited transit windows prohibit the system from providing lightweight, highly-maneuverable, and rapid transportation to and around locations in space.

New Physics

As discussed in Easy Access to Space, there are also several concepts for Efficient Interplanetary Travel that rely on unverified physics. Similar to new physics concepts for Easy Access to Space and Ubiquitous Access to Abundant Power, most of these concepts focus on methods of generating or storing energy. These concepts could result in a breakthrough interplanetary propulsion system with performance well beyond what is feasible with demonstrated theories. Due to their unverified potential, these concepts are not discussed in Efficient Interplanetary Travel. Instead, more information on these concepts and their application to interplanetary travel can be found in the New Physics excerpt, page 27.

Technology Trajectory

NASA and other space agencies are implementing new approaches for interplanetary propulsion. In 1998, the Deep Space 1 technology demonstration mission validated the first application of SEP in deep space.[193] This thruster was transitioned for the discovery class mission DAWN, and currently NASA is developing a next generation xenon thruster, NASA's Evolutionary Xenon Thruster (NEXT), with improved performance.[194] JAXA is developing another approach for interplanetary propulsion, through a technology demonstration of solar sails. The IKAROS technology demonstrator, launched in May 2010, successfully deployed and demonstrated a combination thin-film solar sail with embedded solar cells. The project has demonstrated propulsive force and electricity generation.[195] Finally, satellite propulsion using electrodynamic tether technology is being researched by space agencies and private industry.[196] These technologies could provide initial momentum for the development of breakthrough interplanetary propulsion systems.

Building on current research, there are several technologies related to breakthrough technology concepts that could develop within the next 10 to 15 years. These technologies follow evolutionary paths to a potential breakthrough capability, and some of the technologies (such as ionic liquid propulsion) are components of proposed breakthrough concepts. Additional research beyond demonstration of these technologies will be necessary for high-power, rapid, and efficient propulsion systems for Efficient Interplanetary Travel. A few of these near-term electric propulsion technologies were highlighted in the report, *Technology Horizons*: *Game-Changing Technologies for the Lunar Architecture*:

- Electrostatic Ion Thruster: A form of electric propulsion used for spacecraft propulsion that creates thrust by accelerating ions with static electric fields (Coulomb Force). Electrostatic thrusters include Hall-effect thrusters, gridded thrusters, and field emission electric propulsion.

- Electromagnetic Ion Thruster: A form of electric propulsion used for spacecraft propulsion that creates thrust by accelerating ions with magnetic fields (Lorentz Force). Electromagnetic thrusters include pulsed inductive thrusters, magnetoplasmadynamic thrusters, and several radio-wave-driven plasma thruster concepts.

- Liquid-Based Ion Propulsion: Uses ionic liquids, which are highly conductive and yield pure ion extraction.

Current research trends indicate that interplanetary propulsion systems will continue to advance, resulting in new capabilities by 2050. Propulsion systems are likely to get lighter and will provide more velocity change with the same amount of propellant. Breakthrough concepts may develop through focused research or a breakthrough in physics. Targeted research that may modify technology trajectories and lead to a breakthrough concept can be found in each of the technology concept areas.

Research on advanced terrestrial reactors and fission surface power systems developed by NASA may merge to improve nuclear propulsion concepts, providing increased power with less mass. The National Ignition Facility is exploring the physics behind nuclear pulse and may inform future pulse propulsion concepts. Solar-powered propulsion and electric thrusters are codeveloping through several SEP projects at government agencies. Separate research is pushing new electric thruster concepts, which would improve power density. In addition, space agencies around the world, and a few non-governmental organizations, are developing solar sails and demonstrating lightweight material technologies that could enable future concepts. As noted in Easy Access to Space, beamed power technologies are developing in commercial organizations to support power transfer. Many of these commercially-developed technologies could support interplanetary propulsion with additional development. Basic research into matter-antimatter interactions continues at national labs. Fermilab is pushing antimatter production rates, and, as efficiencies increase, new production techniques could enable inexpensive antiprotons. Material technologies are the primary sources of new development for tethers. Nanomanufacturing techniques are improving, and human-scale structures built from nanotubes are becoming more common. Future techniques may enable cheap, mass production of carbon nanotube fibers for tethers.

Technologies for Efficient Interplanetary Travel are still early in the technology development trajectory. Many of the technology concepts highlighted are currently supported by basic research and material science. System design and integration will be necessary before new capabilities are available. For the foreseeable future, development of interplanetary propulsion systems will be the domain of national space agencies, supporting private industry and space-orientated organizations. After initial successes, private industries may develop new propulsion technologies to support a budding deep space transportation economy. However, the timing of this will depend on social and economic considerations, in addition to technical maturity, and cannot be predicted at this point.

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SPACE OASIS

Way stations for resupply, service, assembly, and maintenance in-orbit

SPACE OASIS

Way stations for resupply, service, assembly, and maintenance on orbit

> **BREAKTHROUGH**
> Servicing and assembly stations in space are available for routine, autonomous refueling, assembly, and robotic maintenance of spacecraft. Stations range from small mobile refueling stations to monolithic concepts capable of supporting crew accommodations.

Today, spacecraft are typically launched in one large launch, and in-orbit assembly of large space structures is inefficient and costly, requiring astronaut EVA and robotic arm maneuvering. Additionally, the repair and maintenance of spacecraft is often cost-prohibitive compared to launching a new spacecraft, so most spacecraft are de-orbited once they reach end-of-life.

The Space Oasis breakthrough capability imagines a future where servicing and assembly stations in space are available for routine, autonomous refueling, assembly, and robotic maintenance of spacecraft. Stations range from small mobile refueling stations to monolithic concepts capable of performing complex servicing and assembly tasks and even supporting crew accommodations. Spacecraft can autonomously dock to the station to be serviced. Autonomous maintenance robots are reliable and readily available to inspect and repair spacecraft as needed. Stations provide upgrades to spacecraft, such as telescopes, with new and improved parts and instruments. Finally, some stations can provide in-orbit assembly of large space structures. These structures arrive at the station in separate cargo containers to be robotically unloaded and assembled.

Advances in autonomous servicing and maintenance and the presence of reliable refueling stations in orbit significantly decrease costs, extend the life of in-orbit assets, and create opportunities for exploration farther into space. A way station could provide a platform for assembly of large-scale structures in space, adding new in-orbit assets to a space architecture. A way station in low Earth orbit could pave the way for multiple stations at strategic positions within the inner solar system, supporting long-distance exploration missions.

Related Capability Areas

The types of way stations envisioned in the Space Oasis breakthrough could have a major impact on access to and travel through space. As such, refueling and maintenance in orbit has long been studied by government space agencies and the commercial space sector. How these stations could impact other breakthroughs in this study is listed below.

- **Easy Access to Space –** In-orbit refueling enables the use of smaller, more flexible launch vehicles, allowing for more uniformity in launch vehicles and potentially reducing development and operations costs. This improves the market for competitive launches and potentially encourages more investment and innovation in launch vehicles.[197]

- **Efficient Interplanetary Travel –** Interplanetary propulsion systems could be refueled, inspected, and maintained at orbiting service stations. This maintenance and servicing would increase mission travel distances and safety.

- **Living Off The Land –** In-situ resources could be used to resupply in-orbit propellant storage and transfer depots. This would decrease the costs of refueling the depots themselves, improving the sustainability of the overall in-space infrastructure.

- **Ubiquitous Access to Abundant Power –** The envisioned multifunctional way stations would require complex systems and robotics to enable full functionality. All these systems will require abundant power from multiple locations throughout the solar system.

Supporting Technology Concepts

Space Oasis technology concepts include technologies for propellant storage and transfer as well as advanced robotics concepts to allow autonomous assembly, inspection, maintenance, and repair services. A mix of these technology concepts will be essential to achieve the robust, flexible way stations described in this breakthrough.

Supporting Technology Concepts	
In-Orbit Propellant Storage and Transfer	Storage and transfer of propellants for in-orbit refueling of spacecraft.
Autonomous Robotic Assembly	Robots to autonomously assemble large space structures or spacecraft in orbit.
Service and Maintenance Robots	Robots designed to autonomously inspect, diagnose, and repair spacecraft and structures in-orbit.
Swarm Robotics	The coordination and control of a large number of simple robots that collectively produce complex swarm behaviors.

In-Orbit Propellant Storage and Transfer

This technology concept comprises the storage and transfer of propellants (usually cryogenic fuels) at strategic locations in space, such as low Earth orbit or Lagrange points. This technology could enable a robust, flexible transportation infrastructure for exploration beyond low Earth orbit.[198]

Current space exploration architectures require rockets to lift not only payloads, but also all the fuel required for future in-space travel and maneuvers. This leads to large rocket launch masses that are primarily attributable to propellant. According to a Georgia Tech study, over 85% of mass delivered to LEO via Ares V and I rockets will be propellant.[199] As missions are designed to travel further and faster, potentially ferrying larger payloads, the propellant required after launch will be an increasingly important driver for the initial

PARTNERING OPPORTUNITES

IN-ORBIT PROPELLANT STORAGE AND TRANSFER

- United Launch Alliance (ULA)
- Masten Space Systems
- Boeing
- DARPA

launch mass. One solution to this challenge is to aggregate and store propellants required for in-space travel and maneuvers in orbit, launched on a variety of vehicles.

Several conceptual systems have been researched to launch and store fuel separately from a payload. These concepts include single in-orbit fuel tanks for short-term storage; flexible, modular systems; and large, monolithic structures that store propellant for multiple missions.[200] Short-term storage (less than 200 days) using an orbiting fuel tank would allow NASA to launch large, customized systems without fuel to lighten the launch; these systems would then mate with fuel tanks already on orbit. Modular systems could exist as a staging point for multiple standardized fuel tanks or linked tanks that provide a large volume for propellant storage and are built up incrementally. The monolithic concept uses a large tank volume, launched with a heavy-lift vehicle or assembled on orbit. The tank could interface with and refuel multiple spacecraft. This type of monolithic concept requires periodic resupply missions to refill the tank volume.

Though it still faces some technological hurdles, small-scale propellant storage and transfer is a more near-term concept. Due to the benefit of in-orbit refueling and the state of technology development required to complete a simple cryogenic fuel depot, this technology was identified by The Review of U.S. Human Spaceflight Plans Committee (Augustine) report as a critical component for sustainable exploration.[201] Future propellant storage and transfer concepts include gaseous propellant for electric and plasma propulsions systems, nuclear fuel, or potentially antimatter storage. These systems would require resupply from Earth and ISRU sites, or reusable spacecraft could scavenge fuel from upper atmospheres. Though this breakthrough focuses on in-orbit operations, fuel storage and transfer technologies could also be used on planetary surfaces to provide atmospheric gases and fuel for outposts.

The temperature extremes, long-term storage requirements, and microgravity environment of space pose many technical challenges for advanced in-orbit propellant storage and transfer. The technologies for cryogenic propellant storage and transfer are common and well understood for terrestrial applications, but there are several key technologies still in development to overcome the many challenges for propellant storage and transfer in space. Some examples include passive multi-layer insulation, active cooling techniques for zero-boil-off storage, efficient pressure control, accurate gauging methods to determine how much fuel is in a reservoir, liquid acquisition, and autonomous operations.[202] Additionally, reliable knowledge of low-gravity cryogenic fluid management behavior is critical for long-term storage and transfer of cryogens in low-gravity propellant.[203] Specific challenges relating to the microgravity environment include microgravity mass gauging, liquid acquisition, fluid transfer, autonomous rendezvous and docking, and autonomous leak-free feed lines.[204]

Orbital fuel depots also face technology hurdles at the systems level. To reliably provide storage and refueling at remote locations, these systems must be self-contained, providing thermal management and avionics. Current concepts also assume these systems will operate autonomously, requiring sophisticated operations, multiple autonomous dockings and undockings, and the ability to interface with multiple user groups. As way stations are located further from Earth, maintaining, communicating with, and resupplying the stations will become more complex. To enable multiple missions, the system will need to incorporate flexibility, and optimal locations must be chosen. However, to increase capabilities, some concepts are designed to enable near-term launch and use.[205]

Autonomous Robotic Assembly

Autonomous robotic assembly is the process of using robots of varying degrees of intelligence to construct large complex structures in space without human intervention. Robotic assembly could enable construction of solar power satellites, large communications arrays, modular spacecraft for long-range travel, and science structures, such as large telescopes. The advantages of on-orbit assembly include inherent serviceability and expandability, launch packing efficiency, smaller launch units, structural efficiency, the ability to build very large structures, and that the complexity of a structure does not have to increase when its size increases.[206]

PARTNERING OPPORTUNITES

AUTONOMOUS ASSEMBLY ROBOTS

- Skyworker – CMU Robotics Institute
- FIMER – USC Information Science Institute
- Crawling Robots – Vienna University of Technology

Robotic assembly can be achieved by first constructing a support system using independently-operating assembly robots that move along the assembling structure in groups or swarms of small robots.[207]

All of these types of robotic assembly have been demonstrated in laboratory environments that use various methods to simulate microgravity. Researchers at NASA LaRC developed the Automated Structure Assembly Laboratory (ASAL). The system can assemble a modular truss structure using a commercially available manipulator arm. The robot sits on two linear motion bases that position it for strut insertion. The structure itself sits on a rotary motion base allowing the structure to be turned, placing the unfinished portion in front of the robot platform. The disadvantage to this process is that it requires the robot platform to be constructed in order to move the robot. However, this platform is simple, could be reused for further construction activities, and would support maintenance and repair of a structure.

Carnegie Mellon University's Skyworker is an independently-operating, attached, mobile manipulator that can walk and work on a structure being assembled. These robots can autonomously inspect, maintain, and carry components, performing precise assembly and servicing operations using three different end-effectors.[208] Another example of an independently-operating robot is University of Southern California's free-flying, intelligent fiber/rope, matchmaker robot (FIMER). FIMER uses self-reconfigurable and adjustable tethering to autonomously dock to components being assembled. FIMER is essentially an adjustable rope with a free-flying head at each end. Each head has a simple robotic arm for manipulation and can fly autonomously and dock with components or other robots. As the heads fly and attach to different components, they then pull the two parts together by reeling in the rope/tether to make them dock.[209]

Kobe University, ESA, and NASA collaborated to develop a system to assemble a large phased-array antenna in orbit. In this concept, a set of satellites deploy and hold a large mesh net that creates the basic structure of the phased array antenna. Robotic antenna elements then emerge from the satellites and crawl on the mesh to their allocated positions, creating the large phased-array antenna.[210] A suborbital test of this approach in 2006 successfully demonstrated deployment, retrodirective wireless power transmission, and the movement of two tiny robots across the mesh.[211]

There are many challenges to robotic self-assembly in orbit, including mobility, dexterity, autonomy, intelligence, power, and communications. Whether the robots are attached to their own structure or move along the structure being assembled, they must have the ability to move and manipulate flexible structures in microgravity. Structures to be assembled in orbit should use a modular design to make assembly easier; assembly robots will still require enough dexterity to handle the pieces and inspect components before insertion. If there is a problem with a component, robots must be able to diagnose and make decisions regarding what to do with the component. The completion of all these tasks requires intelligent software. These robots must perform reliably in the harsh radiation environments of space and therefore must be ruggedized and capable of self-maintenance. Finally, while researchers have demonstrated single types of robots, complex assembly tasks such as those required by a Space Oasis will require diverse operations and varying types of manipulation. Meeting these needs will require either a set of reconfigurable robots or multiple types of robots moving on or about a structure.

Service and Maintenance Robots

In-orbit service and maintenance includes diagnosing problems, determining maintenance actions such as replacement of parts for upgrades or due to failure, refueling propellant or cryogenic coolant, and repairing deployment failures. The Hubble Space Telescope is an excellent example of the utility of in-orbit servicing and maintenance.

Robots designed to diagnose and repair spacecraft and structures in orbit may be designed to complete single repetitive tasks typically completed by humans or may be multi-purpose robots designed to use tools and other end-effectors to provide multiple functions as required. Several highly dexterous robots have already been developed for servicing missions, including JSC's Robonaut, University of Maryland's Ranger, and

> PARTNERING OPPORTUNITES
>
> SERVICING AND MAINTENANCE ROBOTS
>
> • MaintenanceBot – Cornell University, Sibly School of Mechanical and Aerospace Engineering
> • Toyota

Dextre developed by MD Robotics. Dextre has been docked to the outside of the ISS; its mission is to demonstrate in-orbit, robotic servicing and maintenance.

More advanced robotic concepts include free-flying robots, self-reconfigurable robots, and swarms of robots. Researchers at Cornell University developed and simulated the MaintenanceBot concept, a free-flying, two-armed robot on the meter scale. One arm of MaintenanceBot is used for repairs, while the other is used to anchor the robot to the spacecraft.[212]

Self-reconfigurable, modular robots are able to change their own shape by rearranging the connectivity of their parts to adapt to new circumstances, perform new tasks, or recover from damage. These systems are well suited to space, saving mass and volume. One set of modules can be reconfigured to perform a variety of servicing and maintenance tasks. The modular parts improve packaging efficiency, and they only require spare modules for repair rather than replacement of the entire robot.[213] (This topic is covered in detail in Go-Anywhere Roving, page 110.) A set of these modules could be programmed to configure into several robot types that provide multiple repair and maintenance tasks. A far-term instance for these robots is known as The Bucket of Stuff. In this concept, a "bucket" of reconfigurable modules can be called on to provide multiple tasks with simple commands like "inspect the structure." The modules then configure into whatever shape is required to complete the task.[214]

Finally, a robot swarm could also provide multiple servicing tasks. For example, a swarm of robots could move out across the spacecraft to more quickly and efficiently inspect the craft than a team of multiple robots. A long-term vision for this technology combines robot swarms with modular reconfigurable robots. In this example, the swarm of inspection robots could configure themselves into the robots required to provide any maintenance repairs or upgrades identified in an inspection.[215] Swarming robotics is discussed more fully below.

Swarm Robotics

Swarm robotics refers to a large collection of simple machines (such as robots or satellites) that when working together produce complex behaviors, like a swarm of bees or colony of ants, acting like a much larger organism with much greater functionality than an individual drone. Also similar to biological swarms, machine swarms are highly-robust, flexible, distributed systems.[216] For space systems, this robustness (the ability to function even if part of the swarm fails) is particularly important, as portions of the swarm are likely to fail due to radiation exposure and other risks on orbit.

Swarms have a large number of individuals, each one having little intelligence, and they do not need to communicate with each other or a master controller to decide their actions. These individuals interact with their neighbors in simple ways, and these simple, local interactions produce complex global behaviors. This ability is known as swarming intelligence and is the goal of intelligent programming for swarming robots. [217]

PARTNERING OPPORTUNITES

SWARM ROBOTICS

- Swarm – Rice University, Multi-Robots Systems Laboratory
- MAST – U.S. Army Research Laboratory, Collaborative Technology Alliance, headed by BAE Systems
- SensorFly – CMU Robotics Institute
- SeaSwarm – MIT SENSEable City Laboratory

Swarming provides flexibility and scalability for large-scale space systems. These properties allow robot swarms to assemble large structures in space, be programmed to self-assemble into a larger structure, or fly in formation to simulate the performance of a larger structure.[218] Additionally, the properties of swarms are the same regardless of the size of the individuals; swarms can be comprised of individuals ranging from nano to macro scale. Most swarming research is focused on the idea of smaller individuals. This is particularly useful for space systems, improving packing efficiency and launch mass. At the millimeter-scale, thousands of robots could be packed into a launch, or, alternatively, they can be packed in the nooks and crannies left by larger systems. [219] Small scale also improves mission reliability. Tiny machines can survive rough impacts, allow for low-cost mass production, and introduce the possibility to consider individual robots as disposable when used in the harsh environment of space.[220]

James McLurkin of the Rice University Multi-Robots Systems Laboratory has developed one of the largest swarms, with about 100 individuals. The swarm was first developed while he was with iRobot Corporation. He examines the work of biologists studying natural swarms to gain a deeper understanding of swarm intelligence. Using this swarm, he has demonstrated different swarming behaviors, including boundary detection and simple sorting.[221]

The U.S. Army Research Lab has formed the Micro-Autonomous Systems and Technology (MAST) collaborative technology alliance to develop a swarm of robots to “enhance warfighter’s tactical situational awareness in urban and complex terrain by enabling the autonomous operation of a collaborative ensemble of multifunctional, mobile microsystems.” Within five to ten years, they hope to create a swarm of both flying and crawling robotic “insects” to perform autonomous searches in both indoor (buildings) and complex outdoor (cave) environments as well as provide perimeter defense. The alliance is headed by BAE Systems, and other team members include University of Pennsylvania, University of Michigan, University of Maryland, North Carolina A&T, Caltech, JPL, UC-Berkeley, University of New Mexico, and Georgia Tech. [222]

Other research and development into robot swarms include SensorFly, Carnegie Mellon University's miniature helicopter swarm, and Sea Swarm, a swarm of oil-cleaning robots developed at MIT's SENSEable City Lab.

One of the major challenges for swarm robotics is programming swarm intelligence. Currently, swarm behavior is still at a basic level. Swarms work to detect the boundaries of their network and decide whether to go beyond it,[223] or they may align themselves using simple sorting techniques.[224] This is still far from developing the complex behaviors needed for in-space servicing. Moreover, the long-term goal is to create robots that work as a swarm but can also join together when required, forming a functional, three-dimensional, moving organism to conduct complex tasks.[225]

Other challenges arise from the development of tiny machines, including issues with lifetime, particularly for micro-mechanical parts; development of testing systems and techniques for micro- and nano-scale machines; and packaging of components and interconnections.[226] Additionally, development of swarm robots faces the same challenges as other autonomous robot systems, including power, thermal, communications, and mobility. These systems must also be adapted for use in space. The swarms must be tested for performance in microgravity. Though robustness of the swarm has been discussed as an advantage, these systems must still be designed to endure high levels of radiation and extreme temperatures, to ensure that enough members of the swarm survive. [227]

Technology Trajectory

Space way stations are frequently cited as a critical step in creating a routine and self-sustaining space exploration architecture. As such, NASA and other commercial and government organizations have been studying concepts for orbital servicing and maintenance for some time. One of the most publicized demonstrations was DARPA's Orbital Express program. In 2007, the Orbital Express program successfully demonstrated in-orbit refueling and maintenance of a communications satellite. Commercial companies have also become interested in the concept of servicing communications satellites. It is unclear whether a way station providing these services would be a government-funded or commercial endeavor. Both models exist in similar infrastructure systems on earth. It is unlikely that a commercial system can develop without a strong, long-term commitment from the government as an anchor tenant for the system. Commercial and government customers for space way stations are also likely to have different needs, with commercial satellite customers likely to be in the near-earth geostationary (GEO) and non-geostationary (NGSO) orbits.

In-orbit servicing stations that provide multiple assembly, inspection, and maintenance services would require the launch of extensive, heavy infrastructure with large production and launch costs. These upfront costs would make such systems unlikely to be developed without a robust consumer base for these services, which currently does not exist. To alleviate this problem, potential commercial providers and government contractors intend to start small, developing more simple spacecraft to provide limited services to manufacturers of current spacecraft, primarily GEO satellites. European company GEO

Ring is developing a five-element system to provide on-orbit refueling, inspection, station-keeping, and orbit transfer for communications satellites. This system can be incrementally deployed, building up to full capability over time.[228] In Canada, MDA is developing a system that can refuel GEO satellites as well as provide towing services to adjust orbits or ferry satellites to graveyard orbits.[229] These more simple systems could represent the first step to further development of servicing stations providing more capabilities.

Currently, larger space systems use automated deployment techniques to assemble in-orbit. While a number of robotic assembly concepts have been demonstrated on Earth, in-orbit, autonomous, robotic assembly has not yet been attempted.

Autonomous robots are a large field of study in academia, the government, and commercial sectors. Both NASA and academia have successfully demonstrated potential in-orbit service and maintenance robots in the laboratory, including Robonaut and Dextre. Dextre is currently docked to the ISS and is scheduled to perform its first task in January of 2011.[230]

Swarming robotics has significant interest in the space, military, and artificial intelligence communities. While simple, swarming behavior has been demonstrated in the lab with swarms of up to 100 robots, the full realization of actual swarming intelligence still requires much research and demonstration.

All of these robotics technologies require breakthrough advances in intelligent systems to achieve the required levels of autonomy and decision-making. Intelligent systems is discussed in Crosscutting Technologies, page 222.

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HEALTHY, HAPPY ASTRONAUTS

Enhancing astronaut well-being with protective, medical, genetic, and behavioral solutions

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Long-term space operations face circumstances hostile to long-term human health. Most prominent among them are the physical effects of long-term exposure to microgravity and increased levels of radiation. Operations considerations include the high workload generally required of space operations, the 24/7 nature of the missions, compromised acute care capabilities, and the sheer distance from home. Seemingly pedestrian issues can become paramount when time is measured in months rather than days. For example, issues such as connections with family and social networks, food and associated rituals, communion with plants and animals, and extended amounts of time in close quarters with colleagues are important.

BREAKTHROUGH

Space travel combines technologies and processes that allow for comfortable, safe, and productive travel. The risks of radiation and microgravity are limited; automated first aid technologies manage contingencies; living spaces are comfortable and private; and virtual communications maintain connections to family and friends.

The Healthy, Happy Astronauts capability describes a future where space travel combines technologies and processes that allow for comfortable, safe, and productive travel comparable to the conditions of living and working on Earth. Future technologies to promote physical, mental, and emotional health among crewmembers draw from the medical and biological world. These technologies can also include communications, structural, and spacecraft technologies with a specific bent on alleviating the particular stressors faced in space. The risks of prolonged exposure to radiation and microgravity are effectively limited by a combination of nutrition, exercise, medical therapeutics, and the spacecraft's physical structure. Automated first aid technologies manage contingencies. Living spaces are optimized for comfort and privacy. Daily operations are designed for manageable stress levels, while contemplative practices and pharmaceutical supplements help productivity. Advanced communications and virtual environments keep astronauts connected to family, friends, and events on Earth.

Related Capability Areas

Healthy, Happy Astronauts is closely related to Super Humans. While this section considers reducing risks associated with spaceflight to acceptable occupational levels in terrestrial spheres, Super Humans reviews future technologies that will augment and develop human capability beyond the baselines accepted as given today. In some instances, the technologies in each section are similar or identical; the difference is their applications. Despite the potential overlap in the technologies, the distinction is significant for a number of reasons. Two of the main reasons, discussed under the Super Humans section, are (1) the legal and ethical issues often associated with some forms of "performance enhancement," and (2) the difficulty of articulating and innovating to a particular level of human performance.

Other related areas include Seamless Human-Computer Interaction, Self-Sustaining Habitats, and On-Demand Manufacturing.

- **Seamless Human-Computer Interaction –** Includes a number of technologies with an impact on the health and well-being of astronauts. The interfaces which astronauts use in their daily operation of computers and machinery define the majority of their activities, and therefore will have a strong effect on well-being. Intuitive, voice, neural, and other interfaces could have a positive impact. Human-computer interaction may also involve future forms of communications (virtual worlds, five senses virtual reality) that allow explorers to connect to real and virtual communities as a retreat from their habitat.

- **Self-Sustaining Habitats –** Includes the structural, protective, and interior spaces in which astronauts reside. Critical technologies for human health binned under the habitat section include radiation protection, biological structural materials, and other technologies like in-space food growth. These affect crew health, but are related to the structure of the habitat or outpost and therefore are discussed in that section.

- **On-Demand Manufacturing –** Links to one of the health technologies below, the ability to print organs. This technology uses 3-D printing technology, a keystone concept for on-demand manufacturing. Just as 3-D printing allows you to print custom spare or production parts, so does organ printing allow for biological parts.

Supporting Technology Concepts

Technologies for Healthy, Happy Astronauts are broken into five main areas. DNA and genomics include the potential uses of genetic manipulation for selection and inoculation against the risks of space travel. A section on nanomedicine discusses the diagnostic, drug delivery, and therapeutic aspects of this emerging technology as it relates to space. Robotic surgery looks at the potential for teleoperated or autonomous surgeries in space for addressing acute conditions or in preventative or regenerative interventions. Regenerative medicine discusses several concepts for regrowing or rejuvenating parts of the human body that have degenerated by age, disease, or by space-specific threats like exposure to radiation and microgravity.

Finally, evolutionary breakthroughs are technologies that work with some of the basic day-to-day activities, including eating rituals, social alignment and protocols, and virtual worlds, to keep astronauts happy and productive. The health implications of these technologies are more subtle and long-term, as they are focused on degenerative conditions, physiological risks, and sociological concerns. Outside of the specific operations and workload, long-term space missions strain food choices and the range of available social experiences, to the detriment of health and happiness. Technologies to mitigate the negative effects of this long-term exposure are desirable for existing missions and may be a necessity for longer-term missions, such as those to Mars.

These concepts are based on open-source research, workshops with subject matter experts, and individual interviews. Basic and applied research on genomics is important for many of the technologies profiled in this section; additional relevant information can be found in the Crosscutting Technologies, "Synthetic Biology," page 234.

Supporting Technology Concepts	
Food and Nutrition	Technologies and techniques for nourishment, satiation, and enjoyment.
Anti-Radiation Pharmaceuticals	Pharmaceutical approaches to mitigating the risks and damage associated with radiation exposure.
Meditation Research and Technologies	Technologies and techniques for mental strength, stamina, focus, and positive social orientation.
Virtual Communications and Human Computer Interaction	Immersive environments to augment communications and increase available experiences.
Artificial Gravity	Applications of centrifugal force to simulate a gravitational environment.
DNA and Genomics	Genetic manipulations to optimize health and prevent disease.
Nanomedicine	Molecular-scale medical interventions.
Robotic Surgery	Teleoperated or autonomous surgery technologies.
Regenerative Concepts	Organ and tissue regrowth and revitalization.

Food and Nutrition

Food, technologies associated with nutrition, and rituals associated with eating times combine to form the core of human experiences. Long-term missions in space or on planetary surfaces will find sourcing and consuming food among the most important to human health and happiness. Food flown in space currently requires a shelf life of over a year, and available food choices can all be experienced within a 10-day period. As mission length increases beyond a year, greater shelf life constraints dwindle choices further, with negative psychological consequences. A number of technology areas address these issues. Technologies for the production, consumption, and experience of food include those for growing plants in space, taste-altering drugs, technologies that mimic food, and printed or synthetic meats.

PARTNERING OPPORTUNITES

FOOD AND NUTRITION

- MIT, Media Lab
- Eindhoven University of Technology
- Purdue University, Department of Food Science
- Stanford University, Stanford Prevention Research Center

Growing plants in space is not a new approach, but, operationally, it has not advanced beyond scientific experimentation in space and simply providing psychological benefit.[231] The resources required to grow (and then prepare) food outweigh and require more energy than simply packing ready-to-eat meals. However, there is a benefit to occasionally having fresh food. Also, since plants convert CO_2 into oxygen and waste matter into food, they are ideal long-term candidates for an integrated life-support system. Future genetic and technological modifications could increase the percentage of certain plants that are edible and have plant cells produce sensing and communications capabilities.[232] Planetary surfaces expand the potential volume available for plant growth, and plants might not be entirely ill-suited to life in Martian or Lunar regolith,[233] though they would still require genetic modification. In general, for a given amount of food, growing food in space or on extraterrestrial surfaces has a far higher mass cost.[234]

There are two connected concepts for synthetic meat: cultured meat in the near term and grown meats in the long term. Neither approach includes cultivation of meat from sentient life. In 2009, researchers in the Netherlands announced having grown cultured meat in a laboratory using cells from a live pig, following three years of similar research.[235] A prediction of a five-year timeline to commercialization coincided with the discovery. NASA had begun and abandoned growing meat in a laboratory with the University of Maryland in 2005, before the work in the Netherlands.[236] The primary challenge is reproducing the texture and feel of natural meats that result from exercise. A future concept for these technologies includes growing animal parts rather than simple tissue. In this way astronauts could enjoy a leg of lamb or pork shoulder, without the hassle and necessary resources required of raising livestock.

The food replicator is a technology originally conceived in science fiction, with preliminary studies done through collaboration between NASA and a famous chef.[237] More recently, the idea has been picked up by MIT.[238] The general concept is a machine that is able to manufacture and cook nearly any food option through bottom-up combinations of basic molecules. The machine would have a database of menu options and would be able to assemble and cook thousands of recipes with a small number of stable, storable inputs. The machine is in very low levels of readiness, but would have the potential to support enough menu variability to sustain astronauts over missions of almost any length.

If food cannot be directly manufactured to the correct specifications, taste-altering drugs have the potential to fill the gap between food and the positive experiences of food. A berry known simply as “miracle fruit” is a prominent example of a food containing substances capable of rewiring taste buds, so that normally bland or acidic food nonetheless gives a very positive impression. Originally, the berry allowed certain West African tribes to happily subsist on abundant foods they would not normally consider an option.[239] The fruit is currently used recreationally in the U.S. Technologies employing the same mechanism have the potential to orient astronauts positively towards menu options otherwise optimized for storage and nutritional qualities.

Mass and power-friendly solutions to the challenges of long-term food and nutrition in space will be an ongoing goal for NASA. Plant growth in space consumes more inputs than it produces, though the positive psychological effect of fresh food may justify some of that cost. Grown meats have demonstrated proof of concept, but have not yet attempted to generate consumer demand, which may dwarf the technical hurdles mentioned above. While the concept of food replicators that can produce anything from sushi to earl grey may be a distant dream, those that can use a more constrained menu to create high-quality menu options may be only several years out.[240]

Anti-Radiation Pharmaceuticals

Pharmaceutical solutions for radiation protection are a very promising solution for long-term missions, due to the very high amounts of shielding mass required to protect a habitable volume from galactic cosmic radiation (GCR). While solar particle events can be predicted and can be stopped with about 10 cm of water, GCR is persistent and in the best case requires a (clearly massive and impractical) foot-thick barrier of liquid hydrogen. Trading this or other more massive or operationally challenging solutions (burying the habitat in regolith) for an internal medicine solution could be a major augmentation to architecture designs.

PARTNERING OPPORTUNITES

ANTI-RADIATION PHARMACEUTICALS

- Armed Forces Radiobiology Research Institute (AFRRI)
- Defense Advanced Research Projects Agency (DARPA)
- Rice Institute, Rice Quantum Institute, Smalley Institute of Nanoscale Science and Technology

There are several pharmaceutical approaches to mitigating the damage of radiation exposure. These approaches are considered in the companion study, *Technology Horizons: Game-Changing Technologies for the Lunar Architecture*, as they are all active development programs or commercially available. The most mainstream approach to dealing with radiation damage is to administer powerful antioxidants, as the exposure to radiation causes substantial damage through the creation of free radicals in the body.[241] Other approaches include temporarily switching genes that prevent programmed cell death and the use of enzymes that temporarily stop cell division when cells are the most susceptible to DNA damage. However, these approaches may not be as effective for persistent effects.[242]

Since the innovation timeline in pharmaceutics is far tighter than in aerospace, it is more difficult to anticipate pharmaceutical breakthroughs beyond what is being investigated today. Advances in our basic understanding of physics can take decades to manifest as aerospace technologies, while breakthroughs in our understanding of the human body can begin commercialization almost immediately. For that reason, while we anticipate macro-level concepts like Nanomedicine and Genomics to hold promise for future therapies, we do not speculate on particular technologies in this timeframe.

In the context of radiation pharmaceutics, it is worth noting that an alternative hypothesis called Radiation Hormesis suggests that low levels of exposure to radiation may activate regulatory mechanisms in the body that have a positive effect on human health. The results of radiation exposure would not then be linear, as is commonly understood (Linear No-threshold Model, or LNT). Instead, a low, ambient dose has some beneficial effect by stimulating natural healing mechanisms in the body. The theory is based on evidence in experiments with animals and plants,[243] and it contends that the studies we do have on low doses of radiation in humans are insufficient to overturn LNT.

Meditation Research and Technologies

Recent research into meditation, or mindfulness training, shows a number of potential benefits to the health and happiness of astronauts on missions of any length.

Mindfulness training aims to calm the mind by creating intense focus on one object or idea for extended periods of time. Often, the centering focus is simply one's breath. In research settings, a standard course called Mindfulness Based Stress Reduction is used. This is based on several ancient mind-training systems, but it is secularized and updated with modern knowledge.[244] Through the training, individuals learn to direct and control their focus. The purpose is to bring greater awareness and attention to everyday tasks and prevent the mind from following thought patterns that distract from the intended goal.

PARTNERING OPPORTUNITES

MEDITATION RESEARCH AND TECHNOLOGIES

- University of Pennsylvania, Department of Psychology, Jha Lab
- Massachusetts General Hospital / Harvard University, Laboratory of Sara Lazar

The results are demonstrative, with positive effects not only on memory, but also on emotional and social performance. The underlying mechanism being studied is the short-term working memory. Research shows that this capacity acts like a muscle in some ways. [245] It can become exhausted and require recovery. It can also be exercised for strength and endurance. An example of when this comes into play is during a class, when the professor alerts students to the present importance of what is being said, by announcing that everything in the next ten minutes will be on a pop quiz that immediately follows. According to studies, the alertness level of trained and untrained groups is relatively consistent, but the untrained group is essentially exhausted at the end of the 10 minutes, whereas the trained group can continue productively.[246]

Counterintuitive findings with positive applications for life in space concern the emotional and social implications. Trained groups are more likely to identify and change bad habits, and they are more able to see problems from another person's perspective. They also do not respond to social threats; when confronted with an angry face, trained groups do not mimic that emotion, as reliably done in control groups.[247] The implications for space include greater productivity and focus professionally, as well as tools for greater levels of social cohesion and happiness.

While meditation is ancient, research is still trying to understand the basic mechanisms of the process. As mentioned, the base of the research is a simple system engineered for accessibility and for the removal of religious underpinnings. Greater innovation in these systems, teaching modules, and technologies to assist training stand to expand these benefits.

Virtual Communications and Human-Computer Interaction (HCI)

Virtual communications technologies show promise as a communications resource for astronauts in space and for connecting the public to NASA activities. HCI technologies are discussed in detail under their own section (see Seamless Human-Computer Interaction, page 202), but the health applications are mentioned here.

Virtual reality refers to technologies that immerse the viewer in an alternate, artificially-created reality; these realities may be virtual worlds, with a stable set of parameters and rules to which the participants agree and are bound to. These technologies show promise as a tool for communications, morale, and computer interface. Virtual communications has the possibility to address a number of potential difficulties faced over the course of long-term missions. The absence of very basic experiences like certain colors, smells, natural settings, or animals have a psychological effect on astronauts.[248] Forms of augmented reality (AR) can change the perception of spacecraft interiors. AR lenses read Radio Frequency Identification (RFID) multipliers embedded in physical equipment to make, for instance, a wall of electronics appear as a wallpapered surface with hanging art. In some therapeutic applications, treatments of burn patients have used virtual and augmented reality to distract from the pain of treatments and in overcoming phobias and stress disorders.[249] Training modules could also fill the long gaps in time during an interplanetary mission. HCIs and virtual worlds could also reduce training by making relevant data available upon perception, decreasing memorization requirements.

PARTNERING OPPORTUNITES

VIRTUAL COMMUNICATIONS AND HUMAN-COMPUTER INTERATION (HCI)

- Cornell University, Computer Graphics and User Interfaces Laboratory
- Stanford University, Virtual Worlds Group, Computer Graphics Lab
- University of Ulster, School of Computing and Intelligent Systems

Virtual worlds potentially provide an inexhaustible range of experiences outside what is available in a space-constrained spacecraft. In addition to visual and experiential qualities, these worlds can be a setting for communication with communities on Earth. Astronauts would be able to speak with their family and friends at home in a rich setting, imbued with five-sense data. Crewmembers would also be able to communicate with each other this way. Virtual worlds thus allow an enormous diversity of experience and social stimulation despite the constraints of a spacecraft. For long-term missions, this outlet and these opportunities may serve important psychological ends.

Virtual worlds exist now, but, in their current form, latency presents a barrier in communications that is unlikely to be overcome in the 40-year timeline. Evolution of virtual worlds to higher fidelity simulations require not only increases in bandwidth to space, but also the tactile and taste sensors and overall coordination.[250] Another barrier is cultural, on the part of the participating astronauts. It is sometimes hypothesized that future generations that mature during eras of virtual technologies will find them more natural, but this is unknown and could conceivably have the opposite effect. Another unknown is whether the transition between virtual worlds and the reality of a confined spacecraft will present issues.

Artificial Gravity

The effects of long-term exposure to microgravity are one of the core threats to human health, affecting bone and muscle loss, fluid loss and distribution, and changes in the cardiovascular system, immune system, and appearance.[251] For missions to Mars, for example, conducting surface operations after having suffered loss of bone and muscle density in a long-term mission can pose major risks of acute injury. The current operational approach includes exercise countermeasures, which are largely but not 100% effective in eliminating bone and muscle loss.[252] Forms of artificial gravity offer potential relief, eliciting the stimulus required for normal physiological functioning. Artificial gravity can be applied consistently to the spacecraft (long-range) or to humans locally within the spacecraft (short-range).[253]

PARTNERING OPPORTUNITES

ARTIFICIAL GRAVITY

- MIT, Man Vehicle Laboratory
- University of California, Irvine
- National Space Biomedical Research Institute (NSBRI)
- National AeroSpace Training and Research (NASTAR) Center

Long-range artificial gravity spins the entire spacecraft on a tether to create gravity using centrifugal force. The capsule is attached to a tether, which is itself attached to a counterweight. The entire ensemble spins in a two-plane circle. The distance of the tether is required to be about 1 km long, to prevent differences in the gravity gradient from causing physiological problems.[254] While the application and set-up of this procedure is clearly simpler than designing a circular station 1 km in diameter, the interior of the capsule would need to be designed with a gravity environment in mind, which may make the usable or experiential internal volume of the capsule significantly smaller. One operational advantage of long-range artificial gravity is that the consistent application of force saves some of the operational time normally devoted to exercise countermeasures.

A second type of artificial gravity is localized in the human body. Human-scale centrifuges a couple of meters wide can spin an astronaut for a period of time—potentially during sleeping hours—to create forces on the body that simulate gravity and provide the necessary gravitational effects. With the head of the astronaut in the center, 23 RPMs could simulate 1G at the foot of the astronaut. This may be compared to a "gravitational massage," [255] and it may provide the gravitational stimulation needed to avoid negative health effects.[256]

Apart from further testing on humans preceding operations, the potential hurdles for long-range artificial gravity could be substantial, including tether materials, counterweights, reaction and attitude control systems, the effective loss of habitable volume, and the obsolescence of many heritage spacecraft designs.

DNA and Genomics

Genomics applications for space are virtually limitless. Human applications are far fewer than those possible in animals and plants, but recent advances in manipulating DNA speak to the abundance of opportunities held by genetic manipulation. As one example, researchers have demonstrated the ability to change the species of single-cell organisms through DNA manipulation; a yeast cell can be changed into a bacterium, and vice versa, by inserting the appropriate DNA in the host cell. A further advancement demonstrated the ability to do this with synthetic DNA, which was assembled artificially from component parts.[257] This essentially proves the possibility of designing custom species from scratch.

PARTNERING OPPORTUNITES

DNA AND GENOMICS

- National Institutes of Health (NIH), National Human Genome Research Institute (NGHRI)
- Johns Hopkins University School of Medicine, McKusick-Nathans Institute of Genetic Medicine
- Duke University, Duke Center for Human Genetics

While clean sheet human design will fall outside the scope of this study, nearer-term possibilities include varieties of genetic manipulation and selection for space tolerance. In terms of diagnostics, the costs associated with sequencing an individual genome are falling rapidly, with the goal of $1,000 commonly cited.[258] Existing, available consumer products will sequence a portion of an individual's genetic code for ancestral and health risk data. NASA can expect to have the technology to access the full genetic data of anyone considered for spaceflight within this study period. This has effects on selection and may allow precise risk measurements to reduce safety margins and permit longer-term missions.

Genetic manipulation is a further possibility. The applications are essentially endless, but there are several obvious examples tied to current basic research. There are some indications that individuals are more or less susceptible to radiation damage, and that this may simply be a function of genetics. If a set of genes that controlled an individual reaction to radiation exposure were identified, this would be an obvious candidate for gene therapy. Similarly, bone and muscle loss may be able to be reduced or eliminated as a reaction to prolonged microgravity exposure. As discussed in Super Humans (see page 82), a genetic approach to muscular dystrophy is an early candidate for this type of intervention.

It is worth mentioning that these therapies may raise privacy and ethical issues beyond the safety issues inherent in any medical procedure. If genetic modifications survive through successive generations, the risk framework then extends beyond the health of an individual and far beyond NASA. Genetic modifications may need to be "turned off" when the astronaut returns to Earth, and this may run counter to the wishes of an astronaut that would want to maintain their altered state. An additional concern is selection based on genetic factors. In some ways, NASA has already been making decisions based on genetic factors when selecting for a particular body type, level or type of intelligence, or even gender. Still, selection based on genetic analysis will immediately encounter dilemmas if there is racial correlation with a particular trait. A similar, longer-term consequence could be a path of dependency created by the selection of a particular set of traits.

Genetic manipulations of humans face steep barriers, despite the wealth of interest and investment in the technologies. As with all health approaches, very high amounts of testing will be required. Early genetic testing resulted in high profile fatalities and side effects. Successful gene therapy often produces only temporary results in humans. Overall, while the science may be close, the high stakes delay uptake and development.

Nanomedicine

Nanomedicine is the use of nanoscale particles for health interventions. There are currently three main projected application areas: diagnostics, drug delivery, and the development of nanostructured materials. For the purposes of space, nanoscale diagnostics and materials have the possibility of specific impacts on space activities, while precision drug delivery can be an enabler for stem-cell-based regenerative concepts discussed later in this chapter.

PARTNERING OPPORTUNITES

NANOMEDICINE

- Georgia Institute of Technology, Nanomedicine Development Center
- University of Maryland, Center for Nanomedicine and Cellular Delivery
- University of Texas, Health Science Center at Houston, Department of Nanomedicine and Biomedical Engineering

Nanomedicine could enable distributed sensor networks using nano-sized particles. The particles would permeate throughout the astronaut's body. In addition to standard vital signs like blood pressure and heart rate, the sensor network would be able to provide detailed, real-time data on any number of biometrics, as nanosensors can interrogate the functions of elements as small as a cell.[259] These could include analysis of blood, organ functioning, bone density, radiation responses, brain waves, or toxicity levels. The detailed, subcutaneous data allowed by these networks serves health maintenance as well as research purposes. It is also an enabler for the regenerative concepts discussed below.

Nano-patterned materials could support a next wave of first aid solutions required in orbit. New materials with integrated functional nanofibers have a number of first aid applications that would provide rapid response and safer application. Products currently in development incorporate antibacterial and antimicrobial materials. Clotting agents and nonstick adhesives that use Van Der Wall forces are additional areas of research.[260] These types of materials could simplify and improve first aid application and maintain sanitary environments in space.

Drug delivery mechanisms are one of the promising areas of nanomedicine. By varying the size and shape of particles, it is possible to use those particles in a very precise delivery mechanism for a pharmaceutical or biomedical payload.[261] Thus, instead of a drug entering the blood stream and proliferating throughout the body, a kidney drug, for example, could be taken expressly to the infected or deficient area of the kidney. This method stands to increase the effectiveness of the medication, while eliminating the side effects associated with delivery to superfluous locations. In regenerative medicine concepts, where stem cells are grafted to particular organs to help them regrow, a nanoparticle delivery system could be an enabling technology.

Hurdles to the advancement of nanotechnology include further, detailed analysis of intercellular structure and how to navigate and manipulate the anatomy within.[262] As an example, one particular hurdle discovered in 2009 was that the proteins used to coat nanoparticles are degraded by an enzyme called cathepsin L as they enter cells. An additional hurdle is keeping the sensors in the body for more than a short time—currently, 24 hours is the maximum possible when injected into the blood stream. Early-stage drug delivery systems have been recently demonstrated in laboratory conditions, but generally face the barriers of dealing with the very complex, internal environment in the human body.[263] All of these technologies are in the early stages of a long run as an innovation source.

Robotic Surgery

Longer stays in space increase the possibility that an acute or degenerative condition will require surgical intervention. Resources devoted to these kinds of activities will be just as mass-constrained as any other in space, and the likelihood of having saved a spot in the crew for a surgeon with the particular required expertise is vanishingly slim. Advances in telemedicine, telesurgery, robotic surgery, and battlefield care create the conditions for in-space surgical facilities that can service conditions during missions. These same applications are also enablers for several regenerative concepts discussed below.

PARTNERING OPPORTUNITES

ROBOTIC SURGERY

- Defense Advanced Research Projects Agency (DARPA)
- University of California Los Angeles, Center for Advanced Surgical and Interventional Technology (CASIT)
- Intuitive Surgical, Inc.

Telesurgery, where a surgeon remotely operates surgical instruments, is becoming reasonably accepted for its ability to connect specialists to sparsely populated locations or simply to have top surgical talent available internationally.[264] The implications for space travel are clear. Latency in transmission would clearly be a much greater challenge in deep space surgical operations, but the general technology and concept of operations has been demonstrated terrestrially.

A military technology called the Trauma Pod addresses two additional issues for enabling telesurgery in space: facilities and the capability for autonomous operation.[265] The Trauma Pod was the first purpose-designed module that combines teleoperated and robotic approaches, designed to immobilize injured soldiers and apply basic first aid before they can be transported to a hospital. Future versions of the Trauma Pod in design phases will perform wound interventions, with teleoperated robotic surgery working in concert with autonomously administered anesthesia, airway management, fluid administration, and surgical assist.[266] This technology is a platform that, in the future, could facilitate a range of surgeries and be designed to operate in a space environment.

While robotic and telerobotic surgery is advancing at a rapid rate on earth, there are several difficult challenges for which NASA cannot expect external support. First, space missions will always have latency issues that will far surpass similar issues with terrestrial systems. While a one- or two-second delay may be manageable, even during a complex procedure like surgery, a 30-second delay seems intuitively different. For longer missions, autonomy would become far more desirable, and it is also a more far-term technology with substantial computing power requirements. Further, the overall concept is a greater risk in space than on Earth. Fluid management within a microgravity environment would add enormous complexity to an open surgery. Lesser but still serious integration issues include the behavior of the cardiovascular system under anesthesia and recovery in microgravity.

Regenerative Concepts

The natural course of aging, toxins, disease, poor nutrition, injury, and genetic factors degenerate the effectiveness of organs in the body. Regenerative medicine seeks methods of restoring organs to the same level of functioning as in youth. Those methods can include artificial organs or methods of regenerating organs in place.

There are several concepts for growing a new organ that can then be surgically implanted in a host patient. Printed organs use 3-D printers, with cells from the patient, to print an organ that can then function properly in the human body. Other methods incubate molds that are implanted with stem cells that grow into the

PARTNERING OPPORTUNITES

REGENERATIVE CONCEPTS

- University of Pittsburgh, McGowan Institute for Regenerative Medicine
- Armed Forces Institute of Regenerative Medicine
- Stanford University, Institute for Stem Cell Biology and Regenerative Medicine
- University of Wisconsin, Stem Cell and Regenerative Medicine Center

shape of the mold and take on the desired functionality. This has been tested successfully with simple tissue growths like trachea and bladders.[267] More complex organs are a future technology.

An additional method that can be accomplished conceivably without surgery is stem cell grafting. In this process, stem cells applied to the degenerated area of the organ will grow into the appropriate cell type and regenerate the organ. Applying the cells to the particular location without surgery is a challenge. One possible solution, mentioned above, is the use of nanoparticles that target specific regions in the body.

The ability to regenerate functionality to organs and organ systems addresses some of the concerns of what happens to the human body over long periods in space, with resulting exposure to microgravity, radiation, and compromised nutritional choices. For long-term missions, in-space capability for organ transplant or stem cell grafting could save lives in the face of critical conditions, or, if the operation was simple enough, increase vitality and ward off aging. Outside of the possibility of performing these procedures in space, regeneration could be performed on Earth, either before launch or after return, so that any degenerative effects of living and working in space would be arbitrary.

Stem cell therapy's promise may be matched by its inherent challenges. There are very few existing, proven therapies for humans. Delivery of cells to a particular area is a challenge, as is directing their growth as desired at that destination and their acceptance by and integration with the rest of the body.[268] The latter issue poses potentially fatal safety risks.

Technology Trajectory

Anti-radiation pharmaceuticals, food technologies, meditation, and virtual communications are, in general, closer in term than regenerative and invasive concepts. They share several characteristics. First, they are concepts that are being advanced at a rapid rate, due to the general interest, market value, and concurrent economic incentives (also because they are far less complex than regenerative medicine). Second, they draw interest outside of NASA, giving NASA either the option to adopt a wait-and-see approach or to study them in-house, advance the technology, and have a compelling spinoff story. Third, integration into the architecture is relatively simple. They are logistics technologies that will not require redesign of capital intensive equipment. A shorter lead time can be afforded before the technology is infused into the architecture.

Nanomedicine is a future medical horizon, with some early applications today. Nano-patterned materials have commercial products already. NASA studied the concept of nanosensors for astronauts as far back as 2002;[269] current applications of the devices are in sensing and reporting on blood clots.[270] A problem in nanomedicine, shared in regenerative concepts, is that each technology hurdle tends to pose a challenge to our basic science base that can take years and decades to resolve.[271]

Long-range artificial gravity is a considerably low-tech approach that requires very high tech and involved design, testing, building, and integration issues before an operational system may be deployed. Artificial gravity would revolutionize spacecraft design. Minimally, it changes the calculations of what empty volume is considered "habitable," and the user interfaces on machinery would be, as on Earth, limited to locations convenient to a gravity-bound human body. Short-range artificial gravity is a closer solution, but research on efficacy is still required, and the system is still relatively large to fit in a habitable volume.

Robotic surgery is in some terrestrial applications supplanting manual operations. Current robotic surgery platforms are still manipulated by surgeons but offer superior control, visual sensing, and minimal invasion.[272] Hospitals aggressively market their use of these instruments.[273] They currently treat a wide range of conditions and, given the barriers mentioned above, could become standard in the study timeline.

Organ regrowth and transplantation is currently occurring with simple body parts like tracheas and bladders. More complex organs will be possible with development of manufacturing techniques. A nearer-term concept than in-situ regenerative treatments and procedures is the use of these technologies in advance or retroactively, to restore function when the astronauts return to Earth or to prepare for the long journey. This makes losses and degenerations in space less of a concern. Stem cell grafting, while possibly as substantial a challenge as external growth and replacement surgery, eliminates the surgical component, making it more promising.

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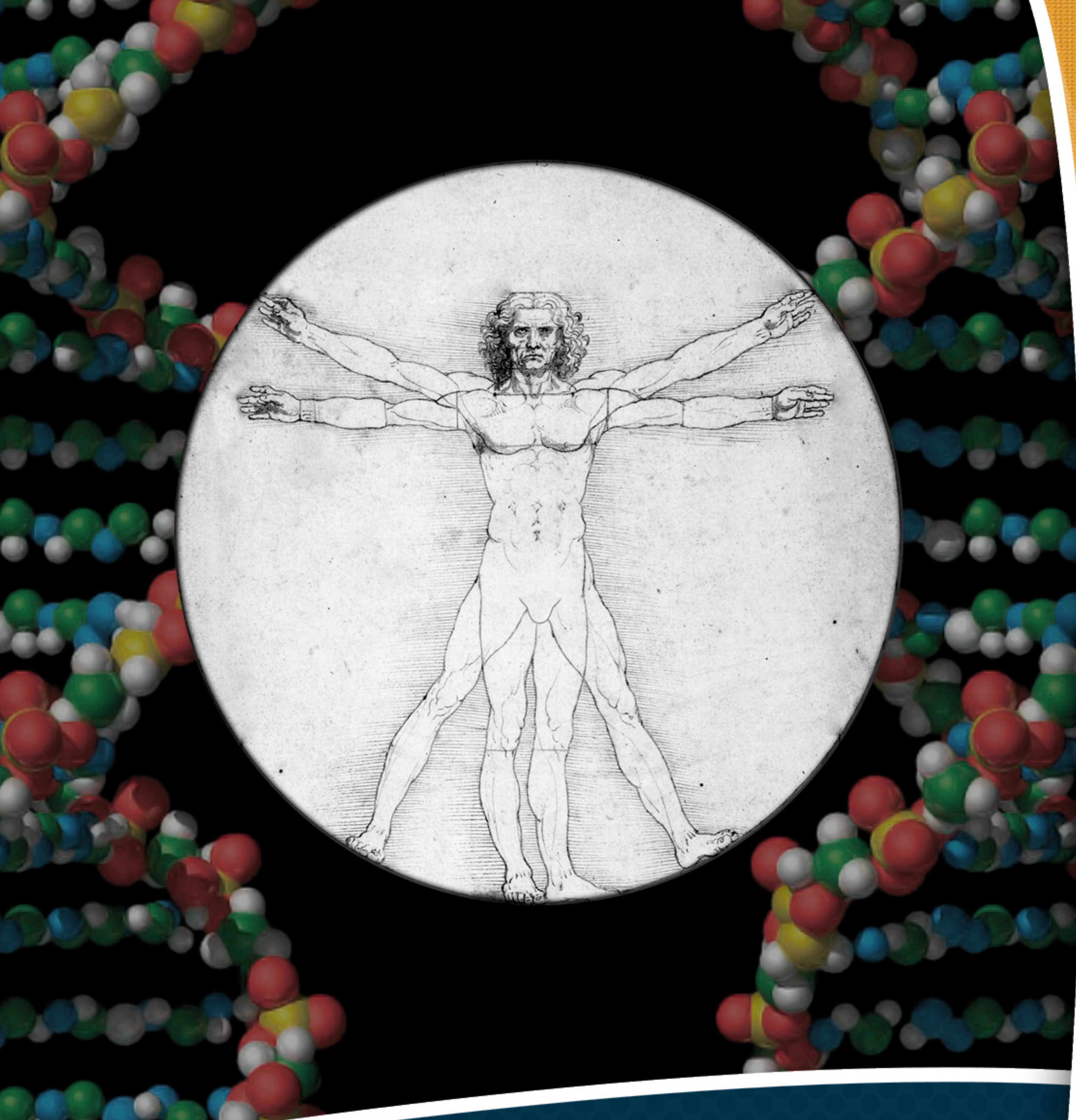

SUPER HUMANS

Augmented/enhanced physical and mental capabilities for exploration

SUPER HUMANS

Augmented/enhanced physical and mental capabilities for exploration

> **BREAKTHROUGH**
> Techniques and technologies expand the limits of human capabilities; reducing the need for sleep, increasing alertness, and mitigating stress. Building and maintenance can be accomplished manually, with strength-augmenting exo-skeletons

Humans have evolved with the environmental conditions on Earth and are not physiologically designed for the space environment. Ultimately, human spaceflight operations are directly constrained by human capability limitations. Humans need sleep and food and are limited in endurance, strength, and memory. Although some of these limitations can be mitigated with training, there are costs associated with training. There may also be opportunity costs associated with existing, systematic astronaut selection biases that unknowingly eliminate a class of capabilities. This section addresses the potential improvement of human performance through medical and mechanical technologies. Beyond maintaining performance levels expected on Earth (see Healthy, Happy Astronauts, page 66), these technologies and concepts can add to and develop expanded human capabilities to the trade space supporting NASA exploration goals.

This capability envisions a future in which advanced techniques and technologies expand the limits of human capabilities. Genetic and regenerative interventions rejuvenate physiological systems before, during, and after space missions, trivializing the negative physical consequences of spaceflight. Anti-aging and hibernation technologies enable very long-term missions in space. Physical strength is increased with novel training and performance enhancement techniques and augmented by external exo-skeletons.

Technologies to overcome the inherent weaknesses of humans in the space environment can enable long-duration and interplanetary missions. Increased natural capabilities as part of these enhancements increase performance and the types of work that can be done by these astronauts (and the types of people that can become astronauts in the first place).

Expanding human performance through medical and mechanical technologies has some associated risks and challenges. The most prominent are identifying ambiguous performance benchmarks and addressing political and social resistance based on ethical concerns.

If technology development seeks to maximize the performance of every system and subsystem that packs on top of a launch vehicle, it seems that the performance of the human should be included among those. However, while there are existing, well-worn metrics and benchmarks for targeting performance of something like an energy storage device (for example, energy density), there are no equivalent biometrics and development goals considered for the enhancement of human capabilities beyond those on Earth. For decades, the space biomedical countermeasures community has focused on maintaining, but not exceeding, Earth-based human performance levels in space. Articulating performance goals may be the first step towards implementing performance-enhancing technologies.

Many technologies that could potentially improve human performance raise ethical concerns. Genetic manipulation and other permanent modifications to the body have the potential to be a particularly sensitive approach, due in part to the resulting permanent effects on the human (and even future generations). The possibility of systematic correlations in talent identification with humans from a particular region of the world is another potential ethical concern. Discussion of the ethics or legal ramifications of future technologies is deliberately outside the scope of this study, as cultural considerations (which are prone to unpredictable change) can obscure technology futures to the detriment of the study goals.

Related Capability Areas

Super Humans is closely related to the Healthy, Happy Astronauts breakthrough capability. The latter includes technologies and techniques designed to mitigate risks associated with spaceflight, thus maintaining normative Earth-based health and performance levels. The focus of Super Humans is on new benchmarks and additional capabilities beyond our known limits. While the approaches in these two areas can be similar, those addressed under Healthy, Happy Astronauts seek to address a debilitation, not to create an enhancement, and are thus less likely to face risks associated with ethical concerns. Many of the technology concepts addressing these breakthrough areas can be identical, but used to different purposes.

- **Seamless Human-Computer Interaction –** The technologies that interface between astronauts and the electronic devices can be seen as conferring superhuman qualities on their users. A neural interface that enables infrared vision, accessibility to an external database through thought, and projections of interpretative data onto one's corneas concurrent with perception are all examples of technology-assisted, performance-enhancing technologies that are also examples of Seamless Human-Computer Interaction.

- **Go-Anywhere Roving –** Discusses technologies for exploring planetary and extraterrestrial media, from surfaces to atmospheres to seas. Exo-skeletons, profiled below, would support extravehicular planetary exploration, extending the range and capability of deployed astronauts.

Supporting Technology Concepts

The future technologies profiled below are separated into three main sections. The first section includes technology areas with similarities to those in the Healthy, Happy Astronauts capability, but whose application represents new human capabilities. These include Regenerative Medicine, Genetic Manipulation, and Anti-Aging technologies. The second section regards Performance Enhancement, similar to the methods used by professional athletes. A section on Mammalian Hibernation discusses some preliminary hibernation research activities and related sleep research. The final section profiles Physical Interfaces, particularly exo-skeletons and visual sensors linked to the brain. These concepts are based on open-source research, workshops with subject matter experts, and individual interviews.

Several of the technologies profiled below work with DNA as a mechanism for producing desired outcomes. Some relevant information on the frontiers of genetic manipulation can be found in the Crosscutting Technologies, "Synthetic Biology," page 234.

Supporting Technology Concepts	
Regenerative Medicine	Organs can be replaced or regenerated largely using stem cells.
Genetic Manipulation	Can customize human capabilities, for disease resistance, increased strength, and essentially unlimited, long-term opportunities.
Anti-Aging	Includes genetic therapy to slow the aging process and cessation of disease in other areas.
Performance Enhancement	Training, techniques, and medical intervention to increase performance and prevent physical damage.
Mammalian Hibernation	Mimics hibernating mammals to produce a similar sleep process in humans.
Physical Interfaces	External technologies that digitally or biologically interface with humans; includes exo-skeletons and infrared vision.

Regenerative Medicine

Healthy, Happy Astronauts considers a class of regenerative medicine technologies, using stem cell grafting, organ printing, and organ growth, to replace organs. For that breakthrough capability, the technologies were applied to combating the effects of microgravity and radiation damage.

Much of regenerative medicine leverages the properties of stem cells. Stem cells, which originate in the early stages of embryonic development, can renew and reproduce themselves without differentiating and can later grow into any kind of human cell, from neurons, to blood cells, to organ cells. Stem cells can be grown and stored separately, and they are capable of persisting in this state long beyond the lifespan of their original organism.[274] When grafted in the place of dying or aging cells, they can reverse congenital, degenerative, and acute damage. They can also

PARTNERING OPPORTUNITES

REGENERATIVE MEDICINE

- University of Pittsburgh, McGowan Institute for Regenerative Medicine
- Armed Forces Institute of Regenerative Medicine
- Stanford University, Institute for Stem Cell Biology and Regenerative Medicine
- University of Wisconsin, Stem Cell and Regenerative Medicine Center

be printed or placed in a mold, be incubated outside the body, and grow into an associated organ or body part for implantation. These scenarios are discussed in Healthy, Happy Astronauts. (See page 66.)

Here, we consider two scenarios where regenerative medicine could enhance performance. In the first scenario, new organs are grown or implanted before the mission. Astronauts are thus essentially refreshed; years of damage and decline from natural aging is reversed and reset. Experienced astronauts can have a novel combination of seniority and the vitality of a young body. This could reduce the long-term risks of space and enable longer missions. In the second scenario, the damage and degeneration from the space environment can essentially be ignored and not considered, because post mission, regenerative concepts can be used to regenerate the body to, and even beyond, pre-mission levels.

In both cases, a capability we currently do not possess changes the way we think about the physical damage caused by space exploration. In the same way that we are less careful eating pasta with an old red shirt than a new light colored one, so would the ability to regenerate elements of our body reshape acceptable risk levels, allowing for longer and more ambitious missions in the space environment.

This promising area of research is producing commercial products already, but more complex parts of the human body (like solid organs) require further evolutionary development of these processes. The enormous amount of clinical testing required before commercialization is a barrier to adaptation.[275]

Genetic Manipulation

Similarly, the use of genetic manipulation can be expanded beyond radiation protection and microgravity tolerance. There are essentially limitless opportunities for customization of genetic properties. The first synthetic life was created in April of 2010, when a DNA molecule was built from scratch using component proteins and injected into a host cell, which then took on the designed properties—as a living being. Within the 40-year timeline of this study, the number of properties we may be able to endow using genetic therapy is difficult to anticipate, but increased capabilities could range from better eyesight, to improved mental focus, to increased strength, to altered size (increase or decrease), or modified nutritional patterns. Nearer-term applications include adaptations to accommodate food intake.

Existing genetic therapies for muscular dystrophy prominently exemplify the potential for the creation of enhanced human capabilities

PARTNERING OPPORTUNITES

GENETIC MANIPULATION

- National Institutes of Health (NIH), National Human Genome Research Institute (NGHRI)
- Johns Hopkins University School of Medicine, McKusick-Nathans Institute of Genetic Medicine
- Duke University, Duke Center for Human Genetics
- Washington University, The Genome Center
- University of Missouri / IBM

based on genetic manipulation.[276] Muscular dystrophy is characterized by excessive atrophy that reduces the density of muscles. Studies in mice identified a hormone (IGF-1) that promotes greater cell division and therefore muscle growth. Researchers were then able to inject a virus carrying the IGF-1 gene into mice to successfully promote these changes on a genetic level. Similar therapies may hold the potential for the optimization of humans for the space environment. While this particular therapy seems to have some application for muscle loss in space, the breakthrough is not the application of this particular therapy, but the ability to change programmed, genetic reactions among the target population of astronauts.

Human gene therapy faces technical and safety barriers. The FDA does not currently approve human gene therapy for commercial applications, and early human trials have resulted in premature deaths and cancer. Technical barriers include making the genetic changes permanent, preventing an immune response, identifying appropriate virus vectors, and treating disorders that result from multiple different genetic combinations.[277]

Anti-Aging

Anti-aging technologies and research have potential near- and far-term implications and consequences that reverberate on a number of levels. Anti-aging research ranges from simply extending cosmetic elements of youth to the indefinite expansion of human life.

Technologies that extend human life enable long-term missions in three ways. First, any substantial medical contribution will have applications to disease management and performance enhancement. These advances will influence and affect space medicine. Secondly, as culture adapts to and co-evolves with longer lifespans, the trade-offs of spending five to ten years on a long-term mission are reduced, as it is a relatively shorter proportion of an adult life. Finally, life extension can enable the possibility of very long mission lifetimes due to the combination of these effects. If it was possible to send a crew to Mars or beyond, and have them return to Earth in a time measured in decades, without the crew aging substantially, this would have a transformational effect on how we perform space missions.

PARTNERING OPPORTUNITES

ANTI-AGING

- Leiden University, Holland
- University of South Florida, School of Medicine
- Indiana University, Center for Aging Research
- Tufts University, Human Nutrition Research Center on Aging

Anti-aging includes a number of different, related concepts that would be combined to overcome the aging process. There seems to be a genetic component to aging, and it may be possible to switch off the genes that cause a kind of planned obsolescence in the human body. As the case of a 16-year old woman who has not grown beyond the toddler phase shows, it is possible that there are particular genes, and potentially a small number of genes, that control the aging process, and that the effect of these genes can be reversed.[278] While this idea holds the faint promise that aging is a switch that can be flipped, the more likely scenario has a number of concepts gradually extending human life incrementally. These are generally in the basic research phase, where researchers are still trying to understand the general mechanisms, from a cellular, hormonal, and genetic perspective, often through studies of mice and *C. elegans*.[279]

Performance Enhancement

A second class of technologies and techniques can be considered performance enhancers, which includes approaches used by elite and professional athletes to increase performance. In general, disdain for performance enhancement therapies stems from the inequality they produce in sporting events combined with their negative side effects. Hence, those who are willing to potentially compromise their overall health can gain a competitive advantage, to the detriment of previous ideals of the game. Neither of these issues is likely to impact future space mission applications of these technologies. Advances in these approaches are already minimizing the negative side effects, and the competitive equality required in sporting events does not apply to NASA spaceflight missions. Future iterations of current hormonal approaches (steroids, human growth hormone) could stave off the muscle and bone loss on orbit. Other therapies used in endurance sports, such as the use of erythropoietin (EPO), which increases red blood cell production and thereby oxygen uptake, could be culled to support development and performance before and during missions.

PARTNERING OPPORTUNITES

PERFORMANCE ENHANCEMENT

- U.S. Anti-Doping Agency (USADA) / World Anti-Doping Agency (WADA)
- Université Laval, Facility of Medicine, Quebec City

The results of these improvements may have real effects on space missions in terms of how they impact other systems. Medications that allow astronauts to use oxygen or hydrate more efficiently may make a small percentage reduction in required daily consumables, which adds to a compelling mass savings over a long-duration journey. Similarly, increases in performance in occupational or exercise activities day-to-day will augment crew productivity and health.

As mentioned previously, a key challenge in these approaches is a lack of benchmarks. If given a set of target parameters, it would make sense to find innovative solutions to meet those goals. Arbitrary improvement with potential externalities will not compel investment in this area. However, if the techniques and technologies for recovering from and improving athletic performance could improve health maintenance in space, they could be a valuable source of innovation. The barriers in moving some of the sports-related performance enhancement research into the mainstream will be the testing and development required to demonstrate long-term safety.

Mammalian Hibernation

The possibility of human hibernation has obvious and multiple potential positive impacts for a long-term space mission. Hibernation could save considerable consumables required for sustenance and could reduce the social and psychological stressors from long-term close quarters. (Mammalian hibernation is distinct from and qualitatively different than cryogenic freezing technologies applied to living beings.)

PARTNERING OPPORTUNITES

MAMMALIAN HIBERNATION

- University of Pittsburgh, Safer Center for Resuscitation Research
- Massachusetts General Hospital
- University of Washington, School of Medicine
- University of California Los Angeles, Semel Institute, Center for Sleep Research

There is some indication that, in extreme conditions, humans have demonstrated the capability for hibernation-like states. A British paper published in the late 1800s and republished in 2000 describes a group of Russians that were able to survive on diminished food supplies, by undergoing something like hibernation for six months out of the year.[280] More recent investigations with Yogis have suggested a similar meditation-induced ability.[281] These initial observations, combined with the genetic similarities between humans and hibernating mammals, point to a realistic possibility of this capability in the future.

It is also well known that humans are able to out-survive normally fatal stressors when in very cold environments, and the application of cold is the basis of some applied hibernation research.[282] Cooling core body temperatures (deep hypothermia and circulatory arrest) has been used since the 1950s in cardiac, neurological, and trauma-necessitated surgical procedures, and it is now common. Though the basic mechanism is not completely understood, cells require less oxygen at low temperatures; that is, the cerebral metabolic rate for oxygen ($CMRO_2$), is lower. Circulatory functions can be stopped, and oxygen exchange can be accomplished with external heart and lung technologies, like direct gas interface oxygenators. Pausing heart and lung functions allows for procedures that would pose a threat to or be encumbered by a normally flowing circulatory system.[283] In applied research, animals are injected with cold fluids to reduce body temperatures and induce a hibernation state. They can be revived after several hours, a period of time that the researchers hope to extend to days and weeks, and eventually to humans.

Work with mammals like mice and squirrels has yielded insights into the physiology of hibernation that could be applied to humans, conceivably within the study period.[284] At least one compound, 5-prime adenosine monophosphate (5'-AMP), can cause non-hibernating mammals to do so and is the basis of basic research. More broad studies of sleep patterns fail to show consistent patterns of sleep across different kinds of mammals, leading researchers to think that there may be a wide variety of future possibilities in managing the sleep process.[285] Space travel is one of the clear first applications for those patterns that involve prolonged hibernation states.

The barriers to human hibernation are a lack of understanding of the physiological process in animals and in humans and the subsequent development of modules and processes to nourish and process waste during long periods of time.

Physical Interfaces

The physical interfaces that augment human capabilities may be entirely physical or neural. The technologies profiled below include exo-skeletons and infrared vision.

Exo-skeletons increase and amplify the amount of force applied by the human operator. The current applications of the technology are for military missions, increasing the strength and endurance of soldiers or allowing them to carry heavy loads over long distances. The systems are currently large and bulky and struggle with energy storage capacity, but they are envisioned to be form-fitting and suitable for deployment on infantry soldiers. Exo-skeletons have applications in EVA, especially on planetary surfaces, for the same reasons as in military use. They would allow EVA astronauts to carry greater loads, including larger quantities of consumables, energy storage, and instruments. They could also increase the range of astronauts on EVA; assistance with walking reduces fatigue with existing mission concepts and may extend the range of rovers constrained by walk-back distances. Further, exo-skeletons provide a source of strength for astronauts landing on planetary surfaces after long transits in space, after which, degeneration of bone and muscle could result in a reduced ability to endure EVA motions and a higher risk of broken bones during physical exertion.

PARTNERING OPPORTUNITES

PHYSICAL INTERFACES

- MIT, Schiller Lab
- University of California Berkeley, Berkeley Robotics & Human Engineering Laboratory
- Defense Advanced Research Projects Agency (DARPA)
- University of Cambridge, England, Engineering Design Center

Neural interfaces for infrared vision are an example of a technology that could hard-wire sensing capabilities directly into the nervous system. (While the focus of such research has been on vision and hearing, sensing and smell would employ similar approaches.) The technology to wire visual sensors directly into the visual cortex has been demonstrated on a basic level for almost two decades, despite still facing substantial challenges.[286] A seamless wireless version, using various sensing data, could enable direct perception of an environment. The significance of this possibility is that astronauts can select an ideal sensor for perceiving a given environment. A sensor integrated with the human eye could greatly enhance natural vision, enable astronauts to see in non-visible areas of the spectrum, or allow them to see much further or see a finer level of detail. It is envisioned that these connections could be wireless, avoiding the intensive and intrusive process of wiring a sensor directly into the brain. The ability to see in different parts of the spectrum could prove valuable for operations in space, including navigation, exploration, and science operations. The technology would have to clearly demonstrate advantages beyond the simple use of external infrared vision for viability.

The essential barrier the technology faces is the interface with the human brain and granulating the sensory inputs for a detailed input.

Technology Trajectory

Medical technologies and research has a different trajectory than in the aerospace industry. Breakthroughs in basic science can lead to technologies far more rapidly, so the barriers to the breakthroughs are more often due to a lack of knowledge, rather than an engineering or economic challenge. At the same time, the very large amount of clinical trials required to demonstrate efficacy and safety is a major driver of the process. Knowledge in this area is thus unpredictable and can happen very rapidly, but it also has the overhead of extensive testing before implementation. This dynamic is seen in regenerative medicine, genomics, performance enhancement, human hibernation, and anti-aging.

Of these technologies, genomic and anti-aging technologies have the potential for unpredictably rapid development. The human genome was first sequenced over the course of thirteen years ending in 2003; it is widely believed that personalized sequencing for less than $1000 will be available within the decade. The resources poured into this effort alone may eclipse NASA's overall technology investment resources. Anti-aging combines these genomic efforts with crosscutting research in general health that consequently extends age.

Regenerative medicine is currently employed in simple applications and is a field that receives substantial research support. The field can claim organ transplants as its own, and bone marrow transfers are applications of stem cell therapy. Tissues and organs grown outside the body for transplant into humans have been demonstrated and include relatively simple organs, like bladders and parts of a trachea. Longer-term goals include complex solid organs like hearts, kidneys, and livers. The complexities of surgery in microgravity are less likely to be made routine within the 40-year timeline. Less intrusive regenerative concepts that use stem cell grafting are much more likely candidates for adoption within the time period.

The trajectory for performance enhancement drugs is rapid; however, it is often secretive. The economic incentives for doctors and researchers are often with highly paid athletes involved in illegal or rule-violating activity. The result is not only rapid innovation, but also a lack of disclosure and public awareness of the state of these innovations. Apart from the illegal or rule-breaking aspects of performance enhancement, training protocols have become increasingly scientific and rigorous. Increased funding, spectator popularity, and general participation in distance events like cycling, marathon running, and ultra-distance events have increased knowledge of underlying training theory and methodology and the degree to which workouts are tracked and analyzed. More efficient physical training regimens can increase expected performance levels among astronauts before launch and maintain and expand performance parameters with onboard exercise.

Human hibernation is in the basic research stage of investigation. Relevant current research seeks to understand the general mechanisms of sleep in humans, and the functional elements of hibernating animals. There is not substantial applied human hibernation research, though there has been some renewed recent interest from ESA.

Unlike the above technology areas, visual prosthetics and exo-skeletons pose engineering challenges beyond the frontiers of our understanding. Visual prosthetics have not yet reached the point where they are able to replace the capability of natural eyesight; the issue is not the sensor but the precision with which data can be transmitted accurately into the visual cortex.[287] In assessing this technology moving forward, visual prosthetics will always have to demonstrate value above and beyond external sensors, which come without the complexity of a biological interface. Exo-skeletons are quite simply an engineering challenge. There is no underlying conceptual difficulty, but like all similar mechanisms, innovations in materials and energy storage will serve key roles in the development of this technology.

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SELF-SUSTAINING HABITATS

Completely closed-loop life support for human environments

SELF-SUSTAINING HABITATS

Completely closed-loop life support for human environments

Sustaining human life off Earth requires providing consumables such as food, water, and oxygen as well as disposing of carbon dioxide, human waste, garbage, and other potential biological contaminates. Currently, life-support systems have achieved partial closure, creating oxygen from plant life and recycling waste products. However, living in space requires consistent resupply and storage of consumables. Launch mass requirements for life support increase mission costs, and the requirement for resupply poses potential safety issues, such as unplanned or accidental consumable depletion.

BREAKTHROUGH

Planetary and spacecraft life-support systems within habitats are fully self-sustaining. All required consumables are grown, manufactured, or recycled within the habitat or on the planetary surface, using biological or physicochemical life-support systems as well as in-situ resources.

The Self-Sustaining Habitats capability describes a future where planetary and spacecraft life-support systems within habitats are fully self-sustaining. All required consumables are grown, manufactured, or recycled within the habitat or on the planetary surface, using biological or physicochemical life-support systems as well as in-situ resources. Algae and plants recycle carbon dioxide and waste to produce oxygen and provide food sources. In-situ resources may be used to provide oxygen, complementing habitat life-support systems. Ecological life-support systems are used in conjunction with physical systems, such as regenerative filters and scrubbers, to achieve common goals. Life-support systems incorporate organic coatings and biomimetic architectures, providing safe habitats and eliminating the need for consumables resupply missions.

The logistics of mission resupply is a major driver of how far humans can explore in space. Closed-loop, life-support systems in conjunction with in-situ resources eliminate consumables from the logistics chain. Minimizing the need for resupply while ensuring astronaut safety will allow astronauts to travel further and stay longer than ever before.

A completely closed-loop, self-sustaining system requires that astronauts fully recycle all waste materials and create everything they need in-situ. This requires that they not only produce oxygen, water, food, and spare parts but also make their own clothing and medicines.[288] This completely closed view is mostly likely beyond this study's 2050 timeframe, but many advances in self-sustainability can be achieved within this time. It is important to note that breakthroughs in other areas, such as food technologies (see Healthy, Happy Astronauts, page 66) human hibernation, (see Super Humans, page 82), on-demand manufacturing (page 168), and in-situ resource utilization (see Living Off The Land, page 156) may reduce input requirements or provide consumables and other needs, thereby eliminating the requirement for a completely closed-loop, life-support system.

A self-sustaining system requires study of not only individual technologies but also of how the system works as a whole; this represents a potential breakthrough in itself. Self-sustaining habitats will require a systems approach to keep the system in balance. Individual technologies required for a closed-loop, life-support system are developed, yet complete system stability has not yet been achieved. An important aspect of this capability will be systems engineering to ensure that all these technologies can work together.

Related Capability Areas

A self-sustaining habitat is actually a sophisticated group of technologies that create a balanced system to provide life support to astronauts living in space for long durations. Many of the breakthrough capabilities discussed in this report will impact this system.

- **Living Off The Land –** In-situ resources can provide vital consumables to the life-support system, such as oxygen, water, and eventually food through ecopoiesis. The ability to produce these elements in situ cuts down on the requirements to create them entirely within the habitat life-support system and provides an important secondary resource to ensure the long-term health and safety of inhabitants.

- **On-Demand Manufacturing –** On-demand manufacturing technologies will allow astronauts to produce tools and spare parts for systems in situ. On-demand manufacturing may also allow astronauts to recycle packaging materials to be used as feedstocks for 3D-printing machines or may be designed from digital materials that can be reconfigured and repurposed within the habitat.[289]

- **Healthy, Happy Astronauts –** Includes technologies that will limit the effects of exposure to radiation and the microgravity environment. It also discusses food technologies for growing fresh food in space. That chapter addresses technologies for growing and producing food that astronauts want to eat, while this chapter addresses technologies for the generation of food in a sustainable or closed-loop way. Plants in long-term confinements could create positive psychological effects, decreasing the stress caused by confinement itself.

- **Super Humans –** Includes technologies that enhance human capabilities, including human hibernation, a technology that could greatly reduce the amount of water, oxygen, and food to be generated or carried on a long-term space mission.

- **Ubiquitous Access to Abundant Power –** Self-sustaining habitats will require access to sustainable power sources, which also do not require frequent resupply, to keep all the systems functioning. These may include more traditional power systems or new technologies, including power-producing materials or structures.

Supporting Technology Concepts

There are a variety of technology solutions for self-sustaining habitats, from full life-support systems that propose a complete solution to sustain a habitat to individual technologies that can improve the sustainability of habitat systems. The bioregenerative life-support concept proposes a new paradigm for life support for exploration missions. Higher plant growth, carbon nanotube membranes, and synthetic enzymes for carbon capture are all technologies that could be incorporated into habitats to make them more sustainable or could also be part of a bioregenerative life-support system. Organic coatings, antimicrobial materials, and biomimetic architecture could be integrated into a habitat structure to bring added capability to life-support systems.

Supporting Technology Concepts	
Bioregenerative Life Support	Life-support systems that use organic components within the system to achieve a safe, self-regulating, chemically balanced environment.
Higher Plant Growth Technologies	Advanced technologies that allow photosynthetic plants to grow in enclosed environments.
Carbon Nanotube Membranes for CO_2 Capture	Membranes created from carbon nanotubes for capturing CO_2. These membranes have an ultra-high permeability, higher selectivity, and better stability than polymer membranes.
Synthetic Enzymes for Carbon Capture	A synthetic analog of carbon anhydrase being developed to capture carbon in harsh environments.
Organic Coatings	Coatings created using natural organisms that have useful characteristics, such as bacteria that produce light or recycle carbon dioxide.
Antimicrobial Materials	Specially designed polymers to capture the molecules bacteria use to signal the start of an infection (quorum sensing). These polymers also limit the bacteria's ability to cluster and form biofilms.
Biomimetic Architecture	In this type of architecture, buildings are no longer inert objects but are living, either operating with or adapting to their environment.
Biological Conversion Technologies for Refuse	Biological processes that use microorganisms to transform refuse into usable products.

Bioregenerative Life Support

To create a habitable environment, life-support systems must supply food, water, and oxygen while removing wastes, feces, urine, and carbon dioxide. Additionally, these systems must regulate temperature and pressure within the habitat volume to ensure human health and safety and also support plant life. In open systems, consumables such as food, water, and oxygen are supplied from Earth, while waste products are stored and subsequently returned to Earth for disposal. Recycling of wastes is key to attaining greater degrees of system closure.

Bioregenerative life-support systems (BLSS) are based on the use of organic components within a system to achieve a safe, self-regulating, and chemically balanced environment for humans. These systems are designed to have a high degree of closure. All necessary resources are included in an ecologically balanced matrix, including maintenance of atmospheric conditions, potable water, and food production. This also includes waste management. BLSS in outer space requires an active habitat environment that includes botanical constituents (mainly, but not necessarily limited to, photosynthetic plants) and microbial aerobic and anaerobic bioreactors. Human occupants, who depend on the BLSS, also represent an essential component in maintaining the system.

Creating a self-sustaining, bioregenerative system has long been a goal of international space agencies. The U.S., Canada, European Union, Japan, and Russia have all invested in the development of bioregenerative components and systems. Currently, the European Space Agency (ESA) is developing the micro-ecological life-support system alternative (MELiSSA) project. Based on the principle of an aquatic ecosystem, MELiSSA aims to produce food, fresh water, and oxygen from organic wastes (inedible biomass, feces, urine, and CO_2) using the combined activity of several microorganisms and higher plants, which colonize five interconnected compartments.[290] MELiSSA is a small-scale system meant to test technologies and not meant to include humans as part of the system.

PARTNERING OPPORTUNITES

BIOREGENERATIVE LIFE SUPPORT SYSTEMS

- Water, Climate, Energy and Sustainability – University of Arizona, B2 Earth Science
- Closed Ecological Systems – University of North Dakota, Space Studies
- MELISSA – European Space Agency

Previous human-scale demonstrators and testbeds include Russia's BIOS-1, 2, 3, and 3M, NASA's Bioregenerative Life Support Systems Test Complex (BIO-Plex), Japan's Closed Ecology Experiment Facility (CEEF), and Biosphere-2 in the U.S. All of these systems were testbeds for different systems and technical approaches, however, none of these systems managed to provide a stable environment. A full analysis of the instabilities has not been reported.[291]

While there are many benefits to BLSS, including high levels of autonomy and closure, there are significant challenges as well. Biological systems will be larger and heavier than current open physicochemical systems, due to the structures required for plant growth. Therefore, these systems would not be useful for shorter-term missions. While a lot has been learned from the full-scale experiments listed above, none of the systems was completely stable; that is, there were engineering, agricultural, or recirculation instabilities. Challenges have included crop growth being inhibited by lighting and cooling system issues, inability to provide enough species of plants to support dietary requirements, and atmospheric contamination from oxygen-CO_2 instability to toxic gas concentration.[292] All major tests on bio-regenerative systems have been done in Earth 1-g gravity. Transition to the reduced gravities of space will decrease efficiency of some phases of bio-regenerative cycles. Clarification on this issue will require further research (theoretical and experimental).

Higher Plant Growth Technologies

The use of higher plants is central to bioregenerative life-support systems. Photosynthetic plants are used not only for food but also for filtering air and converting carbon dioxide to oxygen. Original research in bioregenerative systems focused on the use of algae. However, there were difficulties with creating palatable and nutritious foods from algae. Researchers continue to develop new technologies, including lighting and soil systems, to optimize the yield of photosynthetic crop plants in simulated space environments. These crop plants are increasingly studied in bioregenerative systems to provide oxygen generation, carbon dioxide removal, and water purification, in addition to food supply. Providing all these elements requires innovative horticulture technologies and approaches, including efficient lighting, innovative growing module designs, and health monitoring concepts.

PARTNERING OPPORTUNITES

HIGHER PLANT GROWTH TECHNOLOGIES

- Vertical Farming – Columbia University, Environmental Health Science, AeroFarms Systems, LLC
- Reconfigurable LED Lighting – Purdue University, Department of Horticulture and Landscape Architecture and ORBITEC
- Cultivars – Purdue University, Department of Horticulture and Landscape Architecture
- Plant Biosensing – University of Florida, Institute of Food and Agriculture Science

When incorporating plants into life-support systems, one of the most basic steps is determining the plant mix to grow. A nutritionally balanced set of crops requires staple crops that provide carbohydrates, proteins, and fats. Staple crops include sweet potatoes, wheat, and rice. These, combined with a balance of vegetables and small fruits, could provide proper nutrition for inhabitants.[293]

However, producing enough crop yield to sustain an outpost requires large planting areas and more efficient plants.[294] Therefore, at least initially, it would be necessary to carry supplies of dietary supplements.[295] Another solution to this problem is innovative greenhouse or growth module design, such as vertical farming. Vertical farming was introduced by Professor Dickson Despommier at Columbia University. Columbia has created the website verticalfarm.com to track and catalog their research. This idea was created as a potential solution to overpopulation. Sometimes called urban farming, this concept requires indoor farming in multiple-story buildings. This type of farming has many similarities to that required for growing crops off Earth, since crops are grown inside a controlled ecosystem.[296] However, there are significant challenges to growing plants off Earth that are not as significant for vertical farming; these challenges include artificial lighting and air pressurization. To ensure one atmosphere of pressure off Earth could require very heavy structures, unless inflatables can be designed to mitigate this challenge.

Growing plants off Earth also poses unique lighting challenges. Researchers continue to improve efficiency of lighting systems. State-of-the-art systems include the use of LEDs and intracanopy lighting.[297] Purdue University and Orbitec are developing reconfigurable, intracanopy, LED systems that bring light only to the photosynthetic parts of plants. These types of systems are highly efficient, significantly decreasing power requirements and cost for growing plants on orbit.[298]

Direct solar lighting of crop plants eliminates the power and thermal costs associated with electric lighting. However, since the plants are being grown inside, it requires a means for transmitting the light to the plants. One concept is the use of highly durable, transparent, inflatable greenhouses.[299] The use of natural sunlight saves on the mass, power, and thermal radiation resources required for artificial light. However, a transparent greenhouse experiences large heat losses during the night cycle, so certain countermeasures, such as using multilayer insulation to cover the greenhouse, are necessary.[300] An alternative to durable, transparent materials uses mirrors or lenses to collect natural sunlight, which is then transmitted to the plants using fiber optic bundles or light pipes. While this method does not require special materials, it would suffer from transmission losses. Additionally, any system relying on natural light will have to be designed to accommodate weather conditions, such as dust storms or wind, and the amount of sunlight received at the planetary surface.[301]

Controlling the plants' growth environment is one approach to growing crops on orbit or planetary surfaces. A second approach is to create cultivars designed especially for growth in space. Cultivars are plants created through selective breeding. These cultivated plants are selected for certain desirable characteristics; in flowers this may be color or fragrance. For space missions, plants may be developed to meet particular environmental characteristics of their growing environments. Examples include dwarf cultivars created to grow in small chambers with minimal pressure; low-light or artificial-light cultivars (developed depending on the lighting conditions); and cultivars developed for use in systems where waste water is recycled directly to plants.[302] High-yield, high-nutrition cultivars would be desirable under all conditions.[303] Purdue University has developed a highly robust strawberry cultivar for use in space. The strawberry cultivars are developed to be day-neutral—they grow regardless of the length of available daylight. Under shorter light periods, they produce fewer berries, but these are large enough to provide the same volume yield. This type of crop is a first step in moving towards efficient crop growth technologies.[304]

Regardless of the methods and systems used to grow plants, monitoring plant health would allow the crew to rapidly respond to problems with crop growth. Sensor systems can be employed to measure environmental parameters such as oxygen levels.[305] Sensors could be traditional mechanical or electric sensors or could be designed into the plant itself, to notify of oxygen levels, water, soil conditions, and other environmental conditions.[306]

Growing crop plants off Earth is a complex but necessary task to sustain a long-term human presence either in space or on another planetary surface, such as the Moon or Mars. While much research, development, and testing has been done, there have been no space systems flown specifically for the purpose of growing crops for consumption.[307] In fact, the effects of space environments, such as pressure levels and microgravity, continue to be studied, and more research is required still for particular varieties of plants. Developing plants that are able to produce food and oxygen at the levels needed for space travel, yet are hardy enough to grow in space, will be a major technical hurdle. Additionally, there are still issues with growing plants in closed systems, particularly the build-up of volatile organic compounds in the atmosphere.[308] Overcoming these instabilities is critical for incorporating plants into a sustainable life-support system. Overcoming this challenge will require sensing technologies and significant Earth-based system research to develop a reliable, stable, and low-risk system for use in space.

Carbon Nanotube Membranes for CO_2 Capture

A challenge for life-support systems is keeping carbon dioxide levels inside the habitat low enough for humans. Different types of filters and scrubbers are used to capture carbon dioxide. An innovative approach is using carbon nanotube membranes. Membranes are thin barriers that selectively filter out some gaseous compounds. Separation occurs because some gaseous components move through the membrane faster than others. This separation results in two gas streams, the retentate and the permeate, either of which can be considered the product of this process.[309] The performance of filtration membranes is measured by 1) permeability, the volume of gas flowing through the membrane and 2) selectivity, the separation factor.

PARTNERING OPPORTUNITES

CARBON NANOTUBE MEMBRANES FOR CO_2 CAPTURE

- ARPA-E
- Porifera, Inc
- Nanostructured Membranes Against Global Warming (NanoGLOWA)

The component gases as well as the type of membrane (organic, such as plastics and carbon, or inorganic, such as ceramics) have significant effects on permeability and selectivity. Due to their atomic smoothness and hydrophobicity, gases flow through nanotube pores more than 100 times faster than through any other nanometer-scale pore,[310] giving carbon nanotube membranes ultra-high permeability and allowing for better selectivity than polymer membranes. The improved selectivity, permeability, and mechanical stability of carbon nanotube membranes can provide decreased system costs and energy required for operation. These membranes can be customized, altering pore size, pore entrance and exit characteristics, and membrane matrix, to allow for the transfer of specific gases.[311]

One of the challenges for developing carbon nanotube membranes is passing only carbon dioxide and not other gases. Researchers are studying adding compounds to the ends of the nanotubes to attract carbon dioxide. While this method weakens the permeability, the otherwise ultra-high permeability of the nanotube membranes makes this a viable solution. However, several compounds must be evaluated to identify the most suitable. Another challenge is finding the best method for manufacture of the nanotubes as well as identifying the best support materials. [312] While carbon nanotubes show a lot of promise, more study is required to characterize their performance. Production techniques for creating carbon nanotubes must be scaled-up to appropriate levels.[313] At this stage, researchers are still developing and testing prototypes. More information on carbon nanotubes can be found in Crosscutting Technologies, page 226.

Because of the worldwide interest in reducing the emission of carbon dioxide into the atmosphere from power plants and automobiles, organizations in both the U.S. and Europe are researching the development of nanostructured membranes for carbon capture. In the U.S., the Advanced Research Projects Agency – Energy (ARPA-E) is funding companies to develop membranes for carbon capture and reverse osmosis.[314] In Europe, a 26-country consortium named, Nanostructured Membranes against Global Warming, is developing five different types of nanomembranes.[315] While these membranes are being developed for CO_2 capture on Earth, their energy efficiency and lower cost could make them a viable alternative for space life-support systems.

Synthetic Enzymes for Carbon Capture

Another technology for capturing excess carbon dioxide within space habitats is synthetic enzymes. The carbonic anhydrase enzyme processes carbon dioxide in organisms, such as E. coli, converting the CO_2 into biocarbonate ions.[316] These biocarbonate ions can then be recycled into substances such as baking soda, chalk, or limestone. Carbonic anhydrase is particularly useful for this process, as it is one of the fastest enzymes known for processing carbon dioxide.[317] Additionally, carbonic anhydrase enzymes do not require separating carbon dioxide from other gases, and approaches using enzymes require less energy and cost less than other methods.[318] Carbon capture using carbonic anhydrase is being developed and tested by Alcoa, Babcock, and Wilcox using patented approaches developed by CO_2 Solutions. Carbozyme Inc. is completing development of liquid membrane for CO_2 removal. NASA originally funded this work for use in advanced life-support systems.[319] These approaches may not produce enough carbonic anhydrase to process the quantities of carbon dioxide emitted by power plants using fossil fuels, but they could still be efficient for air-filtration applications for space.[320]

PARTNERING OPPORTUNITES

SYNTHETIC ENZYMES FOR CARBON CAPTURE

- Enzymes – Carbozyme
- Synthetic Enzymes – United Technologies Research Center and ARPA-E
- Synthetic Enzymes – Lawrence Livermore National Laboratory, University of Illinois and Babcock and Wilcox

The Department of Energy (DOE) is also researching carbon capture using natural carbonic anhydrase enzymes[321] as well as developing synthetic analogs.[322] The synthetic analog of the carbon anhydrase enzyme is being developed by United Technologies Research Center (UTRC) to capture CO_2 in industrial flue gas. The synthetic analog will be a polymer nanocomposite, thin-film structure designed to withstand harsh chemical and thermal environments. This technology has several benefits over traditional enzyme technologies, including that is has no moving parts, requires no consumables, has a lower incremental cost, and is very durable. However, creating a synthetic version of the carbonic anhydrase enzyme is in early stages of development. While these synthetic enzymes appear very promising, there are still major challenges to overcome. Researchers are working to modify an experimental version of the enzyme. Once developed at laboratory scale, it must be tested for performance and durability. In April of 2009, ARPA-E funded a two-year study to demonstrate its feasibility.[323] Additionally, this technology is not being developed for use in space and would face other challenges to become flight-ready. Its performance and reliability must be tested for microgravity environments as well as for integration into life-support systems.

Organic Coatings

Organic coatings can be used to transform traditional structures into "living" structures. These coatings are inspired by and created with natural organisms. Organic coatings can provide simple, low-power solutions to some of the more basic requirements of habitats and life-support systems. A number of these types of coatings were discussed in the companion document, *Technology Horizons: Game-Changing Technologies For The Lunar Architecture*, including self-cleaning and non-adhering coatings and biomimetic adhesives. Two other organic coatings in development can provide breakthroughs for lighting habitats and supporting life-support systems. These technologies include bioluminescent bacteria engineered to be bright enough to light buildings or cyanobacteria developed to metabolize carbon dioxide. One of the central premises of these solutions is that they are relatively simple and cheap.

PARTNERING OPPORTUNITES

ORGANIC COATINGS

- Bioluminescent Bacteria and Cyanobacteria – Bartlett School of Architecture, University of London

Bioluminescent bacteria are organisms that give off a blue-green glow, such as squid, jellyfish, and fireflies. One such bacteria, *Vibrio phosphoreum,* is carried by fish. In some fish, such as the flashlight and anglerfish, this bacterium allows them to glow to attract prey. Researchers from the Bartlett School of Architecture at University College London are studying the use of this bacterium to produce low-energy lighting solutions. The bacteria automatically produce light when exposed to oxygen or water and could be used to cover buildings, walls, or billboards. As found in nature, *Vibrio phosphoreum* would not be strong enough to light a street, however, researchers believe these bacteria can be engineered to increase illumination.[324]

Another organic coating concept uses bacteria to clean the environment. Cyanobacteria are excellent at recycling carbon dioxide, since they require carbon to make the energy they need to live. Researchers at the Bartlett School of Architecture suggest using cyanobacteria to create a building coating that would capture carbon dioxide. These coatings could be designed to grow over structures and would be complementary to life-support systems. However, this ability to grow bacteria on specific surfaces continues to be a challenge.[325] This is compounded for use in space systems, as it requires further study of how these specific bacteria would perform and grow in microgravity environments. Additionally, these coatings may require engineering to make them hardy enough and reliable enough to be integrated into habitat systems.

Antimicrobial Materials

Some bacteria not only survive but grow faster in microgravity environments. Since microgravity has been shown to affect the human immune system, these bacteria pose a serious health risk to astronauts.[326] One technology, being developed by Cranfield University in the United Kingdom, is designed to prevent the formation of bacteria, whether in hospitals or in space.[327] The technology uses specially designed polymers, called signal-sequestering polymers (SSPs), to capture the molecules bacteria use to signal the start of an infection (quorum sensing). Once these molecules have been absorbed by the polymer, communication is disrupted, and the bacteria's ability to cluster and form biofilms is substantially limited. These polymers have several advantages for surface applications. They can be produced in bulk, and they are easily fabricated as coatings or injection molded into materials. While these are being created to mitigate the chances of bacterial infections and biofilm accumulation in products such as catheters and prosthetics, these types of coatings and materials could potentially be used in space systems to further protect habitats and humans from potential bacterial infections.[328]

PARTNERING OPPORTUNITES

ANTIMICROBIAL MATERIALS

- Blocking Quorum Sensing – Cranfield University, United Kingdom

This type of research is currently in its early stages, having been tested on one type of bacteria.[329] Additionally, the effects of microgravity on the growth and virulence of different types of bacteria is not well known and continues to be researched.[330] Further, these technologies must work with other technologies in the system. It must be determined how these materials would interact with other organic coatings used in the system.

Biomimetic Architectures

The idea behind biomimetic architecture is to develop "living" structures that operate like natural organisms. The concept is to design structures that adapt to their environment.

The Philips Design center is developing concepts for designing a living skin for structures, rather than using traditional inert building materials. The skin acts as a membrane, connecting the exterior and interior of the habitat. The skin combines electronics and biochemical functionality to transport air, light, and water into the structure and filter or purify these as necessary. This concept is in the conceptual phase for terrestrial applications and would have to be re-imagined to create skins for space habitats.[331]

PARTNERING OPPORTUNITES

BIOMIMETIC ARCHITECTURE

- Active Building Skins – Off The Grid Sustainable Habitat 2020, The Phillips Design Lab
- Metabolic Materials – Bartlett School of Architecture, University of London
- Viral Architectural – MIT, Kinetic Design Lab
- Fab Tree Habitat – MIT, School of Architecture

Another example of a specific biomimetic technology concept is metabolic materials, which is being researched at the Bartlett School of Architecture. Metabolic materials apply synthetic biology to the development of architectural materials, to develop architectural elements that have functional interactions with their surrounding environment. Metabolic materials have structural properties and are also actively undergoing metabolic processes and chemical reactions. A near-term application is a material that converts carbon dioxide into bicarbonate ions (mentioned in the Synthetic Enzymes section of this chapter). As a result, the material would sequester CO_2 from the atmosphere and thereby strengthen itself and repair damage in the process. Conceptually, this is an example of how buildings would engage in dialogue with their environment. These reactions can be customized by genetically engineering the metabolic processes of the cells. Livable structures thus provide environmental services in the course of their construction, self-construction, or maturity. Researchers at the Bartlett School are currently developing coatings to retrofit buildings based on this technology. They are also investigating metabolic agents that would seek out, petrify, and grow the ancient wood foundations of Venice, Italy, to strengthen and raise the city's base structure. Long-term, they envision buildings that grow into themselves while cleaning their surrounding environment.[332]

Metabolic materials is a very new field of research and still in the early stages of development. One of the major challenges is the development of appropriate protocells, the key functional element of this technology. Protocells are cells without DNA that can be run by a chemical battery, undergo reactions, and follow chemical gradients.[333] Researchers at the Bartlett School predict development of a manufacturing platform for protocells in the next two years, metabolic building coatings within five years, building materials within 20 years, and living buildings within 30.[334]

Biological Conversion Technologies for Refuse

Biological conversion technologies for refuse include biological processes that use microorganisms to transform refuse into usable products. In particular, significant work is underway developing technologies to transform refuse and waste products into energy, such as ethanol, butanol, and hydrogen to be used as alternative fuels. These types of technologies could be developed in sync with planning for logistics on an exploration mission. Packaging or other disposable items planned for the mission could be designed as a feedstock for these biological conversion technologies, or these technologies could be used to find other efficient uses for biomass grown in a self-sustaining habitat.

PARTNERING OPPORTUNITES

BIOLOGICAL CONVERSION TECHNOLOGIES FOR REFUSE

- Butanol From Plant Stalks and Wood Chips – Gevo
- Ethanol and Hydrogen From Cellulosic Biomass – University of Wisconsin, Department of Energy Bioenergy Research Centers
- Hydrogen From Forestry or Household Waste – Lund University, Applied Microbiology
- Bio-Dispersants from Soybean Hulls – Modular Genetics Inc, Columbia University, Iowa State University and Louisiana State University Agriculture Center

Researchers at Gevo have engineered a yeast that can transform cellulose from plant stalks or wood chips into butanol, which can be then used in gasoline or converted into jet fuel. The process can also provide inputs to other products made from petroleum, such as plastics. This process is particularly appealing because butanol has 30% more energy than the same amount of ethanol or other biofuels, burns more efficiently, can be transported using current pipeline technologies, and is already a component of gasoline. Gevo has also developed a process that makes large quantities of isobutanol, a variant of butanol. DuPont and BP have also partnered to develop organisms that produce butanol from various sugar sources.[335] However, this process has not yet been demonstrated on a commercial scale, and researchers do not know the full cost and whether it will be competitive with ethanol and gasoline.[336]

The Department of Energy Bioenergy Research Centers, led by the University of Wisconsin, is studying the anaerocellum bacteria found in the hot springs at Yellowstone. This bacteria can break down cellulosic biomass, the non-food part of plants, into sugars and can also ferment the biomass to form acetate and ethanol. They are also researching a process that uses photosynthesis, leveraging a type of purple bacteria to produce hydrogen from cellulosic biomass. The hydrogen can then be converted to electricity using microbial batteries.[337] Researchers at the University of Lund, Department of Applied Microbiology are working with the caldicellulosiruptor saccharolyticus (CS) bacteria that produce twice as much hydrogen as other bacteria from forestry or household waste. This bacteria has adapted to a low-energy environment and can perform at higher growth temperatures under difficult conditions, such as partial hydrogen pressure. These factors allow the CS bacteria to create more hydrogen while keeping costs down for production. However, it produces less under high concentrations of salt or hydrogen gas.[338]

Not all research on organic refuse recycling focuses on creating energy. Modular

Genetics, Inc. has developed microorganisms that convert agricultural waste materials, specifically soybean hulls, into useful wetting agents known as surfactants. With a rapid response grant from the National Science Foundation, Modular and a team comprised of members from Iowa State University, Columbia University, and Louisiana State University are using these microorganisms to convert soybean hulls into a bio-dispersant for use in the Gulf oil spill clean-up.[339]

These advancements would be the first steps toward developing microorganisms that could break down non-recyclable waste products on a space outpost and potentially convert them into useful products. However, current applications and development are being conducted strictly for terrestrial use. Much more work would be required to adapt these to space systems, including studying how the microorganisms perform in microgravity, high radiation, and extreme temperatures; determining outpost waste products that could be broken down and reused; and identifying the systems issues associated with integrating new microorganisms into habitats.

Technology Trajectory

Advanced life-support systems use a combination of physicochemical and biological methods to recycle and reuse consumables as much as possible. To sustain life further from Earth, life-support systems must become more self-sustaining or closed, recycling and creating consumables in situ. Bioregenerative life-support systems have been attempted many times on Earth, with several systems and test facility demonstrations, including Biosphere, BioHome, BIO-Plex, Bios-3, and NASDA's CEEF project. ESA's MELiSSA system continues research and development of its five life-support compartments. While research and development into closed ecological systems continues, completely eliminating instability from these systems continues to be a challenge. They will need to achieve a significantly stable system for this to be incorporated safely into human exploration missions. This will likely require significantly more testing on Earth and eventually in-space testing. Additionally, ensuring a chemically-balanced environment for humans requires advanced, comprehensive monitoring of the system to indicate perturbations within the system or the environment, which may lead to the degradation of key components of the BLSS. Advanced sensors are discussed in the Environmental Omniscience breakthrough capability, page 180. Additionally, Integrated Systems Health Management is discussed in Crosscutting Technologies, page 222.

Research into carbon separation, capture, and sequestration technologies has become more prevalent due to increased pressure on terrestrial industries to decrease carbon emissions. The use of enzymes for carbon capture is being developed by industry and government and is in early stages of demonstration. Creating more durable synthetic enzymes is at the feasibility stage of development funded by DOE. Another novel concept for carbon capture is the use of nanotube membranes. This concept has garnered much interest and is being studied internationally by academia, industry, and government. Terrestrial needs may differ from the specific requirements for space. Some of these technologies may need to be specifically adapted for space applications.

Organic self-cleaning and antimicrobial coatings, for use as components of a larger, sustainable, life-support system, have been demonstrated. Some are in use by the military and industry as described in the *Technology Horizons* report. However, biological concepts that require the growth of living organisms along structures are still in early proof of concepts stages of development. Still at the conceptual stage is the idea of creating living habitats that are either created from the environment or designed to interact directly with the environment to provide consumables.

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GO-ANYWHERE ROVING

Vehicles for transportation on planetary bodies allowing unconstrained exploration on, over, and under the surface

GO-ANYWHERE ROVING

Vehicles for transportation on planetary bodies allowing unconstrained exploration on, over, and under the surface

> **BREAKTHROUGH**
> Vehicles and personal mobility systems enable quick, easy, safe, and reliable transportation on planetary bodies. Unconstrained access to surface, atmospheric, and liquid environments increases scientific return and enables sustainable exploration.

Exploration of planetary bodies is limited by the mobility of human and robotic rovers. Current technology and operations result in planetary surface missions that traverse millions of miles and then are limited to exploring small areas close to the landing site. *Spirit* and *Opportunity*, two robotic Martian rovers that exceeded design lifetimes by more than a factor of 25, have only traveled 7.7 km and 23.2 km respectively.[340] Current technologies for crewed rovers are not limited by autonomous navigation capabilities; however, power constraints, safety considerations, and EVA operations limit the territory that can be explored. During Apollo missions, the furthest the Lunar Roving Vehicle traveled from the Lunar Module was about 7.5 km, and the longest distance traversed was about 35.9 km.[341] Using current technology and increasing mission frequency to explore a large portion of a planetary body is cost-prohibitive and unsustainable. Future exploration missions need robotic and crewed rovers that are capable of exploring for long durations, cover more land, and are rugged and reliable.

The Go-Anywhere Roving breakthrough capability encompasses a future where access to any location on, under, or over the surface of a planetary body is quick, easy, safe, and reliable. Multiple mobility technology concepts provide complementary abilities and enable transportation on extraterrestrial bodies similar to what is available on Earth. Due to the predominance of solid terrain, land rovers are the most common and can include walking, wheeled, crawling, and hybrid mobility modes. Crewed and robotic flying rovers, including balloons, airships, rotorcraft, propeller aircraft, and jets, traverse planetary bodies with sufficiently dense atmospheres. Humans and robots may use boats and submersibles to explore extraterrestrial liquid environments like Titan's lakes or the sea under Europa's icy crust. New suits and rover suit interfaces enable astronauts to directly access these environments quickly, safely, and with less fatigue or risk of injury. Mobility systems can be quickly customized with advanced engineering techniques, and breakthroughs in on-demand manufacturing systems may enable manufacturing of mobility systems in situ.

A breakthrough in roving capabilities allows astronauts and robotic assistants to escape isolated areas around landing sites. Landing sites can be chosen solely on optimized orbital trajectories and safety instead of scientific interest, reducing fuel requirements.

Missions become more sustainable and cost-effective, because they require fewer launches to explore large territories. Astronauts can conduct expeditions for multiple days or weeks, traveling hundreds or thousands of kilometers from an outpost to survey the environment and collect scientific data.

Through this breakthrough capability, NASA and partner space agencies or commercial organizations will benefit from increased scientific return, resource identification, and accurate geo-surveys. Better data allows agencies to select sites for future exploration and outposts. Robotic rovers will be more intelligent and can provide full site surveys prior to human missions, paving the way for safer exploration. Human and robotic systems will be able to cover more territory to identify resources and sites of scientific interest. Atmospheric and marine rovers will provide robots and astronauts access to environments that have never been sampled directly. This breakthrough in mobility will directly lead to new scientific discoveries, pave the way for ISRU, and increase return from investments in interplanetary travel.

Ultimately, technology systems contributing to this breakthrough could provide a planetary transportation network allowing efficient exchange between multiple sites. Future exploration may include multiple outposts on planets. Long-distance rovers will connect these outposts, enabling opportunities for sharing resources and personnel. Eventually, a network of transportation hubs could develop on planets with permanent human presence.

Related Capability Areas

Go-Anywhere Roving is closely related to several other breakthrough capabilities highlighted in this report.

- **Ubiquitous Access to Abundant Power –** Highlights several power generation and storage technologies that will be vital for breakthroughs in mobility. Rovers will need to generate or store energy for nominal operations as well as peak loads. As rovers travel farther, tackle rougher terrain, and carry more crew they will require more power.

- **Living Off The Land –** Includes technologies, systems, and capabilities that are directly influenced by roving capabilities. Most in-situ resource utilization (ISRU) concepts require one or more mobility elements to identify resources, collect raw materials, move processing plants to resource sites, and transport ISRU products. Limitations in mobility capabilities will help determine what resources are accessible and the throughput of ISRU production. In addition, rovers can use ISRU products to provide spare components and consumables used during operation.

- **Self-Sustaining Habitats –** Includes several technologies that can contribute to or will influence crewed rovers. Crewed rovers have to provide a protective habitat in addition to mobility and will have synergies with life-support systems developed for non-mobile crew environments. Crewed rovers have to interface with stationary habitats to transfer crew, and life-support interfaces are further complicated by interacting with life-support systems for spacesuits.

- **Healthy, Happy Astronauts –** Includes technologies that provide for the needs and safety of astronauts within crewed rovers. Short-duration rovers can rely on simple solutions to provide basic comforts and trauma treatment. As roving missions extend in duration, human factors including ergonomics, living space, meals, medical treatment, and recreation become more important.

- **Super Humans –** Covers all human augmentation technologies, including some personal mobility systems that overlap with technologies to augment strength and stamina. Exo-skeletons or active materials to augment forces on a spacesuit directly impact astronaut capabilities on EVA and can increase dismounted mobility. Other human augmentation technologies may increase EVA performance.

Supporting Technology Concepts

Rovers are essential elements of human exploration. Even with advanced imaging technology, some scientific questions require physical access to locations of interest. Teleoperated and robotic rovers provide opportunities for directly collecting data in situ. Unlike stationary landers, roving vehicles can explore more locations, providing a survey of planetary surfaces. Crewed rovers enable increased mobility for astronauts, improving the efficiency of EVAs and increasing the territory that can be explored. Crewed systems can also provide protection from the environment as a mobile habitat, reducing dependence on a fixed outpost.

Like terrestrial mobility systems, rovers can include ground vehicles, surface and submarine systems, atmospheric vehicles, and hybrid systems. Some terrestrial systems can be directly extrapolated to extraterrestrial environments and are the basis for potential breakthrough technology concepts.[342] Mobility systems can be optimized for the environment and payloads, or rovers can be built with flexibility for multiple environments and functions. Different rover designs provide a range of abilities for astronauts and robotic systems. A few examples of these mobility modes include wheeled vehicles, personal submarines, hot air balloons, and sailboats. Experience with terrestrial analogs and previous planetary rovers will help guide future rover development and will be the basis for successive generations of rovers.

The following section highlights several technology concepts that could contribute to a breakthrough in Go-Anywhere Roving. These concepts are based on open-source research, workshops with subject matter experts, and individual interviews. The technology concepts do not reflect an exhaustive list, but provide a range of concepts that could be developed prior to 2050. These concepts are at the system level and represent fully integrated mobility solutions. Consequently, they are addressed broadly and could cover a large number of specific but similar technologies. In many cases, component and subsystem technologies will greatly influence the development of these systems. Some representative, component-level technologies such as nanotubes, smart materials, intelligent systems, and thermal management are discussed in Crosscutting Technologies, page 216.

Supporting Technology Concepts	
Shape-Changing Rovers	Provide access to remote locations that cannot be reached by rigid rovers.
Roving Hoppers	Provide long-distance mobility through suborbital hops.
Reconfigurable Robots	Can dynamically reconfigure to provide new capabilities that address unforeseen challenges.
Mobile Ice Probes	Provide mobility through thick ice sheets and polar ice caps.
Mechanical Counter-Pressure Suits	Increase astronaut mobility while exploring without a rover.
Rotorcraft and VTOL Fixed-Wing Vehicles	Provide atmospheric exploration capabilities with minimal surface infrastructure.
Flapping Wing Rovers	An alternative approach to powered flight for increased lift in rarified atmospheres.
Balloons, Montgolfiere-Curie, Airships, and Tumbleweed Rovers	Inflatable rovers that provide a range of passive and active navigation capabilities for exploration.
Boats and Sailboats	Provide access to rare, but significantly interesting, bodies of liquid.
Small Crewed or Uncrewed Submersibles	Enable exploration under liquid surfaces and liquid environments buried under icy crusts.

Surface Rovers

Surface rovers enable mobility across the solid surface of planetary bodies. They include wheeled vehicles, walking systems, tumbling systems, slithering systems, and any other mobility modes designed for transport across solid or granular surfaces. Some surface systems can explore caves, lava tubes, and other subsurface features. The solar system has a variety of surface topologies, and several different surface systems will be necessary to fully explore a planetary body.

Shape-Changing Rovers

Shape-changing rovers can alter some or all of their structure to get around obstacles. These rovers have the ability to customize their shape for better mobility and provide additional functionality. Some shape-changing rovers can lower their center of gravity for increased stability, squish under overhead obstacles, increase wheel size to improve mobility through rough terrain, or provide other functional alterations. There are several different technical approaches for shape-changing rovers. Shape-changing rovers are not limited to surface vehicles; however, this report discusses the example within the context of surface systems.

Current research in shape-changing rovers focuses on multiple designs, including rigid vehicles with actuated components in key locations, membrane robots, and nodes with expandable struts. Rigid vehicles can include concepts like the common car that alter exterior topography to improve aerodynamic efficiency or aesthetics.[343] For planetary rovers, this capability could allow for minor exterior changes to permit access to narrow passages or across rough terrain. The second concept is an amorphous robot contained in a flexible membrane. In some cases the membrane and contained fluid include chemical actuators to enable movement.[344] More near-term concepts use flexible chambers filled with air and solid particles to provide directed movement in an amoeba-like gait. As air is pumped into a chamber, available volume increases and the particles become fluidized. By allowing specific chambers to flow, the rover can use gravity to move.[345] Node-and-strut rovers provide mobility through expanding and contracting struts between nodes. Simple rovers with four nodes are possible, but additional mobility modes are enabled with more complex systems and extra nodes. Rigid vehicles with actuated struts and skin are more near-term than flexible membrane robots or node-and-strut rovers and may represent a step towards this functionality.

PARTNERING OPPORTUNITES

SHAPE-CHANGING ROVERS

- Jaguar
- BMW
- DARPA Defense Sciences Office
- iRobot
- Tufts University, Biomimetic Devices Laboratory

Node-and-strut rovers, often called tetrahedral rovers, are particularly interesting for dynamic structures capable of efficiently traversing rough terrain. These rovers combine the best elements of wheeled motion, stepping motion, and other mobility gaits to traverse smooth surfaces quickly, comparable to a walking human, and can adapt a wide range of behaviors to accommodate unique surface features. In addition to mimicking wheeled and legged rovers, this system can mimic mobility gaits found in nature. One example is the amoebic gait that keeps nodes low to the ground and shifts the center of gravity of the rover to induce a series of small, controlled falls. This gait minimizes movements against gravity and is designed to conserve power. Other natural gaits like side-winding or slithering have been simulated with this design.[346] In each case, controlling node position through autonomic intelligence, rather than specifying individual strut movements, saves computing power.[347] The future realization of node-and-strut rovers is a complex, modular, multi-node vehicle that can change shape by expanding and contracting struts on a microelectromechanical systems (MEMS) level. This vehicle would be autonomically smart, enabling precise control of node positions to plan and execute optimal navigation to a target. Nodes and struts could be exchanged with spares or other rovers to provide additional mobility or repair damaged rovers. This mobility system can be combined with a simple, multi-level optometry and sensor suite to collect data and identify targets of opportunity.[348]

Concept cars in development by automotive makers may provide initial research for shape-changing rovers. Jaguar, BMW, and other automotive manufacturers are developing techniques for surface morphing for customizable designs. BMW's concept uses cloth stretched over a movable, flexible frame.[349] These designs are mostly for aesthetic purposes and are far from influencing planetary rovers, but they may promote further development.

DARPA is interested in flexible membrane robots to use in the field. The agency supported research through iRobot and academia for the development of membrane robots, including a $3.3 million contract to Tufts University. DARPA's envisioned application is a small, palm-sized robot that can squeeze through small cracks, gather intelligence, perform search-and-rescue operations, and provide capabilities not achievable by rigid-frame robots.[350] Many of the technical challenges facing this application, and the potential solutions, may be applicable to planetary rovers.

Tetrahedral rovers have been the focus of considerable research at NASA Goddard. Prototypes of single tetrahedral rovers, 4-tetrahedral rovers that carry a payload, and 12-tetrahedral rovers have been built. These prototypes used relatively simple materials and screw-actuated electrical mechanical struts that can achieve 5.29:1 expansion.[351] It may be possible to achieve a goal of 10:1 expansion with electromechanical systems, which would enable climbing and bridging large gaps. However, for precise control, power efficiency, and ruggedness, MEMS smart materials will be necessary. Investigators working on this concept consider the technology to be around TRL 2.[352]

Technology hurdles for shape-changing rovers include smart shape-changing materials, chemical actuators, power management, and controls for novel amorphous robotic systems (for more on "Smart Materials," see Crosscutting Technologies, page 231). The nearer-term concept of a rigid rover with some shape-changing facets may be achievable with current technology and new engineering designs. However, advances in materials could lead to breakthrough capabilities. Power management and supply is a significant challenge to shape-changing rovers. Gaits that conserve power and more efficient energy storage devices will help, but long-duration rovers will need some method to generate or convert power, as well as provide peak power for high-performance operations, such as accelerated movement or climbing. These systems also have to be autonomically smart. The rover can be directed with humans in the loop, but for quick movement the rover needs to make autonomous decisions. For node-and-strut rovers, payload integration is an engineering challenge. Smart, shape-changing materials are highly desirable for shape-changing rovers. These materials would enable larger deformation, more efficient movement, and rugged redundant designs. Membrane rovers, and potentially some smart materials, require further research on chemical pathways for actuators. Predictable, quick, and efficient devices will need to be developed.

Shape-changing rovers would provide unique benefits that directly enable Go-Anywhere Roving. Robots that are not constrained by rigid volumes can gain access to holes, caves, narrow channels, and other features that large rigid robots will not be able to access. In some cases, these features will be the most scientifically interesting, since they provide access to environments that are protected from the planetary surface, allowing exploration of unweathered geological features, unique chemical reactions, and potentially astrobiology. These rovers can aid with resource identification and locate sites that are scientifically interesting. Multiple, self-similar rovers could survey large expanses of planetary surfaces, identify targets of opportunity, and perform precursor research. If MEMS and manufacturing technologies mature, the tetrahedral rover concept could expand into multiple, shape-changing, functional systems based on small, mass-produced tetrahedrons. Compared to current systems, these rovers provide more mobility at lower power and greater flexibility to traverse multiple types of terrains.

Roving Hoppers

Roving hoppers combine traditional mobility modes with rocket propulsion to traverse large impassable obstacles or to arrive at a destination quickly. For this concept, wheeled rovers, like the prototype small pressurized rover, or walking rovers are equipped with a restartable, reusable, suborbital rocket engine and reaction control systems. The rocket can use conventional chemical propellant or a fluid heated by nuclear reactors, solar concentrators, or potentially radioisotope systems. The rover uses normal surface roving for exploration over small distances and the rocket engine to travel long distances.

PARTNERING OPPORTUNITES

ROVING HOPPERS

- Canadian Space Agency
- MIT Department of Aeronautics and Astronautics
- Charles Stark Draper Laboratory
- New Mexico Institute of Mining and Technology, Department of Earth and Environmental Science

The roving hopper concept is not new and was considered during the Apollo era.[353] Several papers have evaluated the concept since Apollo and have proposed similar designs for traversing large distances on a planetary body without extensive infrastructure.[354] Although the concept is well developed, there has not been an opportunity to implement it.

A significant advantage to roving hoppers is they can be built with current technology. There may be difficulties with integrating surface and rocket mobility modes, but these systems do not require a technical breakthrough prior to demonstration. However, roving hoppers face major operational challenges that may limit development. The suborbital rocket engine can require over half a ton of fuel for each hop of a 200 kg payload.[355] If the hopper, or another system, cannot make fuel from in-situ resources, economical operation of a hopper is impossible. Breakthrough rocket propulsion technologies developed for Easy Access to Space may help reduce the fuel necessary for hopping rovers; however, ISRU will likely be necessary for long-duration missions and increased rocket efficiency. Also, with current rocket technology, suborbital hops can be risky to crew and equipment. Drastic failures can result in loss of crew, but even nominal operations could affect crew health due to the stress and shock of repeated landings. Risk can be mitigated with redundancies and back-up systems, but these techniques require additional mass.

If the operational challenges can be resolved through ISRU and reliable rocket engines, this concept could enable planet-wide mobility from a single outpost. Astronauts could travel to remote locations that are identified as scientifically interesting. In addition, roving hoppers enable quick travel between locations without roads or flat plains, potentially providing opportunities to connect multiple bases or outposts.

Reconfigurable Robots

Reconfigurable robots are composed of multiple, independent robots that can combine to increase their functionality. These robots can be self-similar or provide different functions. Each module requires the ability to move independently, align itself to other modules, dock, and share functions with other modules in the completed system. Different approaches can be used to communicate between modules and enable self-reconfiguration.

Several potential designs for reconfigurable robots are possible. Self-similar modules often combine to form hinges, and each additional module provides extra degrees of freedom. Polymorphic Robotic Laboratory's Superbot provides examples of dynamic forms of motion that are enabled by different arrangements of these self-similar parts. In this case, modules sense the nearest neighbors and determine the appropriate movements for global translation.[356] As the modules get smaller, more aware of their environment, and better able to work as a team, new functionalities arise. For instance, large, human-scale mobility systems could break apart into smaller rovers to pass through obstacles, or small modules on robot extremities can reconfigure to provide different end-effectors. In addition to autonomous assembly, these systems are capable of self-repair, by removing damaged modules or reassembling if a section breaks.[357]

PARTNERING OPPORTUNITES

RECONFIGURABLE ROBOTS

- University of Washington, Self Organizing Systems Laboratory
- Cornell University, Computational Synthesis Laboratory
- MIT Distributed Robotics Laboratory
- Carnegie Mellon Robotics Institute
- Palo Alto Research Center (PARC), Modular Robotics Team
- Japan, National Institute of Advanced Industrial Science and Technology (AIST)

Several academic laboratories are currently researching reconfigurable modular robots. The concept was introduced in the late 80s and has evolved into separate concepts. Superbot was developed at the University of Southern California and other universities, including University of Washington, Cornell, MIT, and Carnegie Mellon, have developed additional prototype systems.[358]

Technology hurdles for reconfigurable robots change depending on the system architecture. For systems with differentiated parts, reconfigurable robots can have similar challenges with reliability as conventional robots. The loss of a key module could significantly limit functionality, effecting reliability similar to the loss of a wheel on a rover. For self-similar systems, the module size needs to be scaled down, and the number of modules acting in concert needs to be increased to enable complex behavior. In addition, most of these systems are not designed to carry heavy payloads, and strong, quick, connect-and-disconnect docking systems will need to be developed to support large rovers with human-scale payloads. Computing resources will need to be distributed among the modules or contained in a "brain module," reducing the reliability created through redundancy. Algorithms will need to be developed to enable reconfiguration and mobility mode selections based on environmental factors.

Although reconfigurable robots are currently at a low technology maturity, if successfully developed, they can provide many of the capabilities necessary for Go-Anywhere Roving. The ability to dynamically reconfigure form and function extemporaneously will enable these rovers to cross unanticipated obstacles and access locations that otherwise would not be explored.

Mobile Ice Probes

Mobile ice probes could provide access to sites of interest buried beneath polar ice caps or frozen crusts. One concept for a mobile ice probe consists of a small fission reactor and an instrument module connected by a short tether. The fission reactor provides roughly 500 kW of thermal energy, which is used to heat water to melt ice. By controlling the direction of hot water jets and the buoyancy of the probe, this rover can travel vertically though ice or tack horizontally using a series of angled rises and falls. Meltwater generated from the ice cap fills the space between the instrument module and the reactor, providing shielding for the electronics. Wireless radios transmit data back to a surface facility for analysis.[359]

The mobile ice probe concept is unique in that it provides access to layers of ice containing chemical signatures from a planetary body's history. This system could also access the solid surface under an ice cap or any submerged oceans to gather data or deliver a submersible probe. Scaling the concept up to provide mobility for crew is conceivable but would require additional shielding and potentially a conceptual redesign.

Mobile ice probes are conceptual technologies with limited current development. The concept was proposed by a private company and studied through a NASA Institute for Advanced Concepts (NIAC) report. If development continued on these concepts, terrestrial polar ice caps could provide an ideal analog for testing.

Without further testing and development, it may be impossible to identify the major technology hurdles to developing mobile ice probes. Technical challenges that can be anticipated include challenges associated with the tether, which, if cut or damaged, prevents the flow of water and electricity and effectively destroys the probe.[360] This challenge can be partially mitigated by sending multiple probes to act as a multi-node network. A second challenge is providing the thermal energy to melt ice. A nuclear reactor does provide sufficient heat, but there are challenges to designing one for a small container and controlling the nuclear reaction. These reactors will be designed for safety in case of any accident and will require appropriate documentation and oversight. Other heat sources, such as radioisotope thermal sources, are conceivable but unlikely. For instance, pure, subcritical plutonium 238, a common radioisotope for thermal electric generators, does not have enough thermal energy to continuously travel through Europa's ice sheet. Alternate methods, such as pulsing hot water that is heated over several hours or days, will be necessary to enable locomotion with non-nuclear systems.

Mobile ice probes would be a key technology to achieving Go-Anywhere Roving. This concept is the only identified technology that could provide access to all subsurface ice on a planetary body. It could be useful for exploring Mars and icy moons. If designed with submersible mobility, mobile ice probes could drill through icy crust and explore buried oceans as a nuclear submarine.

Personal Mobility

Dismounted crew are subject to mobility constraints imposed by the suit. Combining flexibility, pressure control, and protection from the environment is difficult. Crew on planetary systems with sufficient gravity can use natural mobility gaits learned on Earth. Low-gravity systems like the Moon require modified gaits for efficient mobility, such as loping and skipping. Mobility on planetary bodies with microgravity may be a learned skill and could require external safety mechanisms. New operational techniques, like anchoring tethers or boots, may be necessary for safe exploration of microgravity environments.

Mechanical Counter Pressure Suits

Current EVA suits use gas to provide a constant pressure to the astronaut's body, however, these suits are difficult to move in, can injure the astronaut, and significantly limit mobility. Mechanical counter pressure (MCP) suits are designed to mitigate some of these challenges.[361] MCP suits use smart, shape-changing, and elastic materials to provide mechanical pressure to all points of the body. This design fits to an astronaut like a second skin, enabling full flexibility and mobility while protecting the astronaut. Bi-phasic smart materials are necessary to allow the suit to relax for doffing and tighten for EVA operations. With smart materials and advances in wearable electronics, MCP suits can include additional functionality, such as life-support systems, sensors, human power harvesting, self-repair, medical systems, or even physical augmentation. These suits can include a disposable exterior for dust control.

PARTNERING OPPORTUNITES

MECHANICAL COUNTER-PRESSURE SUITS

- MIT Man Vehicle Lab

Advanced MCP suits can provide an additional mobility advantage over current suit designs. Electronics and life-support systems are currently contained in a heavy compartment on the back of a suit. This design can lead to balance and mobility issues. By distributing the life-support system around the body, astronauts will have a more comfortable center of gravity and will be able to move easier with less risk of injury.[362]

Research on the MCP suit is ongoing at the Man Vehicle Lab at MIT. Currently, there are existing prototypes based on a proprietary design that can provide mechanical pressure near 30 kPa, sufficient for EVAs.[363] Some testing has been done with integrating wearable electronics into the prototype, and concepts for including life support, sensors, and other systems in the suit exist. Full-body, laser scans could precisely design the suit, but manufacturing technologies for creating a full-body suit are limited. Further research is necessary to mature materials and 3-D printing technologies.

The team at MIT has identified several enabling technologies that could contribute to future generations of MCP suits. These technologies fall into three areas: pressure production, smart materials, and wearable technologies. Pressure production includes material development for conductive, elastic textiles; 3-D printing of these textiles; and manufacturing techniques like electrospinlacing. Representatives at the lab note that a large challenge is shifting these technologies from 2-D textiles to custom-made, 3-D suits for a full-body garment. For smart materials, microactuators that can scale up to human-scale forces for donning and doffing the suit are necessary. These actuators could include shape-changing polymers or ferromagnetic shape-memory alloys that are bi-phasic and can relax or tighten as needed. The main challenge to these is scaling up the force to a macro-scale level without material damage due to brittleness or fatigue (see “Smart Materials,” page 231). Wearable technologies are just as important as the pressure garment, and development is needed to monitor the body, provide membrane life support, harvest human energy, and other secondary functions.[364]

If successfully developed, an MCP suit will allow astronauts to directly access planetary surfaces with unprecedented mobility. These suits could enable increased EVA durations while minimizing fatigue and risk of injury. They would allow human access to rough terrain like cliff faces. Mechanical counter pressure suits can also include human augmentation systems to enable faster travel, increased strength, and improved stamina. With a disposable outer covering, these suits would minimize dust transport between the exterior environment and the habitat. Ultimately, MCP suits will significantly improve access to planetary bodies.

Atmospheric Rovers

Several planetary bodies have dense atmospheres. Venus, Mars, Titan, and the outer planets have atmospheres thick enough for atmospheric rovers. Multiple approaches to overcoming gravity are possible. Some rovers may use aerodynamic lift on an airfoil, such as jets, propeller-craft, gliders, and rotorcraft. Others may use lighter-than-air technologies to float in the atmosphere. Novel atmospheric mobility methods may develop as we learn more about target exploration sites.

Rotorcraft and VTOL Fixed-Wing Vehicles

Rotorcraft and vertical take off and landing (VTOL) fixed-wing vehicles are a class of technologies modified from existing technologies on Earth for extraterrestrial exploration. These technologies provide aerial exploration of planetary bodies with dense atmospheres. They can provide point-to-point transportation or aerial surveys. The technology behind rotorcraft and VTOL fixed-wing vehicles is mature on Earth, but customization will be necessary for other planetary environments. Engineering challenges rather than technical challenges may limit this breakthrough concept.

PARTNERING OPPORTUNITES

ROTORCRAFT AND VTOL FIXED-WING VEHICLES

- Trek Aerospace
- Boeing Rotorcraft Systems
- Advanced Rotorcraft Technology, Inc.

There are multiple concepts for rotorcraft and VTOL fixed-wing vehicles. These systems can resemble single- and multiple-rotor helicopters; VTOL turboprop or jet airplanes; rocket-propelled rotors; rocket-powered, tail launch airplanes; or hybrid wheeled VTOL rovers.[365] Each concept can launch and land in an isolated location without the requirements of a runway. Concept selection will depend on testing, external environment, and operations. These concepts allow for controlled access to planetary atmosphere with minimal infrastructure.

Studies have been conducted to look at power requirements for flight in different atmospheres. Gravitational constraints and atmospheric densities make a large difference in the power required to sustain flight. For thin atmospheres and relatively high gravity, like Mars, flight is challenging, and very high velocities or rotor tip speeds are required. Systems that operate at higher velocities could require significantly more power to sustain flight. Studies have shown that for thick atmospheres, like Titan's, flight is less challenging, and power requirements are around two orders of magnitude less than required for Mars.[366] Also, engineering challenges exist if required velocities or tip speeds exceed the local speed of sound.[367]

Powered fixed-wing or rotorcraft flight is not as efficient as wheeled vehicles. Small vehicles have been considered for the Martian atmosphere, but flight times have been estimated at a few minutes to an hour with available onboard fuel.[368] For longer flights or to lift heavier payloads, like crew, substantially more fuel will be necessary. ISRU can help mitigate the fuel requirements, enabling rovers to land, refuel, and continue their mission, but this increases the difficulty and complexity of operations.

Even with sufficient power, planetary atmospheres can present a large challenge to flight. Thinner atmospheres require faster tip speeds or velocities to generate enough lift to counter gravity. For some cases, potentially including Mars, these velocities could approach the speed of sound. The shockwave generated from a supersonic transition can make flight very challenging and may make rotorcraft operation impossible.[369] In addition, designing, testing, and maintaining these vehicles will be a challenge without detailed information of the environment they operate in. A breakthrough in vehicle maintenance could be necessary for sustainable exploration.

If successful, these vehicles could provide unlimited opportunities for in-situ atmospheric research. Vehicles with powered flight could provide opportunities to survey and explore planetary surfaces and may work in concert with surface rovers. For crewed missions with distributed infrastructure, VTOL rovers could provide quick access between exploration sites.

Flapping-Wing Rovers

Flapping-wing atmospheric rovers are a biologically derived solution for powered flight.[370] These rovers use flapping wings instead of airflow over an airfoil to provide lift. These systems can take advantage of leading edge vortices generated by the flapping wing to increase lift and improve aircraft performance. [371] This approach could be particularly useful for planetary environments with low-density atmospheres, where fixed-wing and rotorcraft are not practical, and could provide atmospheric mobility with low translational velocities. Systems can be designed with alternating sets of flapping wings to reduce or eliminate oscillating motion on the fuselage and payloads.[372] Power systems for proposed flapping-wing rovers include chemical energy conversion systems for mechanical energy and electricity to power payloads. These rovers can be scaled for different atmospheres and missions to provide flexible aerial mobility.

PARTNERING OPPORTUNITES

FLAPPING WING ROVERS

- DARPA Defense Sciences Office
- Nano Air Vehicle
- AeroVironment, Inc.
- Stanford University, Department of Aeronautics and Astronautics
- Georgia Tech Research Institute

Flapping-wing robots have been proposed for Mars exploration and could be designed for other planetary environments. Because of the additional lift gained from the leading edge vortices—approximately seven times the lift expected from a similar fixed-wing vehicle[373]—constraints that could prohibit fixed-wing VTOL and rotorcraft may not apply to flapping-wing rovers. With redesigned control surfaces and different flight algorithms, flapping-wing rovers may also work for denser atmospheres. These systems would potentially enable vertical, or small runway, take off and landing. They may be coupled with surface systems for refueling, coordinated exploration, and sample collection. With larger, more powerful systems, flapping-wing rovers may provide crew or heavy payload transport from point to point.

Subscale technology demonstrators for flapping-wing rovers have been developed. DARPA provided seed money to develop one version of this concept for reconnaissance applications.[374] The subscale demonstrator has applications for larger systems on Mars. According to the laboratory that tested the vehicle, some of the airflow characteristics for the small vehicle on Earth are similar to characteristics for a larger, approximately one-meter wingspan, system on Mars.[375] These tests provide a pathway for extending terrestrial systems to extraterrestrial planetary explorers.

Some of the major challenges facing flapping-wing vehicles are similar to other atmospheric explorers. These systems will be difficult to develop and test without a very accurate model for the Martian atmospheric system. Material development could also inhibit or promote flapping-wing vehicles. As the wing oscillates, it experiences high strains that fluctuate in magnitude and direction with wing motion. These forces increase with the wingspan and lifting capability of the vehicle. Lightweight flexible materials, potentially including carbon nanotubes, are necessary for large payloads or a crewed system (see Crosscutting Technologies, “Nanotubes,” page 226). The power system for these vehicles could be a challenge. They require high peak power and will have flight times that are constrained by the onboard fuel or stored energy. ISRU capabilities could mitigate this challenge.

Like VTOL systems, flapping-wing vehicles could provide a breakthrough for crew movement, atmospheric in-situ measurements, surveys, and coordinated activities with ground vehicles. Flapping-wing systems could be an improvement over fixed-wing systems for applications that require long loiter times in rarified atmospheres. The chemical muscle power system for the flapping wing could conceivably be used to power a legged ground vehicle, permitting hybrid systems that can fly or rove on land as needed.

Balloons, Montgolfiere-Curie, Airships, and Tumbleweed Rovers

Lighter-than-air craft provide another approach to atmospheric roving. Super-pressurized balloons, hot air balloons, and airships overcome gravity without aerodynamic lift. Several specific concepts exist with associated characteristics and challenges. Regular balloons are relatively easy to develop, but their altitude will change due to diurnal heating. Super-pressurized balloons avoid this problem but require stronger, inelastic materials. Hot air or Montgolfiere balloons are more technically challenging but provide control over balloon elevation.[376] Montgolfiere balloons require a source of heat to increase the temperature of the air in the balloon envelope relative to the external atmosphere. Concept missions for Mars and Titan considered using radioisotope thermoelectric generators (RTGs) to provide heat for the balloon and electricity for instruments.[377] With an RTG power source, these balloons could stay aloft for multiple years and passively explore. Regardless of the balloon concept, these rovers rely on global wind currents to travel around a planet and can only conduct opportunistic exploration.

Airships provide an alternative to balloons that do not have to rely on passive navigation. Airships or dirigibles are also lighter-than-air craft, but they have onboard power plants and propellers to provide thrust. The additional weight from the propeller, larger power system, and electric motor requires more displaced air for lift. Consequently, airships tend to be larger than comparable balloons and require denser atmospheres to operate. However, they provide advantages of directed navigation and the ability to hover over a spot for extended observation. A NASA-funded study indicates that Titan and Venus could be viable targets for exploration via airships.[378]

A surface-roving concept similar to balloons, in that it is propelled by atmospheric winds, is the tumbleweed rover. A tumbleweed rover is a heavier-than-air balloon that rolls across a planetary surface propelled by wind. The balloon’s buoyancy could be tailored to maximize the rover’s range. This concept has been tested through terrestrial analogs, and a robotic mission using the technology could be achieved in the near term.[379] NASA researchers have proposed missions for using this technology, including mapping magnetic fields at the surface of Mars.[380] However, it may be difficult for tumbleweed rovers to travel long distances in terrain with deep crevices, craters, or valleys. Estimates of the rover's range depend on the exploration surface, and predicting when the rover will get stuck, effectively ending its mission, will be difficult. Future concepts may include elastic balloons that can be heated to provide lift after the rover gets stuck in a local depression or crater.

Several material challenges could limit advancements for balloon roving capabilities. Balloons, airships, and tumbleweed rovers will need lightweight, strong, airtight materials for the balloon envelope. Depending on the planetary environment, these materials may also need to be temperature-tolerant, radiation-tolerant, resistant to corrosion, and strong enough to survive extreme weather conditions.[381] For tumbleweed rovers, the balloon envelope will also need to be abrasion- and puncture-resistant. Passive navigation systems, like balloons and the tumbleweed rovers, will require a detailed understanding of the planetary atmosphere and wind currents, so atmospheric entry sites can be selected and missions planned. Airships will require a lightweight drive system, including propeller, drive shaft, motor, and power source. Systems relying on RTGs may require a new isotope for fuel rather than the traditional, and increasingly scarce, plutonium 238.

Balloons and related vehicles offer several advantages for mobility on planetary bodies with atmospheres and may contribute to Go-Anywhere Roving. Some balloon systems are low power. Others provide the advantages of powered flight without rigid, and potentially difficult to pack, airframes. All these systems are relatively light and can explore large territories. Initially, balloon systems will be robotic with light payloads; however, the size of the payload is solely limited to the balloon's buoyancy and consequently the size of the balloon envelope. With sufficiently lightweight and strong materials, balloons and airships could provide transport for crew and heavy payloads.

Marine Rovers

Some planetary bodies have liquid features that provide both a barrier to and an opportunity for exploration. Exploration of cold liquid bodies with unknown characteristics and chemical composition could be technically challenging. Future robotic missions may explore these environments and gather data for subsequent human exploration.

Boats and Sailboats

Not all mobility modes developed for space exploration will be applicable to roving on all planetary bodies. About 70% of the Earth's surface is water, and humankind has a rich maritime tradition. Of all the other planetary bodies in the solar system, only Titan has liquid on the surface, in the form of liquid ethane and methane. Robotic missions using a passive navigation "boat" have already been proposed for exploring Titan, and, if developed, a possible landing of the first liquid rover could occur in 2022.[382] Although floating rovers would be restricted to Titan, they still have a role in Go-Anywhere Roving.

Two of the boat concepts proposed for Titan include a simple splashdown capsule with a passive navigation system, much like the Apollo capsules[383] and the Titan Saturn System Mission concept, which includes an orbiter, Montgolfiere, and lake lander working in concert.[384] A third concept includes an aerovehicle, rover, boat, and towed submersible that adapts to specific terrain on Titan.[385] Any of these conceptual missions could collect data on Titan's lakes, weather, hydrocarbon cycle, and chemical composition, while paving the way for future human exploration.

Challenges to a boating mission on Titan's surface arise from the thermal and chemical environment. Titan's surface has an ambient temperature of about 100 K, and the physical properties of the hydrocarbon lakes are unknown. Lightweight and strong materials and systems that can withstand direct contact with cold fluids will be necessary. Temperature-tolerant materials may be integrated into structural materials, such as the hull. Exotic materials, such as ionic liquids for battery electrolytes, may also be useful. It may be necessary to develop low-wetting surfaces for liquid hydrocarbons to prevent the boats from stalling in high-viscosity areas (see Crosscutting Technologies, "Low-Temperature Mechanisms," page 224).[386] Some of this risk can be accepted for initial robotic missions, but materials will need to mature prior to potential human missions. In addition, accurate knowledge of the climate, weather patterns, and fluid dynamics will be necessary to forecast rover position for passive vehicles and to minimize risk for humans.

Small Crewed or Uncrewed Submersibles

Liquid roving surface vehicles are limited to Titan and Earth, but there are other potential exploration sites that may have subsurface lakes and oceans, such as Europa and possibly Ganymede or Enceladus. Subsurface oceans may provide the best possibility for extraterrestrial life and are interesting targets for future exploration. To access these locations and explore under the surface of Titan's lakes, robotic and crewed submersibles will be necessary.

To maximize submarine mobility, planetary submersibles may leverage advanced concepts for terrestrial systems. Commercial companies have built neutrally buoyant, quick, and responsive submersibles for research, resource extraction, and entertainment. One prototype is designed to operate at the deepest point in Earth's oceans and uses hydrodynamic forces similar to lift on an airplane wing to provide responsive control.[387] Alternative terrestrial designs include deep-sea robotic systems capable of construction, maintenance, and repair tasks.[388] In either case, extraterrestrial systems will have to be self-sufficient with onboard power generation and, if the submersible supports crew, life support. Terrestrially, a

PARTNERING OPPORTUNITES

SMALL CREWED OR UNCREWED SUBMERSIBLES

- Deep Flight
- Oceaneering

tether to the surface can provide these functions, but on icy moons this tether is likely to be severed by the ice crust.[389]

There are several technical challenges to submersible rovers. The environments that these explorers will operate in are unknown. In many cases, scientists are unsure if liquid oceans exist as a potential exploration target or how deep they are.[390] Even if buried oceans are relatively close to the surface, the pressures could be too high for current materials. Proposed high-strength materials, like carbon nanotubes, that are tailored to provide tension strength, might not provide the compressive strength necessary for these depths. Robotic systems that can be built without voids may operate at these pressures, but it will be difficult to modify robotic rovers to provide a crew volume.[391] An alternative design may be possible, if crew can survive in an ambient pressure habitat. Some research suggests that mammals can breath incompressible oxygenated fluid and may be able to survive at high pressures, but medical breakthroughs in high-pressure environments and fluid respiration will be necessary.[392] Further information on the environment, temperatures, and pressures that rovers will have to survive is necessary before systems can be designed.

If submersible rovers can be designed for a variety of exploration sites, it would represent a major breakthrough in mobility. Submersible exploration has only occurred on Earth, and only a limited portion of Earth's oceans have been explored.[393] Expanding this capability to other planetary bodies will enable exploration of some of the most inaccessible locations in the solar system.

Technology Trajectory

Current state-of-the art roving technology includes semi-autonomous robotic planetary rovers and terrestrial demonstrators for a next-generation small pressurized rover for crew. Heritage roving technology is limited and includes robotic ground missions Luna 17, Luna 2, Mars Pathfinder, *Spirit*, *Opportunity*, Venus balloon missions Vega 1 and 2, and the Apollo-crewed rover, Lunar Roving Vehicle.[394] NASA is leveraging previous mission experience and terrestrial analogs to develop the state-of-the-art robotic rover, Mars Science Laboratory (MSL). Like other Martian rovers, MSL is semi-autonomous. It is designed for a mission lifetime of 687 days and should travel five to twelve kilometers during its mission.[395] State-of-the-art technology for crewed rovers could provide increased range, 150 miles more than the small pressurized rover's ability. Terrestrial analogs for planetary rovers are testing technologies and systems that could be used for crewed planetary rovers.[396]

At the systems level, there are several near-term technologies that provide the basis for projecting future mobility systems. The Department of Energy and NASA are interested in promoting electric vehicle technologies.[397] Advances in terrestrial electric vehicles could lead to planetary rovers with more power, increased mobility, and the ability to support crewed or robotic missions for longer durations. Several academic institutions and government agencies are investigating autonomous vehicle teams, which could lead to roving systems that include self-coordination among independent explorers. For human explorers, mobility is not restricted to the rover. Astronauts need to directly interact with their environment. Research into advanced pressure garments and other dismounted mobility technologies could influence rover design and significantly change EVA operations.

It is difficult to project specific roving technologies from current activities. Rovers are a systems-level technology, and the development trajectory for new vehicles will be heavily influenced by component and subsystem breakthroughs. New materials, energy storage systems, or computer systems could significantly alter rover capabilities and design. Components and subsystems in development that could heavily influence future rover systems include structural materials, low-weight power systems, computing tools, and guidance and navigation systems.

Research for terrestrial mobility technologies and crosscutting component technologies will likely advance outside the space industry. Many of these technologies could be incorporated into future roving systems with additional research or development. However, it is unlikely that systems-level breakthroughs for extraterrestrial roving will develop without the assistance of a space agency. Consequently, NASA or other space agencies will have to support roving technology research and development, identify and incorporate component or related technologies from the broader economy, and perform systems integration functions.

If roving technologies advance sufficiently in the next 40 years, a breakthrough, as envisioned in this section, may be possible. Alternatively, incremental advancements, which may result in some of the highlighted technology concepts, will improve roving capabilities and impact other potential breakthrough capabilities.

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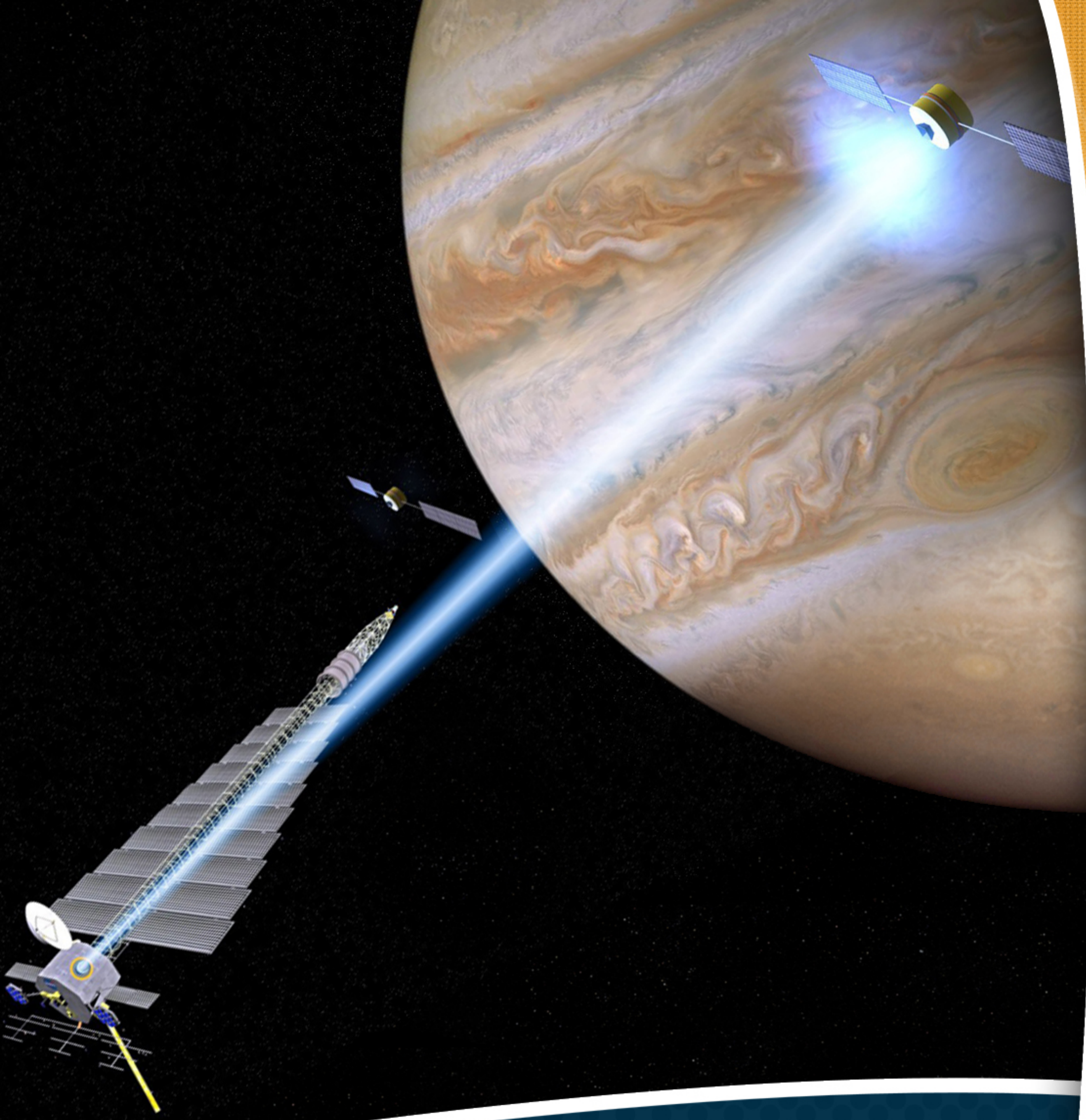

UBIQUITOUS ACCESS TO ABUNDANT POWER

Energy generation, storage, and distribution

UBIQUITOUS ACCESS TO ABUNDANT POWER

UBIQUITOUS ACCESS TO ABUNDANT POWER
Energy generation, storage, and distribution

All space systems need power. Science payloads, propulsion systems, life support, surface mobility, communications, computer processing power, and exploration mission size are all limited by available power. Current robotic probes and human missions have a carefully planned power budget, a critical element of spacecraft design. The power budget defines the maximum power available to a mission and, along with propellant and mass budgets, is a significant limiting factor during the design phase.[398] Often difficult choices have to be made between payloads that compete for power resources. In addition, current power systems degrade over time, negatively impacting operations. Technical solutions that provide an abundance of power through a robust infrastructure, similar to systems on Earth, will significantly change human space exploration.

> **BREAKTHROUGH**
> All exploration systems require power. High-power, low-mass power generation systems enable interplanetary travel, life support, and ISRU. Dense energy storage systems increase the capability of rovers, suits, and sensors. Spacecraft and outposts require advanced, lightweight power management and distribution systems.

A future with a breakthrough in Ubiquitous Access to Abundant Power will abolish a major limitation on human and robotic exploration: insufficient power. Current limitations on where, how, and at what cost exploration missions can generate, store, and distribute power will no longer apply to systems planning. High-power-density technologies will provide abundant power to all exploration systems with minimal dry mass increase. Small robotic rovers could be equipped with fission, or potentially fusion, power systems. Novel approaches to packaging, including flexible systems, ultra-dense energy storage, and wireless power transmission, will enable smaller, more capable exploration systems. Networked power distribution systems will enable modular expansion, enable rapid recharging of energy storage systems, and provide the basis for future infrastructure on planetary bodies with permanent human presence. Ultimately, power will become a secondary consideration when planning missions.

A portfolio of technologies that provide energy generation, distribution, and storage will enable breakthrough power capabilities. Technologies within the portfolio may include breakthrough concepts that radically change the approach to space exploration, such as antimatter-matter reactors. Other, rapidly evolving technologies, such as batteries and fuel cells, will evolve from current and near-term capabilities to support missions enabled by this breakthrough capability.

A breakthrough in Ubiquitous Access to Abundant Power will enable many envisioned, but currently unfeasible, concepts for space exploration. Abundant power for all exploration systems help enable large in-situ resource utilization (ISRU) plants for manufacturing consumables and building materials; self-contained greenhouses that provide food for long-duration crews; large space stations that provide resources and construction services in orbit around Earth, other planetary bodies, and Lagrange points; deep space crewed missions; rapid transportation through the solar system with efficient high-power electric thrusters; and long-duration rovers, among other concepts. These systems would in turn increase the scientific return; provide resources to make exploration comfortable, more robust, and sustainable; and enable human exploration of the far reaches of the solar system. With abundant, ubiquitous power, space exploration agencies can build and power the future of space infrastructure. Abundant power is a direct precursor to expanding human exploration of space.

Related Capability Areas

Power is a critical element for every aspect of exploration. Power plants with high power density are needed for Self-Sustaining Habitats, Efficient Interplanetary Travel, On-Demand Manufacturing, Space Oasis, and potentially Easy Access to Space. Mobile power sources capable of providing constant and peak power over several days or months are needed for Go-Anywhere Roving and Living Off The Land. Everyday Supercomputing, Seamless Human-Computer Interaction, and Environmental Omniscience need pervasive power distribution systems and small lightweight energy storage. Crewed missions relying on Healthy, Happy Astronauts and Super Humans require power for life support, crew accommodations and interfaces, mechanical augmentation technologies, and general comfort. Power feeds into each of the breakthrough concepts; however, one concept stands out as enabling, as well as using, Ubiquitous Access to Abundant Power.

- **Living Off The Land –** Includes multiple processes for extracting, processing, and delivering consumables and resources for space stations or exploration outposts. This breakthrough capability could provide fuel or reactants for power systems, reducing the logistics challenge for some power generation concepts. In addition, Living Off The Land could provide raw inputs for in-situ production of power system components, including solar cells, radiation shielding, flywheel materials, wires, and other components. Power systems that have substantial infrastructure, like nuclear power plants, geothermal systems, and extraterrestrial wind energy, may require advanced ISRU for manufacturing and construction.

Supporting Technology Concepts

A breakthrough in Ubiquitous Access to Abundant Power will require a range of technology concepts from breakthrough innovations to order of magnitude advances in existing technologies. Breakthrough concepts like fusion power plants, high-temperature superconductors, and antimatter reactors will coexist with improved solar cells, batteries, and fuel cells extrapolated from current technology. Many of the near-term technologies are discussed in detail in the *Technology Horizons* report. These technologies are highlighted in the technology trajectory section of this chapter but are not covered among the breakthrough concepts.

The following section highlights several technology concepts that could contribute to a breakthrough in Ubiquitous Access to Abundant Power. These concepts illustrate a range of breakthrough technologies that may develop beyond the next generation of power technologies. Highlighted breakthrough technology concepts focus on power generation, distribution, and energy storage. Other systems and non-breakthrough concepts will contribute to the breakthrough capability in Ubiquitous Access to Abundant Power. (See Crosscutting Technologies, for technologies that contribute to power generation, distribution, or energy storage, including carbon nanotubes, thermal management, high-temperature materials, plasma technologies and synthetic biology, page 216.)

The concepts discussed below are based on open-source research, workshops with subject matter experts, and individual interviews. Several of the breakthrough technology concepts are grouped into technology areas, such as advanced nuclear reactors and new physics. Multiple breakthrough technologies could arise from these technology areas. Specific examples of breakthrough concepts are highlighted; however, the discussion centers on the range of capabilities these technology areas can provide. The technology concepts do not reflect an exhaustive list, but provide a range of concepts that could be developed prior to 2050.

Supporting Technology Concepts	
Advanced Nuclear Reactors	Systems that provide energy through controlled fusion or fission reactions.
Antiproton-Driven Fusion	A type of pulse reactor that uses antiprotons to initiate fusion and provide energy.
Multifunctional Photovoltaic Materials	Photovoltaic materials that provide two or more primary functions.
Microradioisotope Power Sources	Small-scale power systems that capture energy released from radioisotope decay and convert it to electricity.
Extraterrestrial Wind or Geothermal Power Plants	Surface power plants that extract energy from natural process.
New Physics	May provide breakthrough capabilities that extend well beyond performance of systems based on currently validated physics.
Power Beaming and Wireless Power Transfer	Systems that transmit power between two points without a physical connection.
High-Temperature Superconducting Wires	Wires that can transmit electricity without resistance or power loss.
Optical Fiber	Physical links that transmit power as light.

Thermal Capacitor	Energy storage system that stores thermal energy in a physical medium.
Matter-Antimatter Reactor	Energy storage system consisting of an antimatter production plant and a remote matter-antimatter reactor.

Power Generation

Power generation breakthrough concepts cover all breakthrough technologies that extract energy from an outside source—the Sun, nuclear or chemical fuel, or more advanced energy sources—and convert this energy to usable power. Most power generation technologies will generate electricity, but mechanical or thermal energy may also be desirable. Power generation technologies are required on spacecraft, orbital stations, outposts, long-duration rovers, and other architecture elements. A driving metric for assessing power generation technologies is watts per kilogram.

Advanced Nuclear Reactors

Advanced nuclear reactors include fusion and fission reactors that operate at higher power, generate more energy, and are cleaner or safer than current terrestrial systems. In addition, advanced nuclear reactors for space exploration will be designed for the space environment and customized for particular exploration applications. Specific technologies include magnetic and inertial confinement fusion; small, modular fission reactors; and technologies derived from Generation IV fission reactor concepts. Generation IV fission reactors is a classification of next generation reactor concepts for terrestrial power plants, which includes liquid reactors, gas or vapor core reactors, non-classical cooling systems, and new power cycles.[399] Some generation IV concepts are more mature than others, and it is possible that unanticipated generation V concepts could develop prior to 2050.

PARTNERING OPPORTUNITES

ADVANCED NUCLEAR REACTORS

- Argonne National Lab
- Oak Ridge National Lab
- University of Florida
- Los Alamos National Lab
- Idaho National Lab
- Lawrence Livermore Lab
- ITER
- U.S. Department of Energy (DOE) Office of Nuclear Energy

Modular fission reactors are one advanced concept that could add flexibility to an exploration architecture. Modular fission reactors consist of small subcritical units that are combined in a cluster for fission power. Cluster geometry can be designed to enable reactor growth, with each additional unit providing an extra 5-6 kW_e.[400] Cluster geometry can enable mission flexibility. However, fission clusters may not be as efficient as purpose-built reactors.[401] Outside of a cluster, the units are stable and safe to move. With planning, this technology will allow reactors on planetary bodies to expand indefinitely, supplying abundant power for any future needs. On a planetary surface, these reactors could be buried for shielding, and, depending on the properties of the regolith, local resources may be used for neutron reflection to control reactor performance.[402] For spacecraft and space stations, modular fission reactors will be limited by available volume, however, they may improve mission flexibility. In addition, it may be possible to design small clusters that power long-duration rovers, increasing commonality between power generation systems.

Liquid and gas (or vapor) core reactors are two promising generation IV reactor technologies that could be modified for space exploration. Both technologies have improved efficiency, reduced waste, increased safety, and potentially lower cost than current terrestrial concepts.[403] Liquid core reactors include molten salt reactors and the less mature eutectic metallic fuel reactors. In liquid core reactors, the nuclear fuel is suspended in a liquid coolant, and reactions are controlled by channel widths through a neutron moderator, limiting fusion to the reactor chamber.[404] The fission products can be filtered out of the fluid line, and additional fuel can be added as needed without turning off the reactor. This reactor design enables higher temperatures, better efficiency, and increased safety.[405]

Gas core reactors further increase the maximum operating temperature and efficiency over other generation IV concepts. Gas core reactors use a vapor coolant and fuel to enable higher operating temperatures, and they have an added benefit of lower mass than solid core systems.[406] Gas core reactors can use a combination of magnetohydrodynamic generators and thermodynamic generators—such as Brayton cycle generators—to increase conversion efficiency up to 70% efficiency.[407] In addition, like liquid core reactors, the fuel and coolant mix can be processed while the reactor is online, removing fission products and refueling.

In addition to breakthrough fission concepts, fusion reactors may be available for space exploration systems in 2050. There are multiple different fusion power plant concepts. Large, experimental power plants include magnetic confinement with tokomaks and laser-driven inertial confinement systems; however, there are other designs that may develop, such as inertial electrostatic confinement fusion.[408] If successfully developed, inertial electrostatic confinement fusion may be particularly attractive for space exploration and could result in small, portable reactors.[409] In addition, inertial electrostatic confinement reactors could use next generation, low-neutron-producing fuels like He-3 and proton-boron 11, which require reduced shielding and enable high-efficiency power production. Fusion technologies are less mature than fission systems, but they could provide abundant power with readily available fuel, reduced pollution, and increased safety.

Nuclear power research has a strong domestic and international community. In 2002, the Nuclear Energy Advisory Committee (NEAC), which provides advice to the Department of Energy's (DOE) Office of Nuclear Energy, released a report highlighting generation IV reactor concepts and some of the organizations working on those concepts. Argonne National Laboratory, Marshall Space Flight Center, Oak Ridge National Laboratory, Électricité de France, University of Florida, Technische Universiteit Eindhoven, and Los Alamos National Laboratory submitted liquid or gas core concepts for the NEAC review.[410] NASA has also investigated liquid reactor technologies, including a liquid fluoride thorium reactor.[411] South Africa has been developing a modular, pebble bed reactor through Pebble Bed Modular Reactor (Pty) Limited (PBMR), a company established in 1999.[412] Recently, the company faced organizational and financial challenges; however, the company made technical progress, including designing and testing several modular fuel pellets.[413] In addition to terrestrial concepts, Idaho National Laboratory has proposed modular fission designs for the lunar surface.[414] Currently, NASA's ETDD Fission Power Systems project is pursuing an effective surface power plant for exploration using existing fission technology.

Fusion power research has its own large, international community. There are several major magnetic confinement facilities to investigate terrestrial fusion, some of which the U.S. federal government contributes to or directly supports, including National Spherical Torus Experiment, Alcator C-Mod, and ITER.[415] Lawrence Livermore National Laboratory sponsors the National Ignition Facility, and several academic institutions are researching other approaches for fusion energy.[416] However, most terrestrial research activities focus on the deuterium-tritium reaction, which releases energy as neutrons and requires heavy shielding and thermal conversion systems. In the future, these reactors may produce power for terrestrial power grids, but it is unlikely that this technology path will result in a space power system with a low alpha (kg/kW). Currently, fusion research into concepts that support space exploration is limited, but there is some tangential research for concept development and precursor technology demonstrations for fusion propulsion systems.

Technology challenges for advanced nuclear reactors vary for each of the concepts. Advanced fission concepts have mostly design challenges to ensure safe, efficient, and cost-effective operations. Modular fission reactors are the most mature design in this section; however, both liquid and gas core reactors could develop and be implemented by 2050. Molten salt reactors require research into salt processing, fission product removal, and waste processing, in addition to general design challenges like corrosion resistance.[417] In addition to many of the challenges to liquid core reactors, gas core reactors require very-high-temperature materials that can operate at high pressure; may have challenges associated with uncertainty in high-temperature chemistry for the fuel vapors; and thermal variations that can significantly affect the distribution of fuel and coolant vapors.[418] Fission reactors may face similar social and political constraints as nuclear-powered propulsion systems. Launching nuclear materials and operating nuclear reactors in space will likely require additional documentation and scrutiny; however, as noted in Easy Access to Space, these challenges are outside the scope of this report. Fusion technologies are the least mature of advanced nuclear reactors and may require further basic research in plasma science to develop a small system with positive energy generation. General challenges for fusion power on spacecraft include high temperature, high pressure, and sufficient confinement time.[419] (See Crosscutting Technologies, "High-Temperature Materials," and "Plasma Technologies," pages 219 and 229, for more information.) In addition to specific challenges, all advance reactors for space exploration will need to provide high power with low mass.[420]

With advanced nuclear reactors, spacecraft, stations, outposts and long-term exploration missions will have access to abundant power. Some systems like modular fission and small fusion reactors may be developed for crew or rover portable devices, increasing access to abundant power in remote locations. For exploration beyond the inner planets, self-contained, large power sources like advanced nuclear reactors will be necessary.

Antiproton-Driven Fusion

Antiproton-driven fusion is an alternative technique to sustained fusion reactors. It reduces some of the challenges associated with conventional fusion, specifically sustaining high temperature and pressure in a confined plasma. This technology is based on the same techniques as micro fusion pulse propulsion, discussed in Efficient Interplanetary Travel. However, instead of producing fusion products to provide thrust, energy is extracted from these reactions and converted to electricity. Like micro fusion pulse propulsion, antiproton-driven reactors require a source of antiprotons that are injected into a fuel pellet via a low-energy particle beam. Energy is extracted from the fuel pellets using technologies similar to those used by laser-pulsed inertial confinement fusion reactors. These technologies may include thermodynamic generators that use reactor chamber coolant as a heat transfer fluid and systems that extract energy by directly coupling fusion products to magnetic fields.[421] By using antiprotons, the energy gain can be increased by an order of magnitude over conventional inertial confinement fusion.[422]

PARTNERING OPPORTUNITES

ANTIPROTON-DRIVEN FUSION

- U.S. Department of Energy (DOE) Office of Science
- Lawrence Livermore National Lab
- Fermi National Acceleratory Lab
- University of Michigan

Some of the same research and institutions support antiproton-driven fusion as micro fusion pulse propulsion, and many of the same challenges apply. Antiproton-driven fusion will require a steady supply of antiprotons, which currently are very costly to manufacture. In addition, the energy required to make and store antiprotons is not factored into the energy gain for the fusion reaction. Each pulse will require about 3x10^13 antiprotons to produce 160 kA of electrical current.[423] If including the energy required to generate the antiprotons, this fusion technology may be less efficient than other fusion methods. In addition to challenges associated with the antiproton-fusion-driving system, techniques for efficiently extracting energy to convert to electricity will be required. Research in terrestrial inertial confinement fusion reactors will help identify promising pathways for antiproton-driven fusion conversion systems.

Antiproton-driven fusion is an attractive energy generation technology for space exploration. Antiprotons could be manufactured on Earth in large plants where energy is abundant, then delivered to power plants in other parts of the solar system. Nuclear fuel pellets can be manufactured from abundant resources and potentially could be produced at an exploration outpost with ISRU. With a steady supply of antiprotons and nuclear fuel, antiproton-driven fusion can provide abundant energy for large space stations, outposts, and extended exploration missions with relatively small power systems.

Multifunctional Photovoltaic Materials

Multifunctional photovoltaic materials represent a breakthrough capability that may result from incremental development in photovoltaics. Basic research in photovoltaics is focused on material identification and characterization, while later stage development seeks to improve efficiency, reduce cost, and increase life expectancy.[424] This research results in improved performance, reduced production costs, and thinner, more versatile solar cells. Currently, solar cell technology is integrated into a range of everyday objects, including building materials, windows, sound barriers, and laptop bags.[425] With continued incremental development, new materials, and new manufacturing techniques, solar cells may become cheap, light, and versatile enough to be integrated into all structures, fabric, vehicles, sensors, and other exploration systems. A breakthrough in materials and solar cell processing may enable manufacturing of multifunctional systems that generate power and provide other primary functions, with minimal additional cost and weight.

PARTNERING OPPORTUNITES

MULTIFUNCTIONAL PHOTOVOLTAIC MATERIALS

- U.S. Department of Energy (DOE) Solar Energy Technologies Program
- DOW Chemical Company
- University of California Los Angeles
- University of Delaware, Center for Composite Materials
- JAXA

Multifunctional photovoltaics could arise from several different technology trajectories. Quantum dot solar cells are particularly attractive for space applications due to inherent radiation resistance, which may significantly increase solar cell lifetime.[426] Several research organizations have developed techniques for dispersing quantum dots in a solvent, potentially leading to a multifunctional paint that provides energy generation and aesthetics.[427] With additional nanotechnologies, this paint could provide corrosion resistance, self-healing properties, or dust-mitigation coating.

Two similar technologies, organic solar cells and synthetic photosynthesis, are pathways to thin-film solar cells that can be incorporated into other structures.[428] Proteins that enable synthetic photosynthesis can be extracted from crops, and with synthetic biology it may be possible to grow synthetic photosynthesis surfaces. Related breakthroughs in synthetic biology may enable synthetic photosynthesis materials that provide carbon fixing and other environmental functions. (See Crosscutting Technologies, “Synthetic Biology,” page 234). Structural materials that provide energy may result from a combination of carbon nanotubes and photovoltaic technologies. Carbon nanotubes increase the conductivity and improve the performance of many photovoltaics, and they may provide structural stability for rigid, thin-film cells, reducing the mass of photovoltaic arrays.[429] (See Crosscutting Technologies, “Nanotubes,” page 226.) Over the next 40 years, new photovoltaic materials will likely be developed to significantly improve these applications, in addition to providing new, multifunctional capabilities.

The solar cell industry is a multi-billion dollar enterprise with private and government funding. In 2010, the DOE budgeted $247 million for solar cell technologies, the bulk of which went to photovoltaic research.[430] The European Commission estimates that governments and private industry will invest 16 billion euros on solar cell technologies and facilities over the next 10 years.[431] Most of this research results in incremental improvements for efficiency and cost reduction across all types of solar cells, however, new capabilities have and will continue to develop.[432] Dow Chemical Company markets an integrated thin-film solar cell shingle for commercial housing.[433] The University of California, Los Angeles recently developed a spray-on fabrication system for applying polymer solar cells to any surface.[434] In addition to these examples, material and system research is ongoing at a host of academic institutions and private companies.[435] Space-specific multifunctional solar cell technologies are also beginning to develop. Japan's IKAROS project includes a multifunctional solar sail and cells. Inflatable structures to provide solar power for microsatellites are possible.[436]

Challenges to the terrestrial solar cell market are cost per kilowatt and lifetime.[437] Thin-film, organic, quantum dot, and synthetic photosynthesis solar cells have the potential to reduce cost of production and can be incorporated into lightweight solar arrays. Lifetime is a particular challenge for organic photovoltaic and synthetic photosynthesis solar cells. New technologies may extend the lifetime of organic cells to about five years, potentially long enough for consumer markets.[438] Lifetimes for synthetic photosynthesis are environment-specific. Surfactants can extend these lifetimes to several weeks, but a breakthrough will be necessary to maintain the aqueous environment necessary for photosynthesis proteins.[439] (See Crosscutting Technologies, "Synthetic Biology," page 234, for additional technologies that could support engineered organic or synthetic photosynthesis solar cells.) Terrestrial challenges overlap with space exploration challenges; however, the space environment is more extreme, and space systems require a higher level of ruggedness. In addition, solar cells for spacecraft have an added challenge of minimizing specific mass (kW/kg), which is not reflected in the terrestrial market. This challenge often leads to different development trajectories for space and terrestrial applications. Exploration-specific research will be necessary to develop and validate terrestrial technologies for lightweight, radiation-hard, long-duration solar arrays.

If multifunctional solar cells can be incorporated into a space exploration architecture with minimal additional cost, risk, and weight, then power generation can be provided by distributed and ubiquitous systems. With these technologies, power generation will be limited by surface area and proximity to the Sun; however, with improvements in low-power electronics and energy storage, many architecture elements could become power self-sufficient, potentially including suits, rovers, portable electronics, sensors, and other distributed systems.

Microradioisotope Power Sources

> **PARTNERING OPPORTUNITES**
>
> **MICRORADIOISOTOPE POWER SOURCES**
> - DARPA Strategic Technology Office
> - University of Missouri
> - University of Toronto
> - University of Pittsburgh
> - Qynergy
> - BetaBat
> - Trace Photonics

Microradioisotope power sources represent an evolution of radioisotope generators that could provide orders of magnitude improvement over current radioisotope generators and a breakthrough capability for distributed power systems. Radioisotope generators under development use plutonium 238 and thermoelectric or thermodynamic engines—most commonly Stirling engines—for power conversion.[440] These mature systems provide a few watts of electric power per kilogram and, in at least one projection, are unlikely to improve beyond 10 W_e per kilogram.[441] However, alternative technologies using different isotopes, nanopatterning conversion materials, improved heat rejection, and lightweight power management and distribution systems could increase the power density of radioisotope power sources to a few kilowatts of electric power per kilogram. These microradioisotope power sources are scalable and could provide nanowatts for microelectromechanical systems (MEMS), milliwatts for sensors, or watts for rovers, laptops, suits, and other portable architecture elements.

Microradioisotope power sources primarily use solid-state power conversion technologies to convert energy from radioactive decay to electricity. There are several conversion methods: betavoltaics, which directly converts energy from radiated electrons into electron-hole pairs in semiconductors; thermoelectric conversion, which relies on the thermoelectric effect to convert heat from radioactive decay into electricity; thermophotovoltaic, indirect thermal conversion through emitted thermophotons and solar cells; and a few mechanical solutions like self-reciprocating cantilevers.[442] Another conversion system, using alphavoltaics, is very promising for microradioisotope power systems due to the low requirements for shielding. These systems use intrinsically radiation-hardened quantum dots to convert energy from alpha particles to monochromatic light, which is then converted to electricity through high-efficiency photovoltaics.[443] Initial research suggests total efficiency could exceed 10-16% with near-term technologies, 20% for alpha to photon conversion, and 50-80% for monochromatic solar cells.[444]

Selection of radioisotope is just as important as the conversion system for microradioisotope power sources. Plutonium 238 has a relatively low specific power at 0.55 W/g and 0.39 W/g in a Plutonium oxide fuel compound.[445] Identified alpha sources with 10 W/g or greater are possible, and other sources may be economically produced with breeding reactors.[446] There is a trade-off between specific power and isotope half-life. However, designs for liquid microradioisotope generators exist, and it may be possible to design liquid microradioisotope power sources that are easy to refuel, mitigating challenges with low half-life.[447] Selecting an isotope with a high-power density, low-energy secondary gamma radiation, and relatively stable or low-energy daughter particles is an important step to designing a microradioisotope generator.

Government agencies, academic institutions, and some private companies are investing in the first generation of microradioisotope power sources. DARPA sponsored a micro isotope power source project with the objective of designing a 35 mW_e power source in less than 1 cm^3 package.[448] NASA researchers assisted DARPA with the development of this prototype.[449] Researchers at the University of Missouri have developed a liquid semiconductor betavoltaic to reduce radiation damage.[450] The University of Toronto and University of Pittsburgh have collaborated on a design for a tritium power source for chip-scale devices.[451] In addition, there are a few small companies developing microradioisotope power sources, including Qynergy, BetaBat, and Trace Photonics.[452]

There are several challenges to microradioisotope power sources that will require engineering and design solutions, and some cases require new materials and physical models. These systems are relatively complex, and several of the potential technologies have multi-stage energy conversion processes. Improvements in efficiency, lifetime, and mass are necessary at each of these stages. New nanomaterials may be required for efficient conversion of radiated particles without material damage. For MEMS power sources, nanomanufacturing techniques will be necessary to develop nanowatt sources on the scale of 100 nm.[453] Scaling these systems up for multi-watt sources will also require new techniques for efficiently packaging energy conversion materials around the radioisotope source.[454] Performance, volume, and mass of secondary systems like thermal control, ultracapacitors for peak power, and power distribution could drive characteristics of microradioisotope power systems and will require separate development. In general, research will be needed to identify optimum combinations of isotopes, energy conversion material, shielding, thermal control, and power distribution. Ultimately, a single scalable solution may not be possible, and multiple technologies will have to be developed for different applications.

Microradioisotope power sources have the potential to replace power generation and storage devices from nanowatt sources to tens of watts. If systems with advanced energy conversion, shielding, and thermal control develop, 20 W_e power sources approximately the same size and weight as a AA battery may be possible. NASA has identified a range of missions concepts with power requirements from 5 mW to 50 W, most of which could be served by a microradioisotope power source.[455] With microradioisotope power sources, NASA could replace batteries, fuel cells, and power generation technologies in all portable electronics, medical technologies, sensors, spacesuit power, and some satellites and rovers with radioisotope power sources that last for years or decades.

Extraterrestrial Wind or Geothermal Power Plants

Wind and geothermal, or cryo-thermal, power technologies could fill niche applications in the Ubiquitous Access to Abundant Power capability. Extraterrestrial wind and geothermal power systems provide passive power generation over a wide range of power loads. Both these concepts are based on maturing terrestrial industries, with a selection of technologies that may have applicability to solar system exploration. Although

PARTNERING OPPORTUNITES

EXTRATERRESTRIAL WIND OR GEOTHERMAL POWER PLANTS

- U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy
- Idaho National Laboratory
- Northern Arizona Wind Working Group

exploration systems that use wind or geothermal energy will be limited to a small set of planetary bodies and operational areas, many of these locations have a high potential for scientific value.[456] For instance, areas on Mars with increased geothermal flux may correspond to areas with methane venting.[457] Cryovolcanoes on Enceladus, Europa, Ganymede, and other icy bodies may provide information on subsurface features, including liquid oceans and potentially evidence of life. On Venus, Titan, and other planetary bodies with dense atmospheres, wind power systems could collect scientific data in addition to providing operating power for aerostats, rovers, and science stations. With extraterrestrial wind and geothermal power systems, breakthrough capabilities may be possible for a few select missions.

Wind and geothermal technologies are supported by an active and maturing terrestrial renewable energy industry. Although extraterrestrial systems may require unique designs, new materials, and long-term, maintenance-free operation under extreme conditions, the fundamental challenges to extracting energy from natural processes will be similar. NASA could leverage techniques, system approaches, and potentially complete technologies from terrestrial industries. Earth wind power systems come in a variety of sizes, from ~1 kW to 2.5 MW, and usually these systems can provide scalable, modular power.[458] On other planetary bodies, wind energy will be dependent on the size of turbine or airfoil and local dynamic pressure.[459] Current research for wind technology includes advanced rotors, system reliability, and integration with terrestrial power grids.[460] Geothermal energy is also scalable from large, multi-well power plants providing hundreds of megawatts to small—few kilowatts—generators.[461] The operating power for geothermal plants on other planetary bodies will be dependent on local heat flux and existing subsurface features. Current research for geothermal energy includes improved systems, low-temperature power plants, and artificially-created fluid reservoirs for geothermal energy.[462] Conceptual studies have considered using some of these technologies on other planetary bodies, however, directly applicable technology development is limited. One NASA Institute for Advanced Concepts study proposed a floating wind power generation system tethered to a lower altitude buoyant rover for planetary exploration of Titan and Venus.[463] In addition, there are papers providing initial discussion of geothermal energy on Mars; however, additional science is necessary to characterize available resources.[464]

There are many challenges to implementing wind and geothermal power plants on other planetary bodies. Large plants for outposts, ISRU facilities, or permanent extended exploration missions may require extensive infrastructure and challenging ISRU tasks, like construction of a wind tower or drilling geothermal wells. Terrestrial systems are not optimized for reduced mass. Designs for lightweight, low-volume wind and geothermal systems may enable transportation from Earth. Alternatively, ISRU manufacturing will have to mature to minimize the logistical burden of building a large power plant. Even for small plants, an accurate understanding of the environment will be necessary to design efficient systems, and precursor science missions will likely be necessary. Even if wind and geothermal power plants can be designed and optimized for niche applications, there is no guarantee that they will trade favorably with nuclear, solar, or radioisotope solutions.[465] Further research, concept design, and environmental characterization will be necessary before the benefits of these systems can be assessed.

Wind and geothermal power plants will not provide Ubiquitous Access to Abundant Power for all exploration systems; however, they may provide attractive alternatives for a few select missions. These technologies may align with future science missions, providing a limited amount of power, while characterizing available resources.[466] In the far term, geothermal and wind power technologies may supplement more centralized nuclear or solar systems.

New Physics

Many of the new physics technologies that could enable breakthroughs in Easy Access to Space and Efficient Interplanetary Travel are designed around concepts for generating power. Some of these new physics concepts could result in technologies for abundant electrical power generation. As noted, these concepts rely on physical theories that are unverified and there is no way to predict if, when, or how a breakthrough technology will develop from these concepts. However, if successfully developed, new physics concepts could provide nearly unlimited power for space exploration, in addition to the broader economy. Due to the unverified potential of these concepts, and their crosscutting nature, new physics technologies are discussed separately. (See page 27, for an excerpt on New Physics.)

Power Distribution

Power distribution breakthrough concepts provide solutions for distributing power from centralized sources to supply distributed demand. These technologies operate across all scales, from distribution between architecture elements, to intra-habitat distribution, to power distribution on an integrated chip. In addition to the listed technology concepts, new materials—especially carbon nanotubes—could provide significant capabilities for power distribution. (See Crosscutting Technologies, “Nanotubes,” page 226.) Transmission efficiency and kilograms per meter are driving metrics for power distribution.

Power Beaming and Wireless Power Transfer

Breakthrough wireless power technology concepts provide energy distribution between centralized sources and distributed loads, thereby reducing mass of the power distribution system. These wireless power concepts ideally have high-efficiency distribution across a variety of length scales and support numerous applications. Some potential applications include high-power distribution between a power generation plant and a remote location;

low-power, local area charging networks for electronic devices; and chip-scale wireless power and communications.

High-power beaming technologies can enable breakthrough capabilities for providing power to distributed outposts, rovers, sensors, satellites, and other architecture elements. These concepts include long-distance wireless distribution from a few watts to hundreds of megawatts.[467] Power beaming technologies are often discussed in the context of space-based solar power, and both Easy Access to Space and Efficient Interplanetary Travel highlighted applications of power beaming. However, power beaming concepts can be designed for a variety of power sources and applications. Space-based power beaming can provide constant power to stationary bases and potentially mobile systems. This application does require a large, solar power satellite; however, high-power solar electric propulsion (SEP) systems could be designed for dual use after arriving in orbit.[468] Nuclear pumped lasers can directly convert energy from neutron-producing nuclear power plants for long-range distribution. Hybrid systems can generate electricity from the nuclear power plant for local use and high-power laser light for long-distance distribution.[469] Generalized surface-to-surface wireless power transmission can enable power distribution to remote locations, rovers, and science stations. Depending on the distance for power distribution and power load, wireless systems can reduce the mass of the power distribution system; however, improvements in conversion efficiency will be necessary for significant advantages over wired systems.[470] Each of these applications can use laser or radio frequency (RF) power transmission technologies with rectenna, photovoltaic, thermophotovoltaic, or heat engine power conversion technologies. System optimization will depend on the distance, conversion efficiency, mass available, and atmospheric effects, if any.

PARTNERING OPPORTUNITES

POWER BEAMING AND WIRELESS POWER TRANSFER

- MIT, Department of Electrical Engineering and Computer Science
- Institute for Soldier Nanotechnologies
- University of Alabama, Huntsville, Laser Science and Engineering Laboratory
- eCoupled
- WiPower
- WiTricity

Local area wireless power transmission, in the tens of feet, provides increased flexibility, comfort, and potentially reduced mass. Inductive power transmission is a common approach to local area power distribution, providing energy to computers, sensors, PDAs (personal digital assistants), displays, and other electronics within a confined space. A single inductive power system can support several devices, proving a total power supply of a few kilowatts of electricity.[471] Current commercial systems rely on surface-to-surface contact to minimize energy loss; however, research at MIT shows increased efficiency through multi-device resonance, potentially enabling efficient transmission over several feet.[472] With improvements in intelligent systems, transmission length, and inductive technologies, these systems may provide abundant power to all systems within a relatively large volume. Local area power breakthrough concepts could enable wireless habitats both within the habitable space and between subsystems that are part of the habitat, such as life support, lighting, and communications. Local area power concepts also could eliminate power distribution systems for large solar cell arrays, reducing the weight of solar arrays for power satellites and SEP systems.[473] With lightweight power conversion and energy storage systems, local area wireless power could significantly reduce the mass of architecture elements by removing internal wires.

Integrated wireless power and communication technologies can improve electronic performance of integrated chips, embedded sensors, and medical devices. With smaller computer architectures, parasitic loads associated with chip interconnects increasingly impact chip performance.[474] Wireless technologies that transmit radiofrequency signals between computer chips could improve performance through high-data-rate, low-power, short-range communications.[475] Currently proposed systems, sometimes called network-on-a-chip, focus on data transmission over a few millimeters; however, future technologies may be able to piggyback data transmission on power signals in a distributed power network.[476] These power and data transmission signals can also directly enable embedded sensors, especially biosensors embedded in astronaut tissue, which have increased risk of infection if external interfaces are required.[477]

Several institutions support research on wireless power transmission for a variety of applications. Government agencies and private power companies are developing long-range power transmission technologies for space-based solar power. Companies like eCoupled, WiPower, and WiTricity have commercialized the first generation of local area wireless power technologies.[478] Industry collaboration, building the industrial base for wireless power transmission, could provide future standards and may influence technology trajectories.[479] Academic and private research, such as efforts at MIT to improve wireless power transmission efficiency, are pushing these technologies to increase distance and power efficiency.[480] For chip-scale wireless power, several architectures have been proposed. With the exception of powering biosensors, most of the research on chip-scale wireless power transfer focuses on communication technologies; however, future chip architectures, with smaller, more complex, and three-dimensional designs, may promote more research on wireless power transfer to improve performance and reduce thermal loads.

Efficiency is a main challenge for wireless power transmission. Over long distances, free space loss, beam diffraction, and—for some locations—atmospheric scattering limit power transmission efficiency. In addition, most power generation systems produce electricity, requiring conversion before and after transmission. Mass of the power converters and additional generation capacity to counter efficiency losses is also an issue for power beaming technologies. With current technologies, power beaming only reduces net system mass for very long distances.[481] Improved efficiency will help, but lightweight, efficient conversion technologies may be necessary, including high-power, solid-state lasers; high-temperature superconducting coils; and improved photovoltaics. For local and chip-scale power transmission, tracking and managing power distribution could be a challenge for complex, multi-component systems. As systems for specific applications are designed, other challenges may arise, such as beam size, accurate pointing, and RF interference.

Breakthrough wireless power transmission concepts could provide efficient power distribution for a range of applications, while eliminating high-mass wires and cables. These systems could reduce maintenance associated with locating and correcting damaged wires. Wireless power transmission could enable flexible, mobile exploration, and can avoid many of the thermal control challenges associated with energy loss through conductors.[482]

High-Temperature Superconducting Wires

High-temperature superconducting wires have the potential to significantly impact exploration architectures with effects that reach beyond power transmission. A breakthrough could include superconductors that work near ambient temperature, greatly reducing insulation and cooling costs, and superconductors with significantly increased—more than an order of magnitude—maximum current density.[483] Current high-temperature superconductors include complex copper and recently discovered iron compounds that operate at over 30 K.[484] Many high-temperature superconductors have a critical temperature—the cut-off temperature for superconducting behavior—over the boiling point of liquid nitrogen, including commercially-available yttrium-barium-copper-oxide wires with a critical temperature of 93 K.[485] A breakthrough in superconducting materials is necessary to push critical temperatures above the current limitations, around 140 K, to ambient temperature, around 300 K.[486] In addition, superconductor performance is limited by the current density and local magnetic field. In 40 years, new superconducting materials may enable breakthrough capabilities for power transmission and related applications.

PARTNERING OPPORTUNITES

HIGH-TEMPERATURE SUPERCONDUCTING WIRES

- American Superconductor
- University of Houston, Texas Center for Superconductivity and Advanced Materials (TcSAM)

Current research on superconducting wires consists of wire development for commercial applications, exploratory research to identify new superconducting compounds, and basic science to understand the physics behind high-temperature superconducting. High-temperature superconductors were discovered in 1986, and the behavior is not yet fully understood.[487] Research institutions, including universities, government agencies, and corporations, are attempting to understand the physics behind high-temperature superconductors, which may enable the development of ambient-temperature superconductors and new applications.[488] As part of this research, new superconducting compounds have been discovered, gradually increasing the maximum transition temperature.[489] The advent of liquid-nitrogen-cooled superconductors has enabled several commercial applications, including improved power transmission wires with smaller footprints and smaller motors, generators, and transformers.[490] Several companies are developing liquid-nitrogen-temperature superconducting wires for power grids, motors, maglev trains, and scientific instruments.[491]

Current superconductor technology has several large challenges for power distribution applications for space exploration systems. Most of these challenges result from superconducting characteristics, including temperature, critical current, and performance in magnetic fields. A better understanding of superconducting behavior may mitigate these challenges. A significant portion of superconducting system mass is composed of cooling and insulation systems. Maximum current densities and performance in a magnetic field limit superconducting applications for dense, high-performance, magnetic coils that could support several propulsion concepts, radiation shielding, and nuclear fusion. Some challenges to power transmission applications will not be solved by improved superconducting performance. Unlike beamed power, superconducting cable will have to be installed between power nodes, potentially requiring complex installation. These wires may require regular maintenance, and significant damage is possible if cooling systems malfunction. In addition, radiation may affect superconductor performance, requiring heavy shielding or burial. Additional research and design will be necessary to identify how high-temperature superconducting wires can impact exploration systems.

Moderate improvements in superconducting technologies could impact exploration systems, however, a breakthrough in superconducting technologies could change components of virtually every electronic system.[492] Ambient-temperature, high-critical-current superconductors could enable small, high-power, and lightweight motors; energy-dense superconducting magnetic energy storage systems; efficient inductive power systems; radiation shielding; magnetoplasmadynamic propulsion; nuclear fusion energy generations; and many other capabilities. Each of these capabilities is enabled by efficient, lightweight power transmission.

Optical Fiber

PARTNERING OPPORTUNITES

OPTICAL FIBER

- Southwest Research Institute, Laser and Optical Systems, Applied Physics Division
- Fiberguide Industries
- Oxford Electronics
- Corning Incorporated

Power transmission by optical fiber offers an alternative to metallic wires. This technology uses a high-power laser to convert electricity into light. Then optical fibers transmit that light, and a power conversion system like photovoltaics provides electricity to the end user. Optical fibers can be used to transmit high power long distances or can provide internal power between subsystems. These fibers enable overlay of multiple wavelengths, potentially providing data links in addition to power transport.[493] In theory, a 100-micron diameter, pure silica optical fiber could transmit 100 kW of optical power; however, flaws in the silica and fiber connection materials currently limit transmission power.[494] Optical fibers have a smaller footprint and are lighter than copper cable, can be used in areas with high magnetic fields or flammable fluids, and are resistant to corrosion in most environments.[495] With improved manufacturing methods, impurities in optical fibers can be reduced, improving attenuation over current capabilities (around 0.2 dB/km) and reducing localized heating, which can lead to fiber failure.[496] A breakthrough capability in optical fiber systems could enable multi-core fibers that transmit megawatts of power over small, lightweight cables.

Current fiber optic research is paving the way for long-distance, high-power transmission. The Southwest Research Institute has demonstrated proof of concept technologies testing fiber optic and conversion technologies up to about 20 watts.[497] Commercial organizations have developed and marketed high-power, solid-state lasers, including fiber lasers, with optical outputs of a few kilowatts; solid-state lasers for defense applications have exceeded 100 kW.[498] Optical-to-electric conversion systems are also being designed that could eventually support fiber optic power systems. The photovoltaic industry is improving monochromatic solar cell efficiency, and current cells exceed 50% efficiency.[499] Other technologies that could improve overall system efficiencies include power sources that provide direct optical power, such as solar concentrators, nuclear pumped lasers, or glowing reactors.[500] With purer fibers, efficient conversion units, and specialized energy generation systems, fiber optic power transmission could approach the efficiency of copper wires at a fraction of the mass.

Most of the challenges with optical power transmission result from current material limitations and engineering challenges. Ultra-pure glass fibers have average attenuation of slightly less than 0.2 dB/km for optimized wavelengths.[501] For long-distance transmission, improvements in fiber optic attenuation will significantly decrease power loss associated with mass growth of power sources. For both long- and short-distance power transmission, fiber connection represents a weak link for power transmission. Connections can collect impurities, provide a site for scratching and other fiber damage, and often use epoxies or other attachment products with reduced optical transmission compared to the fiber. For high-power transmission, fiber connections can provide failure points where thermal heating due to light absorption results in fiber damage. Current laser sources for optical transmission can be very heavy. A commercial 1kW fiber laser weighs about 150 kg.[502] For short transmission lengths, the mass of conversion systems is likely to outweigh the saved mass in copper cabling. Finally, fiber optics have similar operational difficulties as copper or high-temperature superconducting systems, including installation, maintenance, and protection from the environment.

Power transmission via optical fibers could provide new capabilities for exploration systems. These technologies enable low-mass power distribution over the same infrastructure as high-bandwidth communications. Optical fiber power systems could directly support next generation optical computers and may improve interoperability for exploration systems. New fiber manufacturing techniques, improved conversion systems, and optical compatible power sources could replace conventional cabling in future exploration systems.

Energy Storage

Energy storage breakthrough concepts enable increased capability for systems that require more power than is provided by power generation concepts at a given time. Energy storage applications include day-to-day operating power for rovers that are charged from a centralized source, systems to provide peak power demand, overnight power usage for solar-powered grids, and long-term energy storage provided by systems manufactured on Earth or other planetary bodies.

Thermal Capacitor

A thermal capacitor, or thermal energy storage system, provides a scalable, low-cost alternative to batteries, fuel cells, flywheels, and superconducting magnetic energy storage. The general principle behind thermal capacitors is the storage of energy as heat, either direct 'sensible' heat or latent heat in a phase change medium.[503] Sensible heat systems involve storing heat in a thermal mass like a reservoir, rock, or fluid-filled tank. The amount of energy that can be stored at a particular temperature is determined by heat capacity.[504] Latent heat systems store energy through phase changes and can have significantly higher energy densities than sensible heat systems.[505] Both sensible and latent heat systems are scalable. The thermal performance of the thermal material determines useful operating temperatures, while performance of insulation materials provides the lower limit on volume and mass. Proposed thermal storage systems include small—approximately 2 kg and 1.7 kW_{th} hours—thermal capacitors for rovers to large—multi-megawatt hour—storage systems for fixed facilities.[506] Breakthroughs in high-temperature, high-heat capacity materials; multi-phase change materials; high-performance heat transfer fluids; and compact, lightweight insulation could enable breakthrough energy storage capabilities.

PARTNERING OPPORTUNITES

THERMAL CAPACITOR

- U.S. Department of Energy (DOE) Solar Energy Technology Program
- National Renewable Energy Laboratory
- Center for Space Nuclear Research
- Stirling Energy Systems
- Los Alamos National Laboratory, Plutonium Manufacturing & Technology Office, and Civilian Nuclear Programs

Several thermal storage technologies exist for terrestrial applications, and current research targets improvement through better material, heat transfer fluids, and optimized energy conversion systems. Thermal storage systems are often used in conjunction with solar power plants to provide energy during the night. The DOE pursues thermal storage research and development tasks under the Solar Energy Technology Program, with efforts in developing heat-transfer fluids, thermal storage materials, and performance models.[507] For utility applications, cost is a major driver of current thermal storage technologies, and private industry, in addition to government agencies, seeks to develop new, cost-effective systems.[508] The solar thermal industry has also developed related technologies for heat conversion, including Stirling engines.[509] For applications in space, new capabilities or approaches may need to be developed. Thermal capacitors that provide mechanical, rather than electrical, energy have been proposed for RTG-powered suborbital roving hoppers.[510] For larger thermal storage systems, new ISRU techniques will be necessary to manufacture or sinter thermal storage medium from regolith.[511]

Challenges to thermal capacitors differ slightly for portable and large, stationary units. Portable systems require specific high energy and energy density and may need to operate over a very large temperature range. High-temperature materials; phase change material with increased latent heat; compact lightweight insulation; and energy conversion systems that operate over a large temperature range may be necessary for portable systems (see Crosscutting Technologies, "High Temperature Materials," page 219). For multi-megawatt-hour stationary systems, ISRU breakthrough capabilities are necessary to efficiently manufacture several tons of thermal mass. It may also be necessary to bury the thermal mass or build sunshades. For both applications, efficient extraction can be an issue, and due to the nonlinear nature of thermal energy, full discharge may be impractical. These systems also may have to be integrated with energy generation systems to reduce energy loss from the heat transfer fluid between the generator and storage medium.

Thermal capacitors can provide an alternative to more mature energy storage technologies for space exploration. Thermal capacitors have the potential to scale from a few hundred watt-hours to multi-megawatt hours. Currently, thermal energy storage occupies niche applications on Earth; however, a breakthrough in materials could lead to general application thermal capacitors.

Matter-Antimatter Reactor

Matter-antimatter reactors share many similarities with conceptual antimatter propulsion systems. Both systems require a source of antimatter, typically positrons or anti-protons, a normal matter target, and a method for channeling the released energy. However, with propulsion systems, the energy released is used to heat a propellant or directly channeled to provide thrust. As a power source, energy released from matter-antimatter reactions is converted into electricity for many possible applications.

PARTNERING OPPORTUNITES

MATTER-ANTIMATTER REACTOR

- Fermi National Accelerator Laboratory
- Antiproton Source
- Positronics Research, LLC

Matter-antimatter reactors as a power source are a far-term concept, however, they may develop within the 40-year scope. As noted in the Efficient Interplanetary Travel chapter, matter-antimatter reactions have the highest energy density of any system based on conventional physics, and, if this reactor technology develops, it could satisfy many of the applications under Ubiquitous Access to Abundant Power. Although antimatter reactors could replace nuclear, solar, and geophysical power sources, initial concepts for matter-antimatter reactors are based on an energy storage paradigm. Currently, antimatter is produced on

Earth with particle colliders and energy input from terrestrial sources.[512] Efficient production, long-term storage, and reduced cost could enable antimatter 'primary batteries' to be built on Earth and transported to exploration systems.[513] Longer-term concepts may enable harvesting of antimatter from the space environment, which would eliminate the cost of producing antimatter.[514] However, antimatter harvesting would require additional breakthroughs to develop spacecraft with the ability to slow, capture, cool, and return antimatter to the reactor. With harvesting systems, the paradigm for antimatter reactors shifts to an energy generation model. Regardless of the source of antimatter, matter-antimatter reactors could provide abundant energy to any system, limited solely by the practical size of the reactor and storage unit.

Many of the challenges associated with matter-antimatter reactors are highlighted in Efficient Interplanetary Travel (see page 34), along with research institutions working to overcome these challenges. Primary challenges are the cost of producing antiprotons and long-term storage of positrons. Application-specific engineering challenges are likely to arise if antimatter reactors are developed for specific architecture elements. Most current research on practical applications of antimatter energy for space exploration is focused on conceptual studies of propulsion. If the significant challenges associated with cost of production or storage are overcome, and if the logistics chain associated with producing, storing, and transporting antimatter can be designed so that it is competitive with alternative, on-site, energy-generation technologies, then new technology using antimatter as an energy source may arise from space propulsion technologies.

Technology Trajectory

A wide range of commercial organizations, academic institutions, and government agencies support the power industry and associated technologies for power generation, distribution, and storage. State-of-the-art technologies will continue to mature incrementally, and new disruptive technologies may arise. NASA, the military, other space agencies, and industry have modified terrestrial systems and developed custom power technologies for spacecraft systems.

Currently, spacecraft missions and architectures are constrained by power available for a given mission's volume and mass, however, performance is continuing to improve. Some current technologies that are likely to continue advancing and will support breakthrough technology concepts include:

- Batteries: Electrochemical energy storage in the form of a conventional battery will likely continue supporting space exploration for the foreseeable future. New chemistries, active nanostructures, and battery designs will improve performance.

- Fuel Cells: Chemical energy storage in the form of fuel cells can coexist with breakthrough energy storage concepts and are likely to be optimal for some mission classes. New technologies will increase power outputs, ruggedness, and reduce cost.

- Solar Cells: Future space missions may be supported by traditional crystalline and thin-film solar cells, in addition to multifunctional solar cells. Solar cells of all classes are likely to improve in efficiency. New manufacturing techniques may enable solar cell production directly from regolith.

- Radioisotope Power Sources: Traditional, multiwatt, radioisotope power sources will continue to support robotic missions. Engines based on thermodynamic cycles and thermoelectric conversion techniques may improve. New isotopes may provide increased choices for power source design.

In addition to these technology classes, there are several near-term technologies that are on trajectories to significantly impact space exploration. Some of these technologies are highlighted in the report, *Technology Horizons: Game-Changing Technologies for the Lunar Architecture*:

- Advanced Flywheel Technology: A form of mechanical storage, where a rotating disk or rotor stores energy as rotational energy.

- Liquid Battery: A battery specifically designed to store solar-generated energy during off-peak hours. The electrodes are molten metals, and the electrolyte that conducts current between them is a molten salt.

- Lithium Sulfur Rechargeable Batteries: An alternative to typical Lithium-ion battery chemistries, these batteries use sulfur in the cathode. They have a very high specific energy that can be used in all portable and transportation applications.

- Silicon Nanowire Lithium-Ion Battery: A lithium-ion battery that uses silicon nanostructures in the anode. These silicon nanostructures can hold up to 10 times more energy than a typical carbon anode.

- Superconducting Magnetic Energy Storage (SMES): Magnetic energy storage systems that store energy in magnetic fields created by direct current in a coil of superconducting material; used currently by utilities and private grids for power control.

- Stirling Radioisotope Generators (SRG): A radioisotope generator that uses a Stirling engine to convert heat sources into electricity.

- Micro-Scale Fuel Cells: Fuel cells specifically designed to power small electronic devices.

- Proton Exchange Membrane (PEM) Hydrogen Fuel Cell: Uses a simple chemical reaction to combine hydrogen and oxygen into water, producing electric current in the process.

- Nano-Capillary Network Proton Conducting Membranes for High-Temperature Hydrogen/Air Fuel Cells: A novel high-performance membrane material for high-temperature and low-relative-humidity PEM fuel cell operation.

- Inorganic Semiconductor Nanorods / Quantum Dot Solar Cells: Solar cells crafted from semiconducting inorganic crystals (nanocrystals) with adjustable sizes and tunable band gaps.

- Thin-Film Solar Cell Technology: A solar cell made by depositing one or more thin layers of photovoltaic material on a thin substrate.

- Organic Photovoltaics: Nano-enabled polymer photovoltaic materials, normally more lightweight, flexible, and versatile than traditional solar materials.

- High-Voltage Direct Current (DC) Power: The unidirectional flow of electric charge, instead of alternating current for long-distance transmissions.

Power generation, distribution, and storage systems will continue to be complex, multi-technology networks. Breakthrough technology concepts can be developed as a major node of this network, significantly changing capabilities for space exploration. Rapidly evolving technologies based on current or near-term systems will continue to support space exploration, complementing the capabilities provided by breakthrough technologies. Power technologies for space exploration will continue to evolve with terrestrial technologies. Breakthrough technology concepts will affect both space applications and the terrestrial power industry and could be good targets for government and commercial partnerships. The power industry is supported by research and development from larger, established companies, startups, and academic institutions. Within this community, NASA may find a range of potential new partners and applicable technologies.

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LIVING OFF THE LAND

Using in-situ resources for supporting human exploration or transforming the external environment

LIVING OFF THE LAND

Using in-situ resources for supporting human exploration or transforming external environments

> **BREAKTHROUGH**
> Astronauts are able to source consumables and building materials from the outpost site location. Oxygen and hydrogen are extracted from surface materials for use in respiration, water, power generation, and propellants. Other materials can be extracted for use in photovoltaics and as structural materials.

Mass is a major driver of cost and capability for all space operations. Resources for exploration are always limited by volume and mass available for launch; these constraints scope potential exploration missions. Today, traditional exploration missions require that everything for living in space be supplied from Earth. This includes living and working spaces; all the consumables necessary to support humans in space, such as oxygen, water and food; all required science and exploration equipment and maintenance tools; and finally all the propellant required to transport crew to the outpost and back. All of these modules, systems, and equipment comprise considerable mass, volume, and consequently expensive launch costs. In addition, rocket launches must carry all the propellant requirements for roundtrip transportation to the outpost, requiring that most launch mass be comprised of propellant. This leads to multiple, massive launches just for initial start-up of an outpost. To maintain a human presence in space for long periods of time requires frequent resupply missions for consumables, fuel, and outpost maintenance, leading to a long logistics tail for every outpost. Additionally, any disruption in this supply train could lead to systems failures and potentially endanger lives at the outpost. Leveraging resources and materials available at the site of operations could provide major mass reductions, subsequently reducing launches and missions cost while also improving outpost sustainability and safety.

The Living Off The Land breakthrough envisions a future where space missions can launch from Earth with a greatly reduced logistics burden, because astronauts are able to source consumables and building materials from the outpost site location. Oxygen and hydrogen are extracted from surface materials for use in respiration, water, power generation, and propellants. Other materials, like silicon and metals such as iron, titanium and aluminum, can be extracted for use in photovoltaics, structural materials, or feedstocks for fabrication. These capabilities are central to a robust surface infrastructure that includes manufacturing facilities to build equipment, parts, and tools; large mining operations to supply factories with input materials; propellant production facilities; and teams of autonomous robots and machines that support manufacturing, mining, outpost build-up, and maintenance activities. Living off the land also supports these larger operations and human habitation by using in-situ resources to create power generation sites as well as food, water, and oxygen. Outposts with this infrastructure sustain themselves indefinitely and can be used as refueling and resupply stations for exploration farther into space.

The ability to use and develop resources in situ is a key enabler to sustaining outposts or settlements in space. Living off the land saves transportation costs as construction materials, and potentially photovoltaics for power generation, are created with materials found, extracted, and processed from the planetary surface. The capability to live off the land removes the ceiling on the size of the base, the number of inhabitants it can support, and the length of time they are able to subsist.

Related Capability Areas

Because there are so many possible outputs from living off the land, a breakthrough in this area would have a ripple effect through the other breakthrough capabilities. One achievement in in-situ production could provide resources to enable many other breakthrough capabilities. In addition, breakthroughs in systems like power and roving will make living off the land more efficient and achievable.

- **On-Demand Manufacturing –** Metals and other elements like silicon extracted from regolith may be used as feedstock for fabrication processes used to create spare parts and tools.

- **Go-Anywhere Roving –** Rovers are essential for the transportation of resources within a production facility or to an outpost.

- **Self-Sustaining Habitats –** Oxygen and water extracted from in-situ resources can be integrated for use in habitat life-support systems. This allows for life-support systems that do not require complete closure. Ecopoiesis of a portion of the planetary surface is the first step to transforming regolith into a product that can be used for fertilizers for plants or growing algaes for oxygen and food.

- **Ubiquitous Access to Abundant Power –** Extraction and production facilities for in-situ resources will require abundant power. Alternatively, elements like hydrogen and oxygen extracted from in-situ resources may be used for fuel in fuel cells and fusion reactors and also as raw materials for power generation, storage, and distribution technologies. Further, the extraction of silicon, aluminum, and titanium can support the fabrication of thin-film solar cells, providing an in-situ source of energy for the environment.

- **Environmental Omniscience –** Sensing networks will be an important part of the in-situ resource utilization (ISRU) infrastructure. They can support locating resources, guiding autonomous transportation vehicles, remotely overseeing production facilities, and providing other planetary information such as weather conditions.

- **Easy Access to Space –** Hydrogen and oxygen can be extracted from in-situ materials and used to create propellants for rockets, which could be used to fuel return trips to Earth or further exploration. Additionally, autonomous excavation equipment can be used to create space launch infrastructure, including preparing launch and landing sites.

Supporting Technology Concepts

In-situ resource utilization is essential to sustaining life off Earth. Long-term living on another planetary surface would most likely require ISRU preparatory missions to occur before the first inhabitants arrive. Tools and processes for living off the land would be required to first prepare outpost habitat and launch and landing sites, which will be used for loading and off-loading initial equipment and for developing robotics, power, and habitat modules. After initial start-up, ISRU is required to sustain operations and continue outpost expansion. ISRU technologies will be used to produce consumables to sustain humans and to produce materials to sustain, manufacture, and construct buildings, equipment, tools, and parts. Synthetic biology technologies like biomining can be used as an alternative to traditional technologies and can even be used to transform portions of a planetary surface through ecopoiesis, enabling the regolith to generate nutritional materials. Synthetic biology technologies are further discussed in Crosscutting Technologies, page 234.

There are many evolutionary technical advances that will help to enable ISRU. Materials processing, transportation, and mining can all follow terrestrial models for these activities, requiring scaling, testing, and minor modifications for use in space. The technology concepts described below represent breakthroughs that will enable increased efficiencies and customized approaches for space, facilitating significant advancements in Living Off The Land.

Supporting Technology Concepts	
Autonomous Mining Technologies	Autonomous machines for mining and processing regolith, including extracting volatiles, breaking down feedstocks into component materials, and sifting for metals and ores.
Biomining	The employment of microorganisms that are naturally capable of or genetically engineered to process raw materials to produce metals, ores, or minerals for use in other applications.
In-Situ Solar Cell Production	The creation of solar cells for power generation using only materials found in situ.
Molten Oxide Electrolysis	A process to extract elements from ores; uses an electric current sent through a molten material.
Ecopoiesis	The initiation of a living, self-sustaining ecosystem in a planetary environment through the initial seeding of microbial life.

Autonomous Mining Technologies

Autonomous mining technologies include autonomous machines used for mining and processing regolith. This includes extracting volatiles, breaking down feedstocks into component materials, and sifting for metals and ores. These autonomous technologies range from simple machines designed to repeat a simple task to intelligent systems that are able to find and locate resources as well as make decisions, like where to dig and dump. Intelligent systems will be able to locate and work with other machines. The most advanced machines would also be capable of self-maintenance and repair. Some of these technologies could support initial activities like site preparation, which requires transportation and handling of equipment, initial deployment of power generation systems, ISRU plants, and habitat modules.[515] This ensures that basic outpost elements are in place when astronauts arrive at the surface.

PARTNERING OPPORTUNITES

AUTONOMOUS MINING TECHNOLOGIES

- NORCAT
- Colorado School of Mines
- Honeybee Robotics
- Lockheed Martin
- Caterpillar, Pittsburgh Automation Center
- CMU Robotics Institute, National Robotics Engineering Center
- U.S. Army Corps of Engineers

Development of autonomous mining technologies for use in space is occurring across industry, the government, and academia. On June 9, 2010, several teams demonstrated ISRU mining tools:[516]

- Lockheed Martin – bucket drum excavator
- Honeybee Robotics – Mars rover rock abrasion tool and percussive digger
- NORCAT – chassis with plow and load-haul-dump payloads
- NASA KSC/Honeybee Robotics – ISRU pneumatic regolith transfer system
- sysRand – modular excavator
- Colorado School of Mines – backhoe, bucket ladder, and bucket wheel excavators
- ORBITEC – carbothermal regolith reduction module

Additionally, industry continues to develop autonomous mining equipment for terrestrial mining applications to improve efficiency, productivity, and safety of mining operations. Technologies developed for these tools could be used for ISRU activities. Caterpillar has recently partnered with Carnegie Mellon University to develop driverless large haul trucks for use in mining haulage systems. Carnegie Mellon will be adapting its perception, planning, and autonomous software architecture originally created for the DARPA Urban Challenge. Caterpillar was a major sponsor of the CMU team that won the challenge in November of 2007.[517]

There are several challenges with developing autonomous planetary mining equipment, given the requirements of space transportation and the space environment. Space transportation challenges include requiring that machines minimize mass and volume, designing and testing for performance in microgravity and vacuum environments, and designing systems that can traverse variable terrains and handle the unique properties of regolith. Regolith holds two different challenges for mining equipment. These machines must be able to traverse, handle, and manipulate regolith as part of their performance, and mechanical systems must also be robust enough to survive under dusty conditions.[518]

Communications issues such as radio shadows, latency, and limited talk time drive the need for autonomous operations.[519] Intelligent operations would enable development of systems that decide where to dig, efficiently excavate regolith, and decide where to dump, locating dump sites or vehicles. A number of different machines may be required to work together to complete these activities. Challenges for this type of operation include intelligent control systems for multiple cooperating robots and systems for ongoing maintenance of robots.[520]

Biomining

Biomining is the employment of microorganisms that are naturally capable of or genetically engineered to process raw materials to produce metals, ores, or minerals for use in other applications. Bioleaching and biooxidation have been used extensively on Earth for mining copper and gold, respectively. Currently, more than a quarter of the world's copper supply is harvested through bioleaching of low-grade ores. Other metals extracted using biomining processes include silver, zinc, and nickel.[521] Potential products that could be produced through biomining of regolith include iron, aluminum, titanium, chromium, and oxygen.[522]

PARTNERING OPPORTUNITES

BIOMINING

- Techshot
- Idaho National Laboratory
- Brierley Consultancy
- University of Hawaii, Manoa

There are several advantages to using microoganisms over chemical processing methods, including faster extraction rates, lower energy requirements, and lower mass. A single vial of different bacteria is all that is required, since they can be grown in situ. Additionally, microorganisms can be used to produce oxygen, as a food source, and to break down rock to improve it for crop growth.[523]

Researchers at The Open University in England conducted studies using varieties of cyanobacteria on analogs of both lunar and Martian regolith. Cyanobacteria were chosen because they survive in extreme cold, hot, and dry environments on Earth that may enable them to survive in the harsh space environment. The cyanobacteria were launched in low Earth orbit, exposed to the vacuum, cold, heat, and radiation of that environment, and then grown using water on rocks that simulate Martian and lunar regolith. All varieties of the bacteria grew and extracted calcium, iron, potassium, magnesium, nickel, sodium, zinc, and copper from the rocks. Of the cyanobacteria tested, the species *Anabaena. Cylindrica* had the best performance in terms of both withstanding extreme conditions and extraction. Additionally, *A. Cylindrica* is a nitrogen-fixing cyanobacterium[524] that could generate nitrogen-rich compounds for use as fertilizers.

Researchers at Johnson Space Center and Ames Research Center have also been studying cyanobacteria as part of a biotechnological ISRU system that can work with life-support systems. The JSC study envisioned cyanobacteria growth chambers set up on the Moon.

The chambers are supplied with water, sunlight, and regolith to grow the cyanobacteria. These bacteria are then harvested for further use. The cyanobacteria can be broken down by other bacteria to produce fertilizers for plant growth, and the methane produced from this process can be used as fuel. The cyanobacteria can be used to extract iron and other elements from the regolith for in-situ manufacturing and construction projects.[525] Researchers have found that iron oxides interacting with acids secreted by cyanobacteria produce iron and water. Either cyanobacteria or electrolysis can be break down this water into hydrogen and oxygen.[526]

Researchers identify several challenges to maturing biomining technologies. Further characterization of lunar regolith is required, as well as simulant experiments to understand how different microorganisms interact with the very different characteristics of lunar regolith. Terrestrial regolith analogs are available to test both hot and cold environments as well as high radiation, low pH, and deep subsurface environments. Space environmental effects must also be studied, including the effect of microgravity, radiation, large temperature variations, and low pressure on growth, survival, and performance of selected microorganisms. Additional technological challenges include requirements of power and water for initial start-up. Though cyanobacteria can function using natural sunlight, leaching rates are improved with added heat, which requires more power. Further, researchers have suggested that oxygen cannot be extracted directly from regolith using biological organisms.[527]

In-Situ Solar Cell Production

It should be recognized that any of the above mentioned mining technologies, or any ISRU technologies, will require significant amounts of energy. In the in-situ environment, energy can come from fuels (hydrogen) or from the sun (solar cells). In-situ solar cell production is a concept that involves a multi-stage process of extracting silicon (or other semiconducting materials) from regolith, melting regolith to create a substrate, and processing it to produce metallic contacts. Many planetary regoliths contain all the materials necessary to fabricate thin-film solar cells, including silicon, iron, titanium, calcium, and aluminum. Some planetary regolith can also be melted to produce regolith glass, which can be used as a substrate. Additionally, the vacuum environment of the moon and asteroids makes them an ideal location for creating thin-film solar cells, since this environment does not require the construction of vacuum chambers to undertake vacuum deposition of the thin-film materials.[528]

PARTNERING OPPORTUNITES

IN-SITU SOLAR CELL PRODUCTION

- University of Houston, Center for Advanced Materials
- High Frontier

Creating solar cells in situ first requires processing regolith to extract silicon and metallic elements. While a number of methods are available for processing regolith, researchers at the University of Houston suggest molten oxide electrolysis, sometimes called magma electrolysis. This is a simple process requiring no volatiles and therefore does not require encapsulation from the vacuum environment, minimizing initial resources required from Earth. However, this process creates only moderate quality solar cells and is energy-intensive, requiring that initial fabrication materials be brought from Earth to create a power system for regolith processing.[529]

A concept developed at the University of Houston uses a regolith processing unit and a crawling rover, called a cell paver, to fabricate thin-film silicon solar cells on the lunar surface. The cell paver weighs about 150 kg. It is powered by solar cells with an array of small, parabolic solar concentrators linked to optical fiber, which supplies the energy for evaporation of the thin-film materials. The paver is first loaded with required materials (silicon, aluminum, and iron silicide), which are mined in situ and extracted and processed at the regolith processing unit. The paver then moves along the surface moving any large rocks directly in front of it, preparing a bed for fabricating the regolith glass substrate. To create the actual solar cells, the regolith is first melted to form a glass substrate, metal is then deposited onto the substrate for the bottom contact, followed by silicon deposition, top contact deposition, antireflection coating deposition, and lastly metallic interconnects are deposited. The paver can fabricate about 200 kW of solar cell capacity per year from about 100 kg of raw materials. Over five years, enough solar cells can be fabricated to produce 1 MW of capacity.[530]

There are two major issues associated with this technology. First, solar cells created through this method are of moderate quality with low efficiencies, about 3%-5%. There are multiple reasons for this low efficiency, including type of materials available, processing methods, and potentially dust contamination. Secondly, regolith processing requires energy (~ 1 kW for the cell paver capacity described above). Therefore, either an initial power generating unit will have to be brought from Earth to power this system or the cell paver will have to be loaded with the solar cell fabrication materials prior to launch, so that it could fabricate a power generating system to use for regolith processing.[531]

Additionally, any units designed to create solar cells on the lunar or other planetary surface will be subject to the same development challenges as other robotics, rovers, and machines. It must be designed to perform in fractional gravity to microgravity, it must be robust enough to work with large temperature variations, and mechanisms must be able to withstand dusty regolith environments. Development must also take into account maintenance and repair, as well as integration with other ISRU systems that may also be designed to work with the regolith-processing unit.

Molten Oxide Electrolysis

Molten oxide electrolysis (MOE), sometimes called magma electrolysis, is a process used to extract elements from ores using an electric current sent through a molten material to separate materials. For use in space, MOE requires that regolith be heated in a reactor until it becomes a molten electrolyte. Three products can be separated from the molten lunar regolith: gaseous oxygen, a metal alloy of Fe-Si-Al-Ti, and an expended electrolyte that is rich in magnesium oxide. Additional materials may be extracted from regolith on other planetary bodies. The metal alloy is then transferred to a refining cell to extract the Si and metals. This process has also been shown to produce oxygen from Mars regolith simulants.[532]

PARTNERING OPPORTUNITES

MOLTEN OXIDE ELECTROLYSIS

- BAE Systems
- MIT, Department of Materials Science Engineering
- Electrolytic Research Corporation

As discussed in biomining and in-situ solar cell production, lunar and other regoliths contain many elements beneficial for fabricating useful products on the surface. Regolith includes silicon for solar cells, as well as metals like aluminum, titanium, and iron that could be used as feedstocks for manufacturing processes. The challenge is to extract these elements with as few inputs (such as reagents and water) and by-products as possible. Extraction technologies used on Earth, like beneficiation, require large quantities of water or reagents, which, in a space environment, would need to be carried and resupplied from Earth. These requirements make these methods more difficult to sustain further into space and reduce the benefits of a lower logistics tail gained by ISRU. However, MOE does not have these limitations.

MOE requires no pretreatment of regolith and can be used to extract all of the elements mentioned above: silicon, aluminum, titanium, and iron.[533] MOE is attractive for ISRU as it is insensitive to feedstock material, it has a high solubility and low volatility, it does not require import of reagents like fluorine and carbon, and it allows for the selection of the element to be extracted when using a feedstock with multiple elements. The elements can be extracted in sequence based on the stabilities of their oxides.[534]

Studies have already shown that iron, oxygen, and silicon can be produced from lunar regolith using MOE. One challenge for this method is that it requires high temperatures (1300° C – 1500° C) to produce materials for solar cells; however, a lower temperature process (850° C) has been shown to be produce oxygen from Mars regolith simulant and could also be used with lunar regolith. This could be used for propellants or life-support systems. For oxygen production, MOE has been shown to be the lowest power process and is also favorable for mass throughput. However, metal and silicon extraction would still require high temperatures and a significant amount of energy, which would, in turn, require carrying initial power capabilities to the planetary surface.[535] Additionally, all demonstrations have been at laboratory scale. To produce oxygen or metals at the amounts required, these reactor systems will need to be scaled up.[536]

Ecopoiesis

Ecopoiesis is the initiation of a living, self-sustaining ecosystem in a planetary environment through the initial seeding of microbial life. This is different from terraforming, which is creating an Earth-like environment on another planet. Ecopoiesis is the earliest steps towards terraforming.

The most detailed work studying ecopoiesis was conducted under NASA's Institute of Advanced Concepts (NIAC) program, in a project titled "Robotic Lunar Ecopoiesis Test Bed." This project team was lead by Dr. Paul Todd of Techshot (formerly, SHOT). This project is one of the few to undertake ecopoiesis experiments, creating a Mars Test-Bed chamber that simulates conditions on the surface of Mars to test the performance of different microorganisms. The team also conducted a workshop on extremophile selection for ecopoiesis, which identified candidate pioneering organisms. This work also developed a long-term concept for an experimental ecopoietic test facility on the Moon.[537]

Initial pioneering organisms must perform under extreme conditions in space environments. Organisms considered for use in ecopoiesis must derive energy from sunlight or inorganic elements of regolith and the atmosphere; their metabolism must increase the amount of greenhouse gases in order to thicken and warm the atmosphere; and they must be able to withstand (or be protected from) ultraviolet and ionizing radiation, extreme temperature variations, and a vacuum environment. For supporting a human presence, it is also necessary for organisms to be oxygenic photosynthesizers and autotrophic (nutritional).[538]

PARTNERING OPPORTUNITES

ECOPOIESIS

- Techshot
- Lyon College, Sciences Division
- Complex Systems Research, Inc.
- New Mexico Institute of Mining and Technology, Department of Earth and Environmental Science

Cyanobacteria were recommended as the prime candidate at the extremophile selection workshop. Cyanobacteria are robust and nitrogen-fixing. They would have the highest survival and growth rates and can aid in transforming regolith into a soil that can support algae growth.[539] Additionally, cyanobacteria are resistant to high carbon dioxide and are edible and nutritious.[540]

Testing of different cyanobacteria and other organisms has been conducted at the Techshot Mars Ecopoiesis Test Bed chamber with promising results.[541] However, this is still in the very early stages of development. Microorganisms must be tested under a large variety of conditions that occur on other planetary surfaces. After identification of organisms through terrestrial testing simulations, they must be tested in the space environment; particularly, experiments must be developed for testing in actual lunar, Mars, and other planetary environments. All of this testing would still predate the development of an ecopoiesis test facility on a planetary surface. Additionally, Ecopoiesis could raise planetary protection issues, as it could negatively impact the environment being studied. If required planetary protection measures continue into the future, system controls to ensure the protection of the environment will need to be considered.

Technology Trajectory

Living off the land is not a new concept. It has been practiced as an exploration technique for most of human civilization. Adapting approaches and technologies to work in the unique environment of space, to adjust to the available resources on other planetary surfaces, and to operate reliably and efficiently enough to be incorporated into exploration architectures will require significant technology breakthroughs.

Autonomous mining equipment has struggled to reach the terrestrial commercial market, despite seeming on the verge of adoption for about a decade. However, major companies are pursuing it aggressively, expecting markets to materialize in the near term. Development concepts use existing technologies, so market drivers and bias are the greater obstacles. The Mars Science Laboratory could be used for small-scale demonstration projects to encourage technology development and testing.

Biomining has been used terrestrially by industry since the 1950s to extract copper from low-grade ores, and one quarter of copper extraction is completed by microorganisms. However, it is a new concept for use in the space environment, and the same microbes used on Earth may not survive the space environment. Some early in-orbit tests using cyanobacteria have shown very promising results, however, much further testing and development is required. Additionally, while biomining appears promising as a low-power, low-mass, low-cost alternative to more traditional extraction techniques for metals, many in the research community do not believe this method could be used to directly extract oxygen from regolith.

In-situ solar cell production is currently conceptual, though much work has been done to determine the best methods for extracting the silicon and other materials required, and a detailed solar cell paving concept has been created. However, a test of this type of system has not yet occurred.

Molten oxide electrolysis is gaining recognition as a terrestrial means for extracting titanium and in use for steel production. The primary driver is that it is a simple and "green" process requiring no chemical reagents, and it does not produce any by-products, particularly carbon dioxide.

Ecopoiesis is still a very low TRL technology. Much work must yet be done in laboratory environments before it can be tested on a planetary surface. However, some progress has been made through testing of potential initial microorganisms in a Mars Ecopoiesis Test Bed.

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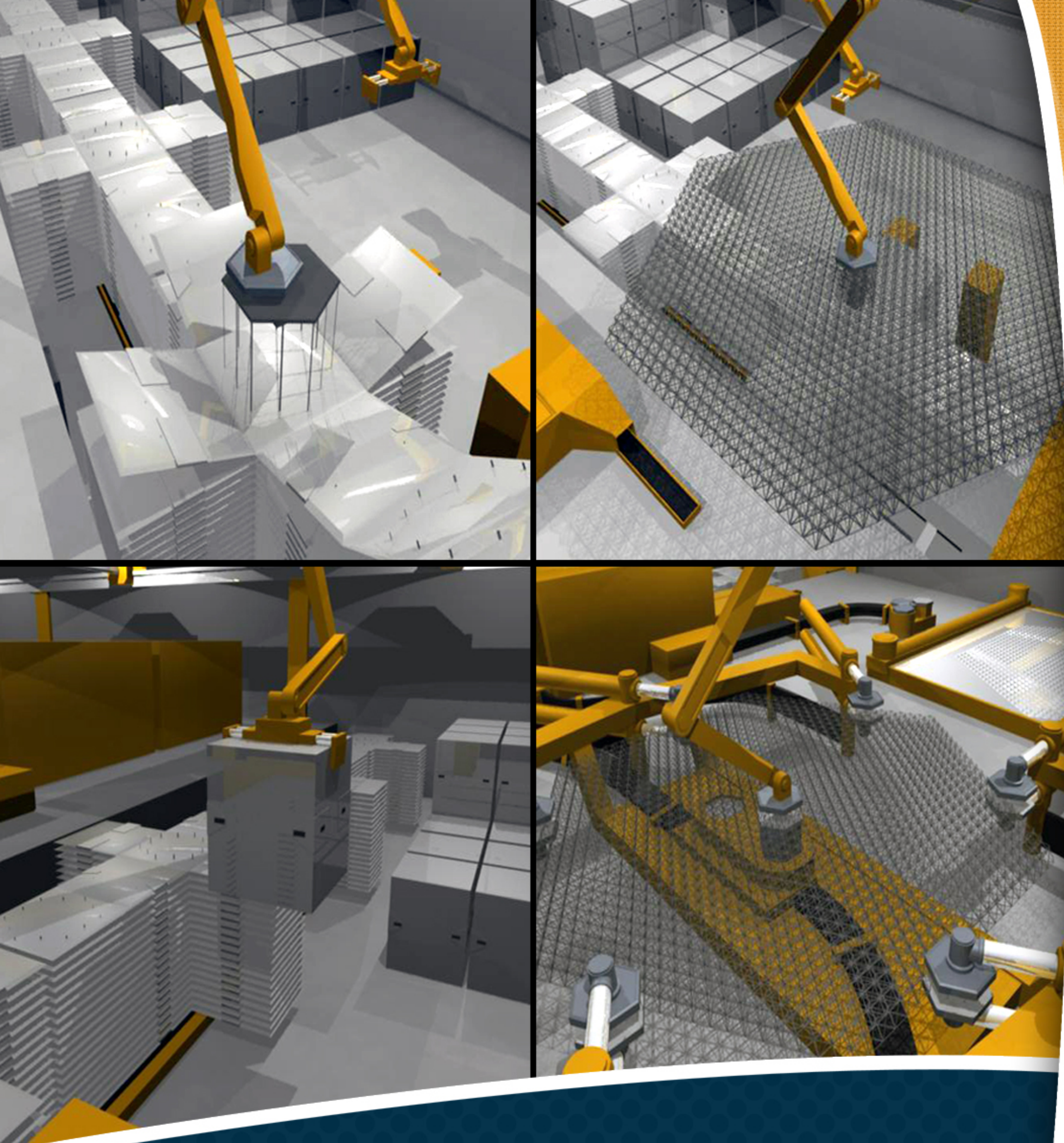

ON-DEMAND MANUFACTURING

Self-replicating machines and autonomous, free-form manufacturing

ON-DEMAND MANUFACTURING

Self-replicating machines and autonomous, free-form manufacturing

Spacecraft and outposts systems as well as rovers and landers require maintenance and repair. Currently, the logistics of bringing along all of the required spare parts for these activities present a significant cost and mass penalty for long-term living in space. The alternative, transporting spare parts from Earth as needed, presents a potential safety issue. If an exploration mission needs a critical replacement part that is not available on the spacecraft or outpost, astronaut lives could be endangered while awaiting a logistics launch. This also effectively limits the distance of exploration to locations within a reasonable reach of logistics missions.

BREAKTHROUGH

Autonomous, self-replicating printing machines allow for free-form manufacture of any part or product, using different feedstock materials, including those mined in situ.

Reconfigurable robots and nanomachines can configure themselves into macro-level systems, such as robotics rovers or haulers.

The On-Demand Manufacturing capability envisions a future where manufacturing modules capable of producing custom parts, tools, and machines on demand are a crucial element of outpost build-up and maintenance. Autonomous machines can manufacture parts, tools, and systems from files entered or uploaded into the machine, breaking down and reforming in-situ materials as manufacturing inputs. Printing and self-replicating machines allow free-form manufacture of any part or product using these inputs. Nanomachines will self-replicate and configure themselves into macro-level systems, such as robotic rovers or haulers. Over time, this kind of manufacturing could encompass an increasing percentage of outpost build-up, leading towards self-building outposts.

Self-replicating machines and free-form manufacturing change the nature of outpost maintenance and repair. They can initially reduce launch requirements for systems spare parts and ultimately create a manufacturing facility on the destination surface. With the ability to manufacture on site using in-situ feedstock, the mass of the overall outpost is not constrained by transportation. Build-up could also continue indefinitely after the initial launches.

Related Capability Areas

Machines that can create spare parts and useful products in a spacecraft or a planetary surface are integral to sustaining a long-term presence in space. As such, they will impact or be impacted by other breakthrough capabilities in this report. The technology concepts discussed in this capability will impact all other breakthrough capabilities by providing parts and tools for everything, from food processors and surgical robots to rovers and virtual reality systems. However, two of the breakthrough capabilities will have a greater impact than the rest.

- **Living Off The Land –** To achieve the greatest mass efficiencies and reductions to the logistics chain hoped for in On-Demand Manufacturing, feedstock materials for manufacturing must be extracted in situ at the exploration destination, rather than being launched from Earth.

- **Self-Sustaining Habitats –** All systems, computers, and even furniture will at some point require maintenance, repair, or even replacement. The on-demand manufacturing technologies will allow astronauts to create parts, tools, and even products necessary to sustain the habitats indefinitely.

Supporting Technology Concepts

On-demand manufacturing technologies include technology concepts that cover continuous advancement of 3-D printing technologies; new digital materials fabricators; and self-reconfigurable, modular robots. These include the innovative concepts of nanomachines that can reconfigure to form new parts and products as well as molecular manufacturing machines, able to fabricate parts at the molecular level. The On-Demand Manufacturing capability envisions a future where several of these concepts come to fruition to allow outpost inhabitants to create parts, tools, and products to sustain equipment and outpost systems.

Supporting Technology Concepts	
3-D Printing	Fabricators that create parts through additive layering of feedstock materials.
Digital Materials	A digital manufacturing process that creates a macroscopic product through the alignment of discrete, multimaterial, microscale parts.
Programmable Matter	A functional form of matter where intelligence is built into the materials.
Molecular Manufacturing	A construction technology, referring to the process of building parts and materials from the atomic level upwards and arranging matter with atomic precision.
Self-Replicating Robots	Robots that can create copies of themselves indefinitely. These robots could then autonomously assemble into useful parts, tools, or systems through self-replication.

3-D Printing

3-D printing machines use an additive process to produce products. These printers have movable nozzles that lay or deposit successive layers of feedstock materials to create products from digital design files.[542] This is the opposite of more traditional manufacturing tools, such as lathes and milling machines, which are subtractive technologies, starting with a block of materials and cutting away to produce a part or product. 3-D printing machines have been designed for use with multiple feedstock materials, including layering fine powders, such as plaster or resins, or depositing layers of polymers, thermoplastics, metals, alloys, clay, ceramic, or plastics. Current machines cannot use all of these feedstocks; they are oftened designed to work with specific types of feedstocks. Current 3-D printing machines typically deposit layers of plastics and are

PARTNERING OPPORTUNITES

3-D PRINTING

- Fab@Home – Cornell University Computational Synthesis Laboratory
- MakerBot – MakerBot Industries
- FabLabs – MIT Center for Bits and Atoms
- D-Shape – Monolite UK Ltd, ESA

used for rapid prototyping of parts or design mock-ups. Current versions of these machines cost around $30,000 and are the size of a small refrigerator.[543]

Two newer 3-D printing technologies, Fab@Home and RepRap, have been created to bring 3-D printing not only to more business but potentially to every home. These low-cost (around $1,000), open-source, desktop-size printers can create functional products from a wide variety of input materials and are controlled by digital design inputs from an ordinary desktop computer. Both of these technologies have created online user communities (fabathome.org and reprap.org) that share their designs and experiments to further the innovation of products and feedstocks for these machines.

Fab@Home was created at the Cornell University Computational Synthesis Laboratory by Professor Hod Lipson and Evan Malone. A Fab@Home printer, or fabber, can fabricate functional custom objects using liquid or paste feedstock materials. The machine uses interchangeable cartridges of feedstock materials that include plastics, plaster, play-doh, silicon, wax, metals, and solder. Some users from the online community have reported using chocolate, cheese, and cake icing. These printers have been used to create everything from food with the French Culinary Institute to small robots. At Cornell, they have produced batteries, electrically activated polymer muscle, and touch sensors. Their goal is to produce a small robot that will literally walk out of the machine.[544] The team at Cornell has also used the machine to produce bricks for buildings. Since they can create circuits, sensors, and batteries, it should be possible to create smart bricks to build intelligent buildings.[545] These buildings could allow for better communications, wireless information transfer throughout the building, and backup power for lighting and other electrical systems.[546]

RepRap is a desktop 3-D printer invented by Adrian Bowyer, senior lecturer of mechanical engineering at the University of Bath. The RepRap machine works by melting plastic filament and building layers of melted plastic into three-dimensional objects. The majority of the RepRap machine has plastic parts that can be created by the machine itself.[547] This machine was also discussed in the report, *Technology Horizons: Game-Changing Technologies for the Lunar Architecture.*

Another desktop, open-source 3-D printer is MakerBot Cupcake, produced by Makerbot Industries. Like Fab@Home and RepRap, the machine is open-source, desktop-size, can create many of its own parts, and has an online user community, called Thingiverse, where users post what they have created and how. Stratasys, one of the leading manufacturers of large 3-D printers for industry, has partnered with HP to create the HP-Stratasys 3-D desktop printer for under $15,000.[548]

Moving in the other direction, ESA is experimenting in creating full-scale structures from an enormous 3-D printer called D-Shape. D-Shape is a 3-D printer that uses sand and a special inorganic binder to autonomously create sandstone buildings.[549] The D-Shape machine can move up and down on four metal-frame columns and side to side on metal-frame beams. The sandstone of the finished structures is superior to certain cements and does not require iron reinforcing. ESA is currently testing this machine to determine if it can work in a vacuum. Another challenge is determining if structures can be built using lunar regolith simulants.[550]

An electron beam free-form fabricator (EBF3) 3-D printer has been developed by NASA's Langley Research Center for fabricating airplane parts. The machine can accommodate multiple metal feedstocks simultaneously. Working in a vacuum chamber, the electron beam is focused on the feedstocks, which are melted and then layered as required by the part being fabricated. The smaller version of the EBF3 was tested on NASA's jet that simulates microgravity, and researchers intend to demonstrate it on the International Space Station. Although this fabricator has advantages in testing over other 3-D printers, it can only accommodate feedstock materials that are compatible for use with an electron beam.[551]

Although currently primarily used for rapid prototyping by industry and producing a small variety of functional objects and electronics, the innovation in parts and products for these machines continues to grow. Though the use of feedstock materials brought from Earth allows mass savings over ferrying spare parts, 3-D printers continue to be developed for more production applications. They could potentially use a variety of in-situ resources as feedstock materials to manufacture products in space, enabling further mass savings on initial launches and reducing the need for resupply launches. However, use in space presents challenges. Aside from the EBF3, none of these machines has been designed with use in space in mind. The machines must be tested for use in microgravity. To allow for maximum flexibility, system parts and mission tools that could be created by these machines must be identified. Additionally, machines must be able to withstand radiation and potentially dusty environments, as well as meet mission mass and power requirements. Not only must the machines be designed for use in space, but the parts they create must be considered as well. These parts will require a rigorous verification and testing process to ensure the quality and reliability of all parts produced, especially for critical components. If in-situ resources will be used with these machines to increase efficiency and supply chain advantages, it must be determined what types of in-situ materials would work as feedstocks, and the printing machines would need to be integrated into ISRU processes.

Digital Materials

Traditional manufacturing processes create the final product by either adding or subtracting material, referred to as analog or continuous manufacturing. A digital manufacturing process creates a macroscopic product through the alignment of discrete, multimaterial, microscale parts, like microscale legos. Biological processes, like DNA and amino acids, which are created from fundamental building blocks, inspire this type of fabrication. As with other digital applications, digital materials use a parallel manufacturing process that increases the speed of fabrication. The vision for this type of manufacturing is to build systems from millions of microscale discrete parts using massively parallel manufacturing. Aside from speed, this type of fabrication offers several advantages over analog fabrication processes. In analog processes, the precision or tolerance of the final product can be no greater than the precision of the machine. However, with digital materials, the individual parts self-align and interlock with neighboring parts, so the overall precision is determined by the parts, which can be fabricated very precisely. Therefore, in a digital materials process, the final piece can have much better precision than the original machine. Digital materials processing also offers perfect repeatability, reversibility, and each discrete building block can be recycled.[552] Theoretically, systems or parts created in this manner can be broken back down into their original building blocks and rebuilt into other parts. Additionally, the final properties of the macroscopic product can be tuned by altering the digital microscopic structure.[553]

PARTNERING OPPORTUNITES

DIGITAL MATERIALS

- Cornell University Computational Synthesis Laboratory
- MIT Center for Bits and Atoms

Digital materials is a field that is still in the early stages of development and facing a number of challenges. Two of these challenges are inherent to all digital technologies: resolution and increasing complexity. The resolution of the final macroscale product is reliant upon the resolution or size of the discrete parts; this is similar to the resolution of digital pictures being dependent upon the pixel count of the camera. The size and shape of the digital materials chosen will dictate the resolution of the final shape that can be achieved. However, as the size of the discrete part decreases, the complexity of the parallel manufacturing process increases, causing a subsequent decreased processing speed.[554]

The selection of digital materials that can optimize digital parallel processing is also a challenge. To rapidly produce functional robust products requires materials with a shape that:

- can passively self-align to neighboring pieces during assembly
- is symmetrical, invariant to rotation and flip, allowing for ease of manipulation during assembly
- can achieve rigid connections with neighboring pieces to ensure stability of the final structure
- fits together exactly to assemble both dense (completely filled) and sparse (more lightweight) final structures[555]

The make-up of the materials is also a challenge. The digital materials manufacturing process may require up to millions of discrete parts to produce a final product; therefore, they must be made of materials that can be produced cost-effectively in large quantities.

Currently, testing has been done at both MIT and Cornell using discrete digital materials at the centimeter scale. These tests used simple materials made from plywood and plastics.[556] Further testing will be required to test processing of multiple materials and the creation of functional discrete parts. Additionally, this technology will require extensive study for use in the space environment. Challenges include determining performance in microgravity, effects of radiation on performance and manufactured parts, and effects of dust on performance of the machine as well as manufactured parts.

Programmable Matter

Programmable matter is the next step or extension of digital materials and modular robotics. Programmable matter represents a functional form of matter where intelligence is built into the materials. With programmable matter, the matter or discrete pieces can autonomously and reversibly assemble into functional products and systems upon external command.[557] Each discrete piece contains the following capabilities: actuation, power, computation, communications, and even potentially other functionalities, such as light emission or display capabilities.[558] When fully realized, programmable matter can completely change the way we view and use everyday objects. For example, researchers envision tools that can reshape into others, like a hammer that morphs into a wrench,[559] or everyday objects that can resize as required, such as a measuring cup that could resize to exactly what you need.[560] However, this technology is still in the early stages of development. Researchers are currently working to develop mechanisms that may bring this technology to fruition.[561]

> **PARTNERING OPPORTUNITES**
>
> **PROGRAMMABLE MATTER**
>
> - Programmable Matter by Folding – Harvard University, Wyss Institute for Biologically Inspired Engineering and MIT CSAIL Center for Robotics
> - Cornell University Computational Synthesis Laboratory
> - MIT Center for Bits and Atoms
> - DARPA

Researchers at Harvard's School of Engineering and Applied Sciences (SEAS), the Wyss Institute for Biologically Inspired Engineering, and MIT's Computer Science and Artificial Intelligence Lab (CSAIL) Center for Robotics have achieved an early success in this research. They have created self-folding sheets based on origami. Referred to as origami robots or "programmable matter by folding," these sheets are comprised of rigid, interconnected triangular tiles and elastomer joints. The sheet is covered with thin foil actuators, flexible electronics, and thin material stickers containing the circuitry that prompts the actuators to fold. The sheet will fold, based on placement of the stickers, when it receives the appropriate electric current, and magnetic closures hold the folded edges together. The current sheet can only form two shapes: a boat and an airplane, however, this work proves that matter can be imbued with enough intelligence, mechanically and electronically, to autonomously take on different forms.[562]

Researchers at Cornell's Computational Synthesis Laboratory are working to prove self-assembly and repair, using centimeter-sized cubes with similar electrical and mechanical functionality.[563] Researchers at MIT's Center for Bits and Atoms are also working with centimeter-scale prototypes of paintable displays and modular robots to determine if millimeter- or smaller-scale programmable matter is achievable.

These researchers all seek to determine how to overcome some of the basic challenges of programmable matter, which include challenges for determining best methods for actuation, power requirements and sources, communication between the discrete building blocks, and fabrication methods. There are several challenges associated with fabrication, including determining the feasibility and costs of fabricating thousands of tiny machines. Additionally, it must be determined how robust these systems will be to defective parts.[564] Moreover, if programmable matter is to be used in space, further challenges associated with working in the harsh environments of space will arise. If programmable matter is to be used as tools, they must be made of materials that can withstand galactic cosmic radiation. Programmable matter must also be able to withstand dusty environments that can inhibit mechanical actuation and potentially reconfiguration. Finally, programmable matter will require complex information encoding to allow for shape-changing into multiple states.

Molecular Manufacturing

Molecular manufacturing is a future construction technology, referring to the process of building parts and materials from the atomic level upwards, arranging matter with atomic precision. Closely associated concepts include molecular nanotechnology, molecular engineering, molecular fabrication, and atomic precision manufacturing. While technologies like scanning probe microscopes exist for top-down manufacturing with atomic precision, bottom-up molecular manufacturing does not currently exist. Theoretical and computational models show that it does not violate any fundamental physical laws.[565] Manufacturing at the molecular level would allow unprecedented precision, enabling low-mass, high-strength products and new capabilities. Additionally, molecular manufacturing would allow for customizable properties of the final, macro-level production materials, allowing nearly unlimited resources to be produced from a given input.

PARTNERING OPPORTUNITES

MOLECULAR MANUFACTURING

- Atomically Precise Manufacturing – Atomically Precise Manufacturing Consortium and DARPA
- DNA Assembly Lines – New York University, Department of Chemistry

A prominent example of contemporary research is being done by the Atomically Precise Manufacturing Consortium. The group, a collaboration between industry leaders and government agencies, is working to manufacture a number of devices, such as ultra-low-power semiconductors for wireless communications and sensors with ultra-high sensitivity. These devices will be manufactured using the established ability to remove hydrogen atoms from silicon using a scanning tunneling microscope. DARPA, the Texas Emerging Technology Fund, and industry members fund the consortium. The consortium team is lead by Zyvex Corporation and includes team members from the University of Texas, Dallas and Austin; University of Illinois at Urbana-Champaign; University of Northern Texas; University of Central Florida; National Institute of Standards and Technology; General Dynamics; Molecular Imprints Inc.; and Integrated Circuit Scanning Probe Instruments.

Other research focuses on using DNA as assemblers. Chemists at New York University have programmed DNA "arms" to pass a gold particle between them.[566] The scientists use DNA as a construction material. The DNA strands fold themselves into platforms with movable arms constructed of DNA strands. These developments could lead to DNA computer chips (see "DNA Computing," in Everyday Supercomputing, page 192) and drug factories. However, researchers feel that it will be decades before DNA assembly lines will be ready to produce practical products.[567]

Molecular manufacturing is in the very early stages of development. Researchers at several institutions have demonstrated the ability to remove, replace, and transport single atoms using different techniques, including scanning probe microscopes and mechanical forces.[568] Thus, the general concepts have been proven, but there has been little applied development.

There is uncertainty over when this technology will come to fruition, with estimates ranging from within the next decade to 50 years from now. Two landmark reports, one from the National Academy of Sciences (NAS) and one from the Foresight Institute, raise and attempt to address the critical issues.

The NAS reviewed the status of molecular self-assembly and molecular manufacturing in 2005. They noted that the creation of large-scale objects through molecular assembly would require mechanisms to operate at a very low error rate, very high speed, and near-perfect thermodynamic efficiency. The NAS committee found that while many strategies for achieving this state existed, they could not be readily evaluated due to lack of experimental demonstration. They also concluded that the realization of creating large-scale usable devices was strictly theoretical and that "proof of principle" studies must be achieved.[569]

In 2007, the Foresight Institute published "Productive Nanosystems: A Technology Roadmap." This document answers many of the issues brought up by the NAS review. Working groups comprised of over 70 research scientists, nanotechnology theorists, and business leaders collaborated over three years to identify pathways across multiple disciplines to achieve macroscale, functional products from atomically-precise manufacturing. The Roadmap presents detailed R&D (research and development) pathways across nanoscale disciplines that provide a structure for developing both research agendas and commercialization pathways for molecular manufacturing. Following this roadmap, the working groups predict that production of complex, macroscale products is achievable within 30 years.[570]

Self-Replicating Robots

As the name implies, self-replicating robots are robots that can create exact copies of themselves. Typically self-reconfigurable and modular, these robots can autonomously assemble into useful parts, tools, or systems through self-replication. Theories of self-replication are based on biological life, which uses self-reproduction as a means for sustainability and evolutionary adaptation, like DNA that can create copies of itself using sets of identical building blocks.

PARTNERING OPPORTUNITES

SELF-REPLICATING ROBOTS

- Self-Replication from Random Parts – MIT Center for Bits and Atoms
- Self-Reproducing Machines – Cornell Computational Synthesis Laboratory
- Self-Replicating Lunar Factories – Johns Hopkins University, Department of Mechanical Engineering

Much of the initial work in self-replication builds off research on self-reconfigurable, modular robots. These include robots that are able to change their own shape by rearranging the connectivity of their parts to adapt to new circumstances, perform new tasks, or recover from damage. Self-replication goes beyond self-assembly, comprising robots that are able to make exact, functional replicas of themselves. Several means of self-replication have been studied to date. (For more information on self-reconfigurable, modular robots, see Go-Anywhere Roving, page 110.)

Researchers at Cornell University Computational Synthesis Laboratory have developed self-reconfigurable, modular robots that are able to configure themselves into a useful shape that builds an exact replica of the original robot. The original robot is constructed of several modular, centimeter-scale building blocks. This robot then reconfigures itself to be able to build a replica from a set of “feeder” blocks. Once the replication is complete, the robot configures back to its original form.[571]

Researchers at the MIT Center for Bits and Atoms demonstrated self-replication of a reconfigurable string of input parts. Programmable electromechanical components that could be reversibly latched and unlatched were used as input parts and were randomly distributed in the environment of the initial string. This initial string is then able to select the appropriate building blocks, while autonomously correcting errors made during replication. The parts interact by randomly floating on an air table. When a component part latches onto the original string, it is assessed by the neighboring component to determine if it is appropriate. If it is, it is permanently latched, and if not, it is released. Researchers note that advancements in MEMS technologies could make it possible to miniaturize the components and, if mass-produced, could create systems that self-replicate and fabricate themselves from individual parts into complex structures.[572]

These small-scale, self-replicating systems could provide many benefits to space exploration, particularly requiring launch of less spare parts and tools, decreasing resupply launches, and subsequently improving sustainability. One input robot can be replicated and reconfigured from individual components to construct a variety of parts and tools. The modular parts improve packaging efficiency, and they only require spare modules for repair rather than replacement of the entire robot.[573] However, these systems have only been tested at the most basic levels in the laboratory, and many hurdles remain before they will be flight ready.

These systems have not been specifically designed or tested for use in space. For use in space, these systems must be designed to withstand harsh space environments, such as the ability to perform in microgravity and under high radiation. Additionally, they must be dust-resistant or tested for performance in dusty environments. Finally, fabrication of components parts presents another potential hurdle. Complex tools, parts, or systems constructed in this manner would require many parts. These parts must either be carried from Earth or, to maintain sustainability, fabricated in situ. Fabrication in situ will require research and development into the types of materials that can be used as well as an understanding of the types and throughput of available in-situ fabrication systems.

Self-replication has also been demonstrated at a larger scale. In 2004, the NASA Institute for Advanced Concepts (NIAC) funded Johns Hopkins University's Department of Mechanical Engineering to complete a study on self-replicating lunar factories. This study evaluated and constructed "toy" models of self-replicating technologies that can make use of lunar resources. This study looked at full-scale (as opposed to nano-scale) manufacturing factories and robots, demonstrating robots that could make functional copies from pre-assembled subsystems, and considered how subsystems could be constructed from lunar materials. However, many challenges remain to bring this to fruition, including studying how the factory components would be integrated. Additionally, the initial factories and robots would have to be launched to build up the manufacturing capacity required for self-replication.[574]

Technology Trajectory

The technology concepts in this breakthrough capability range from desktop 3-D printers, which are in an advanced stage of development, to those at a very low TRL with only the most basic principles tested, like molecular manufacturing and self-replicating nanomachines. Regardless of the concept used to create parts in-situ, these parts will require rigorous verification and quality testing methods to ensure that they are reliable. This will be especially true if critical parts are to be created in this manner. Therefore, all in-situ, on-demand manufacturing systems must be accompanied by a quality verification system, and any proposed process development must include this feature.

While 3-D printing is currently a mature technology for rapid prototyping, development continues to bring it to the point of fabricators in the home to create everyday products. Researchers in the field compare where they are now to desktop computing in the late 1970s and early 1980s and predict that within 10 years the general public will have these printers in their homes.[575] Additionally, Cornell University has received a grant to give fabbers to public schools in Virginia and hopes that with a successful pilot program they will be able to put more printers in more schools and that schools will eventually have digital fabrication labs, just as they have computer labs today.[576] More effort will be required to test for space applications, securing ISRU feedstock for manufacturing and assuring the technologies can work in a low-power, high-radiation, rugged environment.

Digital materials and programmable matter have been demonstrated at centimeter-scale in laboratories. Research and development is continuing in both these areas to increase the complexity of objects that can be created and decrease the size of individual parts from which final products are created.

Finally, molecular manufacturing and self-replicating nanomachines are still at very low technology readiness levels. Studies have been completed to determine the feasibility of these machines and basic research has been conducted. The promising applications of nanotechnology and atomically-precise manufacturing have generated interest from both academia and industry. However, there are still decades of research and development to be conducted to bring the ideas to fruition.

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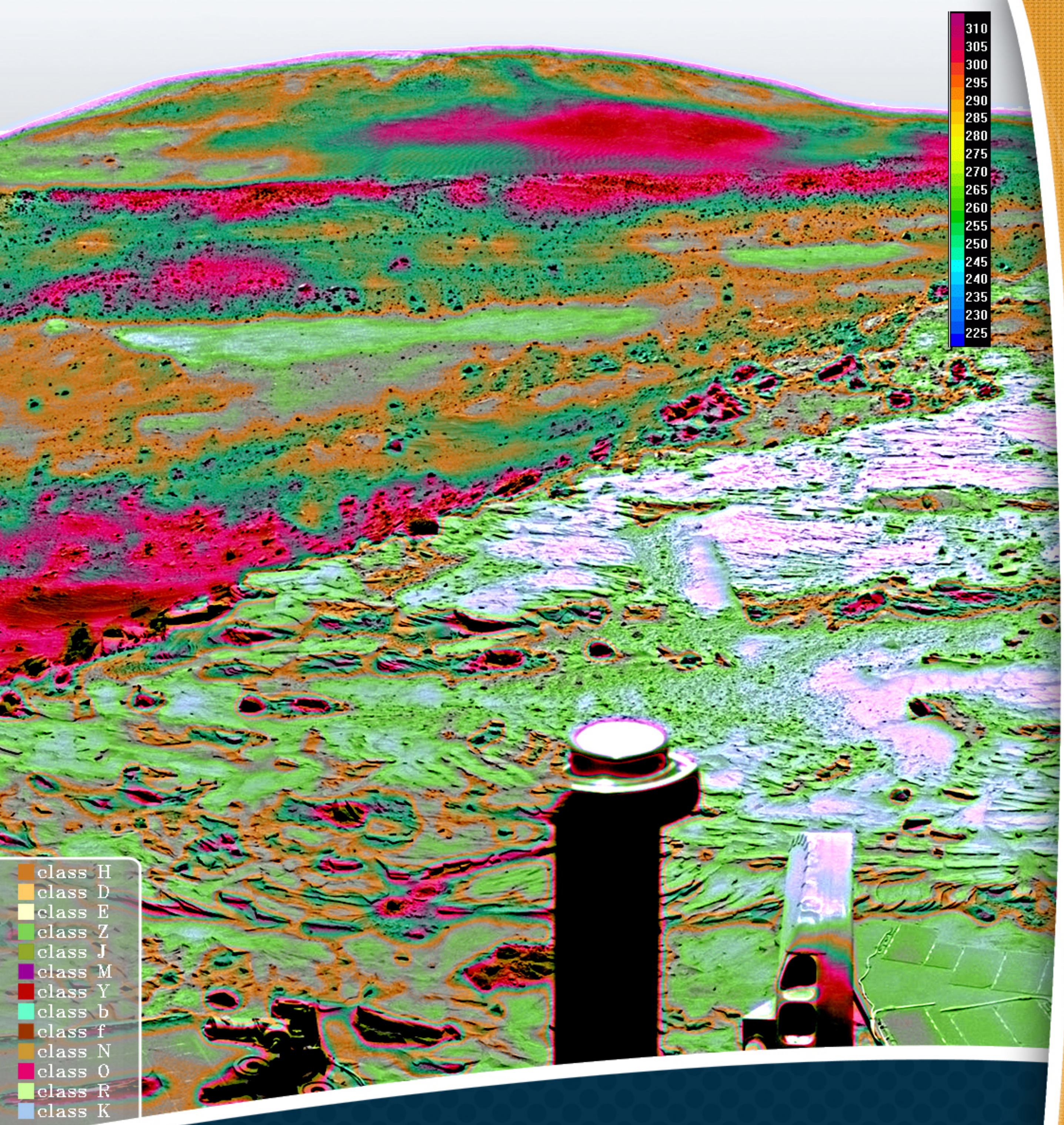

ENVIRONMENTAL OMNISCIENCE

Pervasive, sensing networks enabling comprehensive awareness of environments and manufactured systems

ENVIRONMENTAL OMNISCIENCE

Pervasive, sensing networks enabling comprehensive awareness of environments and manufactured systems

Space exploration has an inexhaustible demand for information. Astronauts and ground controllers require information regarding systems health and environmental conditions. They seek to collect and analyze scientific information about explored surfaces. Current sensor technologies gather some information, but they do not provide an expansive view of systems, equipment, and the environment. As space exploration advances, it will require more, new, constant information on all elements of space exploration, and all of this information will have to be fused to create a useful picture.

> **BREAKTHROUGH**
>
> Sensors are in all equipment, devices, clothing, structures, and the human body. Sensors are wirelessly networked together, so the data is fused and presented to astronauts and ground controllers automatically. Real-time monitoring of an entire outpost or spacecraft enables many applications, such as integrated systems health management.

The Environmental Omniscience breakthrough capability envisions a future where sensors are routinely designed into all equipment, devices, clothing, and structures both inside and outside of habitats. Motes of smart dust sensors and biomimetic-sensing devices are scattered throughout the internal and external environments to continuously gather and analyze data, including mapping planetary surfaces. Sensors embedded within the human body monitor health and can provide treatment for certain ailments. All sensors are wirelessly networked together so the data may be fused and presented to astronauts and ground controllers automatically. Real-time monitoring of an entire outpost or spacecraft enables many applications, such as integrated systems health management (ISHM). (ISHM is discussed further in Crosscutting Technologies, page 222.)

One of the impacts of this capability is an increase in safety and reliability of missions. Pervasive sensing allows astronauts and ground controllers a real-time, comprehensive picture of the maintenance status of all systems, equipment, structures, and the health of all crew. Because the sensors are intelligent as well as networked, the sensors can help maintain the safety of systems independent of crew or ground control. For example, if sensors on the planet's surface detect an approaching dust storm, those sensors could communicate the information to sensors embedded in a rover conducting an EVA. The sensors in the rover analyze the transmitted data and determine how much longer the rover can safely continue to collect samples before it has to return to the outpost. This constant state of self-awareness, with instances of self-recovery, reduces the likelihood of systems failures and improves system performance overall.

This capability also impacts scientific knowledge. A pervasive sensing network can create a real-time picture of the external environment on the planetary surface. This increases human understanding of planetary bodies, including topography, mineral compositions, and climate and atmosphere. Having this constantly updated and increased knowledge of the planetary environment can guide decisions on where more exploration is needed and could enable virtual exploration of planetary surfaces by ground control. (See Seamless Human-Computer Interaction, "Virtual Reality," page 207.)

Related Capability Areas

Achieving the full vision of the Environmental Omniscience capability is supported by development in three other breakthrough capabilities, including Everyday Supercomputing, Seamless Human-Computer Interaction, and Go-Anywhere Roving. The sensor technologies in Environmental Omniscience also support Healthy, Happy Astronauts and Self-Sustaining Habitats.

- **Everyday Supercomputing –** The Environmental Omniscience capability imagines that pervasive sensing networks will envelop a planetary body and be embedded in every system of the exploration architecture, gathering data that is continuously analyzed and updated. This requires a massive amount of computing processing power and data storage, even by future technologies' standards. The breakthrough technologies in Everyday Supercomputing can provide the processing power to accomplish this extensive level of data analysis.

- **Seamless Human-Computer Interaction –** Without a convenient interface, using the massive collections of data produced by pervasive sensing networks might overwhelm human analysts and users. The technologies in Seamless Human-Computer Interaction can comprehensively and clearly depict the output of all data gathered. For example, instead of presenting important alerts as code or text, a virtual assistant could convey the message as clearly as a human being, with both visual and sound cues. Intelligent interface technologies could also help prioritize alerts, so the human user can easily identify the most urgent alerts.

- **Go-Anywhere Roving –** Teams of robots with sensors will be part of pervasive sensing networks, ensuring a complete picture of the environment. Rovers can deploy sensors and also provide additional data gathering when needed. For example, if a sensor detects an anomalous result, a rover could investigate further to either verify the result or replace a faulty sensor.

- **Healthy, Happy Astronauts –** Implantable biosensors not only monitor crew health, but they can also treat and prevent diseases. These sensors are imperceptible to the human wearing them, which may increase an astronaut's level of comfort and reduce any stress associated with invasive medical monitoring and treatment.

- **Self-Sustaining Habitats –** Habitats will be outfitted with sensing systems to monitor and maintain the outpost, and these systems will depend on the use of a pervasive sensing network. Sensors embedded in the structure and operating systems will continuously gather and analyze data about the status of the habitat and alert the crew to potential faults.

Supporting Technology Concepts

The sensor technologies in this breakthrough capability have to be everywhere and working all the time. Two features in sensor technologies that make this possible are miniature sizes, such as smart dust sensors, and efficient, long-lasting power, which is achieved with self-powered sensors. Being "everywhere" includes sensing inside the human body, using implantable biosensors.

The sensors in this capability also have to possess a certain level of intelligence, to analyze data and determine when, how, and who to alert when needed. Ubiquitous computing manages the collection, analysis, and use of data in a habitat autonomously. Biomimetic sensors mimic biological sensors on Earth to increase the range of abilities of a sensor, from mastering the human's five senses to imitating the chemical sensitivity of a butterfly wing.

The technology concepts highlighted in this section are based on open-source research and workshops with subject matter experts.

Supporting Technology Concepts	
Smart Dust	A wireless network of tiny sensors.
Self-Powered Sensors	Draw power from the surrounding environment; also called energy-scavenging sensors.
Implantable Biosensors	Tiny sensors implanted in the human body to measure vital signs.
Ubiquitous Computing	Small, networked information processing devices integrated into all objects used in daily activities.
Biomimetic Sensors	Mimic all or portions of a simulated biological sensing system.

Smart Dust

Smart dust is a wireless network of tiny sensors. The sensors, called "motes," are currently about 12mm but are forecasted to be scaled down to the size of a pinhead.[577] Current systems are powered by micro-batteries that can run for up to ten years, and future systems can be powered using self-powered sensors that scavenge energy through vibration.[578] The motes are distributed on a low-bandwidth, low-power wireless mesh network that transmits data using radio signals.[579] Within the timeframe of this study, smart dust sensors will most likely move beyond the capabilities currently envisioned. The dust sensors themselves will become smaller, powered indefinitely through scavenging, with increased communications capabilities, allowing for much larger networks and having increased functionality. As smart dust applications grow in the near term, possible sensing capabilities could expand to include such functions as imaging, sound, radiation, and positioning data. These sensors could even become multifunctional and smarter, comprising a network system similar to ubiquitous computing, described more below.

PARTNERING OPPORTUNITES

SMART DUST

- Dust Networks
- University of California, Berkeley
- HP Labs

Smart dust is based on tiny computer chips called microelectromechanical systems (MEMS).[580] Using MEMS, the motes can measure ambient light, temperature, vibrations, humidity, acceleration, air pressure, or surface pressure.[581] While data is collected and measurements taken, the network of sensors relays signals back to a command computer, which then compiles and analyzes data for the user.[582] The results of the data analysis can also trigger an automatic response in the dust network, for example, lowering the temperature of a building. [583]

Because of its tiny size, long-lasting power, and intelligence, smart dust can be used nearly anywhere, enabling countless applications. In terrestrial applications, smart dust has been used to monitor industrial environments, such as oil pipes or production facilities.[584] "Smart buildings," buildings equipped with a smart dust network, use sensors to monitor occupancy, temperature, fire safety systems, and energy management.[585] Some major U.S. cities are beginning to use smart dust networks to monitor traffic conditions and map parking spaces, allowing drivers to find available parking before they reach their destination.[586] Smart dust is even used in the medical industry, for example, an injection of sensors into cancer cell tissue to track cancer.[587]

The space applications for smart dust are just as varied. Smart dust could be embedded in materials, enabling monitoring in the walls of a habitat or in the clothing worn by a crew member.[588] Smart dust can enable an ISHM system, which requires a constant flow of data from systems and devices to detect and diagnose faults.[589] (See Crosscutting Technologies, "Intelligent Systems and ISHM," page 222.) It is imagined that a smart dust network could pervade an entire planet.[590] Smart dust sensors could be deployed on a planet's surface, to map the planet's features, including soil chemical composition, and to continuously monitor the condition of its environment, including ambient temperature, wind speed, and seismic activity.[591] Mapping a planet's surface would contribute to scientific knowledge and inform decisions about outpost locations and EVA preparation.

One of the main challenges of using smart dust is maintaining reliability of data transmissions on the wireless network. A large network, in terms of physical distance between sensors and the number of sensors, increases the chances of lost data transmissions. [592] In terrestrial applications, this issue is resolved by distributing data on a mesh network, in which data transmissions can hop different channels (or paths) and different frequencies until the data is safely received by the manager node.[593] Mapping an entire planet with sensors will require a very large wireless network; however, the challenge is less difficult on a different planet, since the network would not have to compete with other wireless devices (such as cell phones) for bandwidth, which is the main source of the issue on Earth.

A more space-specific challenge for smart dust is protection from the harmful effects of the space environment. If the sensors are to operate on a planetary surface indefinitely, the sensors will have to be radiation-hardened, dust-resistant, and protected against corrosion and other chemical reactions. Nano-sized electronics could be more vulnerable to corrosive environments than macro sensors.

Self-Powered Sensors

Even though some sensors are powered by batteries that can last a decade or longer, every battery will require replacement eventually. Replacing batteries can be difficult, especially in remote or inaccessible places, such as medical sensors implanted in the human body. Using self-powered sensors can eliminate that difficulty.

PARTNERING OPPORTUNITES

SELF-POWERED SENSORS

- MIT, Microsystems Technology Laboratory
- Georgia Institute of Technology
- PERPETUA, Power Source Technologies

Self-powered sensors, also called energy-scavenging sensors, draw power from the surrounding environment, including solar energy, ambient vibrations, or even differences in temperature between a warm object and the surrounding air. For example, one project at MIT is a medical sensor that, when worn somewhere on the human body, is powered by the difference between the wearer's internal body temperature and the external temperature of the surrounding environment.[594] (Similar technology applications for gathering energy from thermal transfer are discussed in Crosscutting Technologies, "Thermal Management," page 237.) Another MIT sensor project harvests energy from a crystalline material that produces electricity under stress, which can be applied by bending or squeezing the material.[595] At the Georgia Institute of Technology, a similar method is being studied for powering nanosensors.[596] In this design, nanoscale generators use zinc oxide wires that generate electricity when subject to strain, which can be produced by just flexing the wires.[597] Some self-powered sensors combine two or more scavenging abilities to ensure that they can still be powered in situations when energy sources are variant or unavailable.[598]

One of the challenges of self-powered sensors is that they only work with low-power devices. For example, current self-powered sensing technology cannot power cell phones, but MIT researchers predict that the ability to power a portable music player is within reach.[599] In the near term, some sensing devices may have to decrease in size, weight, and energy requirements before switching from battery power to energy scavenging. More research is required to scale up self-powered sensors for use in larger devices in the future.

Another challenge is that current designs still require some energy storage device to accumulate the small flow of energy in a self-powered sensor, adding size and mass to the overall sensor design.[600] Lastly, current vibration-harvesting systems are tuned to very specific frequencies, limiting the number of possible applications.[601]

Implantable Biosensors

These tiny sensors are implanted under the skin to measure vital signs. This enables constant and imperceptible monitoring of a human's health. Currently, these sensors are used to monitor health by measuring lactate and glucose levels. In the future, advancements in biosensors embedded in the human body could enable detection and identification of any disease or ailment, to allow for medical intervention before issues become life-threatening. Examples include detection of initial cancerous cells to stop the spread of cancer or identification of toxic substances in the body from drug interactions or food poisoning.

Implantable biosensors can monitor the level of an astronaut's health or detect the beginning of diseases. Two terrestrial examples are being developed at Clemson University's Center for Bioelectronics, Biosensors, and Biochips (CB3). *In Vivo* Biosensors are temporary implantable biosensors for monitoring lactate and glucose levels, to detect trauma and the severity of an injury.[602] The Brain Tumor Biochip uses DNA microarray technology to improve the diagnosis and treatment of brain tumors and eventually for other types of cancerous tumors as well.[603] CB3 researchers are also studying the integration of carbon nanotubes into biosensor designs, to monitor samples at the sub-cellular level and improve the performance of *in vivo* biosensors.[604] (For more information on carbon nanotubes, see Crosscutting Technologies, "Nanotubes," page 226.)

PARTNERING OPPORTUNITES

IMPLANTABLE BIOSENSORS

- Clemson University, Center for Bioelectronics, Biosensors, and Biochips (CB3)
- University of Connecticut, Institute of Materials Science
- Tufts University, School of Engineering
- Boston University
- University of Rochester Medical Center
- Brunel Institute for Bioengineering

Like CB3's sensor that detects trauma, the University of Connecticut (UConn) is also designing a sensor that measures lactate and glucose levels, but with a much smaller sensor, using nanotechnology. The sensor being developed at UConn's Institute of Materials Science monitors lactate and glucose levels to determine if a human is exhausted or receiving proper nutrition.[605] The sensor is just a few millimeters in length, small enough to be injected into the wrist through a standard hypodermic needle.[606] The sensor will be synchronized with a wristwatch that receives data transmissions from the sensor.[607] The sensor has applications in both treatment medicine and preventive medicine.[608]

Another biosensor technology applicable to both treatment and preventive medicine is an implantable silk metamaterial, being researched at the Tufts University School of Engineering and Boston University.[609] The metamaterial could be wrapped around an organ or under muscle tissue to monitor health, to monitor the rate of a drug-eluting stent, or to treat diseased tissue and prevent cancer formation.[610] As with all biosensing technologies, all of the data received by the implanted biosensor is wirelessly transmitted to where it can be used by the wearer of the sensor or by others.

A challenge unique to implantable biosensors is the human body itself. Of course, the sensors must be non-toxic, but they also have to survive the body's immune system reaction.[611] When a sensor is implanted in the body, the body will try to reject it, and if the sensor cannot be rejected, it is cocooned in a fibrous tissue.[612] Although larger implanted devices, such as pacemakers, can function in this condition, nanosensors cannot.[613] Current research has designed sensors that can survive in the body for up to three months, which might not be long enough to last the duration of a space exploration mission.[614]

Another technical hurdle is the biosensor's ability to transmit data to a device for processing and analysis, such as a command computer or a portable processing device. Because of its unique location, the biosensor may have to transmit data over a range of distances (for example, when an astronaut travels miles from the habitat while on an EVA), and data transmissions will compete with the bandwidth requirements of other wireless devices. One potential solution is for the astronaut to wear a device that receives the biosensor's transmissions, like the wristwatch at UConn. This device could either send data to a command computer to be processed, or if the device was equipped with intelligent software, it could analyze the data transmissions itself.

Ubiquitous Computing

Ubiquitous computing uses small, networked, information processing devices integrated into all objects used in daily activities. The devices collect and analyze data, which is transmitted to other devices to act upon the data. The constant communication between these networked, smart devices can improve the nature of daily tasks in a habitat, by making them less tedious, take less time, and consume less energy.

PARTNERING OPPORTUNITES

UBIQUITOUS COMPUTING

- Things That Think Consortium (TTT), MIT Media Lab
- U.S. Department of Transportation
- IBM, A Smarter Planet
- University of Nebraska-Lincoln

Ubiquitous computing has a variety of applications, and the number of applications increases as the technology advances. Many terrestrial applications eliminate tedious daily tasks. For example, IBM's A Smarter Planet imagines a scenario in which a user's devices, including his computer, car, and refrigerator, are connected to each other and to other smart devices in the environment.[615] This enables the user's alarm clock to respond to the schedule in his online calendar and know what time to wake the user. The user's car is connected to other devices in the city, so it can suggest the quickest route based on current traffic conditions. Other terrestrial applications involve conservation of energy. The most basic way to conserve energy is to turn off a device when it is not in use, and ubiquitous computing can determine when devices need to be on or off, such as turning off electrical light when it determines that natural light is sufficient.[616] Advanced ubiquitous computing systems can be set to specific conservation modes, such as a demand-response design, which monitors market energy prices and uses energy frugally during peak periods.[617]

Potentially, if a ubiquitous computing system is integrated in an in-space or planetary habitat, this technology will provide the same time- and energy-saving benefits in space as it does on Earth. Astronauts could have more time for science and exploration if their devices were automated and working together efficiently. If devices were aware of their own power requirements, they could automatically adjust their energy use as necessary to conserve power. In addition to these space applications, a ubiquitous computing system may be crucial for enabling ISHM, which relies on an interconnected network of systems and devices to monitor the health of systems, prevent system failures, and perform recovery actions. (See "Intelligent Systems and ISHM," page 222.)

One of the challenges of this technology is that it requires complex, intelligent system design to integrate all parts of the ubiquitous system. For example, an alarm clock needs to have the appropriate intelligent system to understand and use data it receives from an online calendar application in a handheld phone.[618] This may be especially difficult for space operations, since an intelligent system might have to be integrated with several generations of architectures, some of which were designed long before this level of intelligent system was conceived. Complex systems engineering may be required to get every level of the architecture integrated.

Another challenge is that innovations in human-computer interface design are required for this technology to be convenient and accessible to the human user. A human-computer interface that allows the user to speak his commands to his appliances, rather than relying on code or text, would simplify his tasks greatly. (See Seamless Human-Computer Interface, page 202, for more examples.)

As with all information technology, as the complexity of systems increases, so does the potential for risk. The more trust and responsibility that a user puts into this kind of technology potentially increase the user's vulnerability to security threats and catastrophic systems failures.[619] An advanced ISHM system could alleviate this risk.[620]

Biomimetic Sensors

The greatest variety of sensors is found in nature. There are biological sensors found in plants and animals for many types of applications, including navigation, spatial orientation, and detection of objects, sounds, or chemicals.[621] Biological sensing systems emphasize redundancy, low power, high sensitivity, and multi-functionality.[622] When a

PARTNERING OPPORTUNITES

BIOMIMETIC SENSORS

- European Space Agency (ESA)
- University of the Mediterranean
- Johns Hopkins University
- University of Zurich
- Italian Institute of Technology
- University of Bath
- Missouri University of Science and Technology
- Air Force Research Laboratory (AFRL)

biological system is understood and simulated, sensors can be engineered to mimic all or portions of the simulated system. Examples include vision sensors inspired by bees and the human retina, a strain sensor inspired by the campaniform sensilla in insects, and a plant-like robot that relies on plant-like sensors. These specific technologies are relatively near-term, but they exemplify the kind of innovation that is possible in the field of biomimetic sensing research.

Two vision sensors funded by the European Space Agency (ESA) mimic biological functions to aid planetary landings. One of the biomimetic sensors mimics a bee's sense of optic flow. Optic flow is used by flying insects to navigate quickly in unfamiliar environments by monitoring the angular speed of images as they sweep backward across the insect's field-view.[623] Bees use optic flow specifically for avoiding obstacles, controlling speed and height, cruising, and landing.[624] The biomimetic optic flow sensor uses the same capabilities to guide a planetary landing.

The second biomimetic sensor is a neuromorphic vision sensor, which receives and analyzes data similar to the human retina. This sensor mimics the retina's physical organization and circuitry to detect and process visual images in real time.[625] These sensors could be distributed on the external surface of a lander, to analyze the craft's motion, speed, and height relative to the lunar or planetary surface and help guide it there safely.[626]

Another ESA-funded project is developing a unique strain sensor that mimics the campaniform sensilla, a displacement sensor found in the exoskeleton of insects.[627] Cockroaches rely on the sensilla to detect strain deformation and to determine load and muscle forces. A micro strain sensor that mimics the campaniform sensilla can be used to monitor lightweight structures or as a force sensor for docking systems or robotic arms.[628]

In addition to improved sensing capabilities, developments in biomimetic sensors can also influence new robotic designs, such as the plant-like robot being developed in Italy. Equipped with plant-like sensors that detect gravity and water, this robot burrows itself into the ground to analyze soil composition, locate water and other substances, or detect harmful pollutants.[629]

The discussed biomimetic sensors will be developed long before the 40-year timeframe of this report, but they provide examples of the range of opportunities in biomimetic sensing research. Within the 40-year timeframe, the development of biomimetic sensors could benefit the architecture in a number of ways, including chemical detection, temperature monitoring, and sensing of ultraviolet to infrared light.[630] Most importantly, like the sensors that inspired the plant-like robot, the greatest contribution of biomimetic sensing will be innovation.

One of the challenges of biomimetic sensing is that some functions desired for a sensing technology will be difficult to identify in a biological system. For example, no biomimetic sensors are known for detecting radiation or magnetism.[631] Another challenge is that designing a biomimetic sensor requires detailed research in the specific biological system being imitated.[632] For example, researchers are just recently designing a strain sensor to mimic the campaniform sensilla, after more than 40 years of research investigating the subject.[633] Finally, another challenge will be the integration of all the capabilities made possible by biomimetic sensors (such as optic flow, strain sensing, etc.) into one fully capable sensor that is miniature, lightweight, low-power, and reliable.

Technology Trajectory

Technologies for Environmental Omniscience range in development from conceptual (ubiquitous computing) to terrestrial usage (smart dust networks).

Research continues to miniaturize smart dust sensors and improve communications in the wireless networks, including mobile and stationary objects. Kris Pister, the computing professor at University of California, Berkeley who invented smart dust and founded the privately held Dust Networks, is working on reducing the size of the smart dust mote from 5 mm (about the size of a grain of rice) to one cubic millimeter.[634] Products using smart dust networks are being researched and developed by GE, Cisco Systems, and Emerson Electronics.[635]

The first attempt at planetary mapping is the HP Labs program, Central Nervous System for the Earth (CeNSE), which aims to map the Earth with intelligent, tiny sensors.[636] HP Labs' current sensors are about the size of a matchbook, and, in their protective casing, they are about the size of a VHS tape, but the goal is to reduce the sensors to the size of a pushpin.[637] The first application for CeNSE is a collaboration between HP and Shell to monitor seismic activity, using low-power, ultrasensitive, MEMS accelerometers developed by HP labs.[638]

Self-powered sensors have applications in several industries, including military, medicine, the Department of Energy, and the oil industry, all of which provide funding to the research and development of this technology.[639] In March 2010, Georgia Tech reported the creation of the first nanometer-scale sensing device to power itself with the conversion of mechanical energy; Georgia Tech researchers have produced two nanosensors based on zinc oxide nanowires and powered by nanogenerators.[640] Self-powered technology is also being researched for powering other electronic devices, such as cell phones, and self-powered sensors can benefit from that research.[641]

Implantable biosensors have a wide range of applications in human health, including health monitoring, treatment, and disease prevention, which are of interest to the military and to many specific research centers in the medical industry, including cancer, diabetes, and diseases of the brain.[642] Current research focuses on miniaturization (integrating nanotechnology) and developing technologies to protect the sensor from the body's immune system.[643] Advancements in self-powered sensors may contribute to the advancement of this technology, since implantable biosensors have to be powered wirelessly.

Ubiquitous computing is in early stages of development, however, due to large potential consumer markets, there is much interest from industry and academia. The Things That Think consortium from MIT Media Lab involves 28 corporate companies, including Intel, Samsung Electronics, and Sun Microsystems, working with the Media Lab to develop projects related to ubiquitous computing.[644] Another current ubiquitous computing project is the IntelliDrive system being developed by the U.S. Department of Transportation.[645] IntelliDrive interconnects sensing capabilities in vehicles between sensing devices in other vehicles, in handheld devices, and in infrastructure components to send alerts of roadway hazards, communicate traffic conditions, and advise transportation plans.[646] IntelliDrive is based on refining existing wireless communication and information technologies, and research is expected to be completed by 2013.[647]

While some biomimetic sensing technologies, such as e-noses, have successfully tested prototypes in academic and laboratory settings,[648] many biomimetic sensing technologies are still in conceptual stages, due to the requirement for in-depth knowledge of organisms being replicated. ESA is funding advancements in at least three biomimetic sensing devices: optic flow (with the University of the Mediterranean), neuromorphic vision (with Johns Hopkins University, University of Zurich, and Italian Institute of Technology), and strain sensing (with the University of Bath). Each of these projects have designed sensor prototypes and conducted experimentation with computer simulations.

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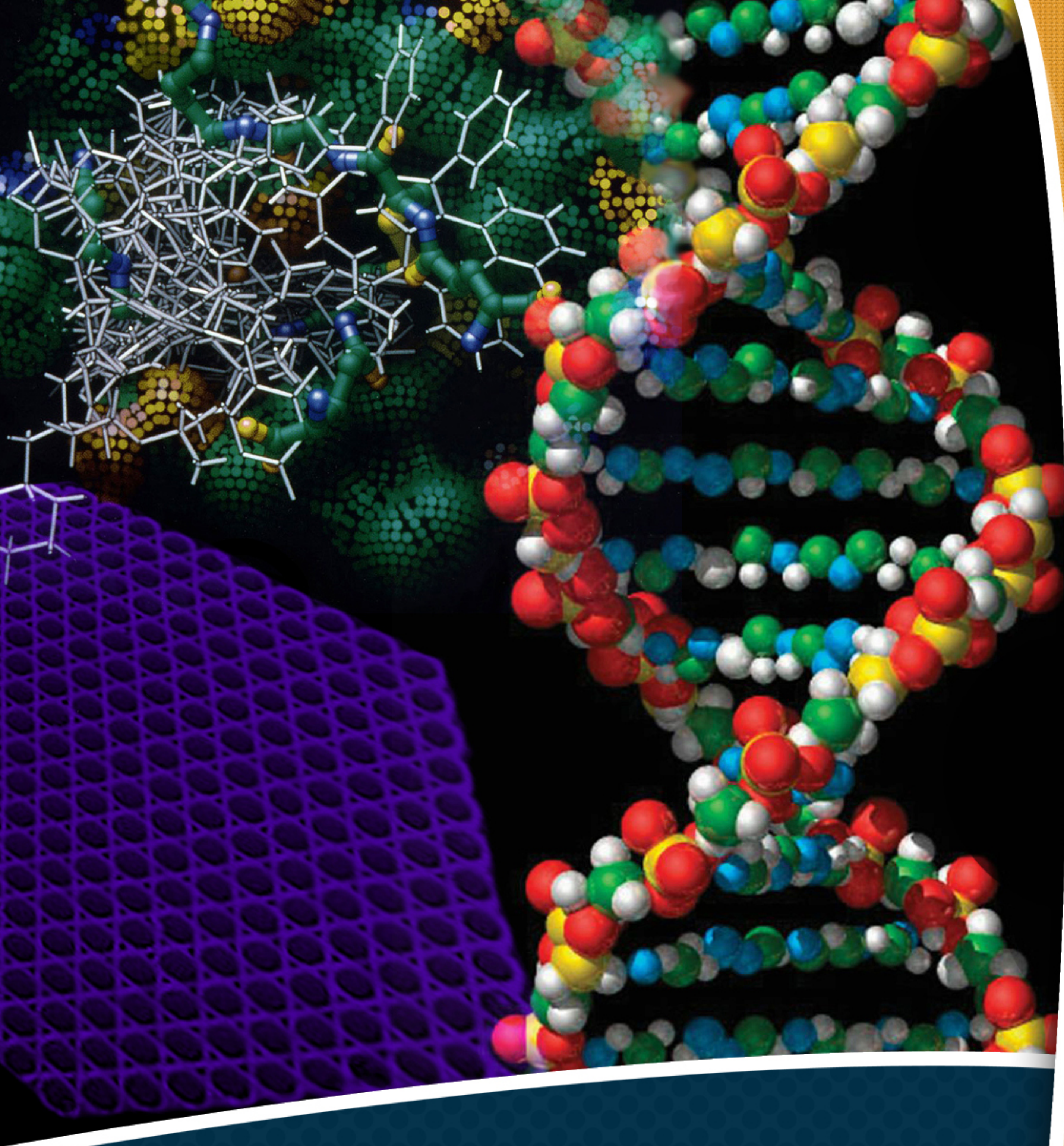

EVERYDAY SUPERCOMPUTING

Supercomputing capabilities available for routine applications in human exploration of space

EVERYDAY SUPERCOMPUTING

Supercomputing capabilities available for routine applications in human exploration of space

Space exploration is driven by the need to acquire data, and all data must be processed to be usable. Current computing technologies cannot sufficiently process all the data that is collected in space exploration. Scientific data gathering is already limited by communications bandwidth and processing throughput.[649] This challenge increases as the amount of collectable data increases, for example, if more sophisticated sensor technology is employed. In addition to science purposes, onboard processing power is needed for future Integrated System Health Management (ISHM) systems, which will most likely grow in scope and importance as space exploration systems become more complex and travel farther from Earth.

BREAKTHROUGH

Advances in supercomputing technologies provide very high processing power and storage for nearly every device and application. Science and vehicle health monitoring capabilities are greatly increased. Huge amounts of data can be processed without having to send it back to Earth.

This breakthrough capability envisions a future where advances in supercomputing technologies provide very high processing power and storage for nearly every device and application. Science and system health monitoring capabilities are no longer constrained by processing power limitations. High levels of processing power are available even in small portable devices, suits, and rovers.

This capability impacts human space exploration in a number of ways. First, it provides the processing power needed to enable the monitoring and control of the increasingly complex exploration systems of the future. The processing power supporting these systems needs to be onboard or placed strategically in space instead of located on Earth, because communication delays of transmitting data back and forth would be unacceptable in time-sensitive situations. Greater amounts of onboard processing power enable advanced human-computer interfaces like augmented reality (AR) displays and intelligent software assistants for crewmembers. This processing power also allows for more science in space. Performance and objectives will no longer be constrained by how much data can be collected and processed, and scientists, in space and on Earth, will have faster access to the processed data.

Another important impact of dramatically increased computing power is that it will speed up research and development of other technologies and enable new forms of scientific research. The amount of time needed to move from basic research to applied technology will decrease as researchers leverage greater amounts of processing power to run simulations, test theories, and predict outcomes. Computing enables complex, fast, and very precise simulations. Computers are already beginning to gain the capability to make scientific discoveries by extrapolating rules and patterns from massive data sets.[650] This is an example of how computing power will change the world in a way that will greatly impact the space industry.

Some experts predict that the traditional silicon industry will hit the limits of technological development within 10 to 20 years. After this point, we will need groundbreaking new techniques to achieve the rate of improvement that we have enjoyed for the last several decades. Although traditional silicon machines will continue to provide essential tools, new computing platforms will emerge in the market and provide exponential increases in computing power.[651]

Related Capability Areas

Computing is a crosscutting technology that touches all other breakthroughs in this report in some way. Below are the capabilities most closely related to computing.

- **Environmental Omniscience –** Large-scale, wireless sensing networks will require a great deal of processing power to process all of the data gathered by these systems.

- **Seamless Human-Computer Interaction (HCI) –** Some HCI systems and devices, including portable devices, will require levels of processing power not currently available on onboard systems.

Supporting Technology Concepts

The following sections describe the supporting technology concepts that may contribute to realizing this capability breakthrough. No one technology is likely to achieve the breakthrough itself, but rather a combination of several of these technologies could achieve that goal.

The report *Technology Horizons: Game-Changing Technologies for the Lunar Architecture* looked at the 2012-2020 timeframe and covered a suite of near-term computing technologies, including stretchable silicon, clock gating, magnetic random access memory (MRAM), holographic data storage, probabilistic complementary metal-oxide semiconductors (PCMOS), and spintronics.

Supporting Technology Concepts	
DNA Computing	A form of molecular computing using DNA and enzymes for computation.
Optical Computing	Computing with light instead of electricity. The properties of light allow these computers to easily parallel process, making them very fast.
Quantum Computing	Quantum bits (qubits) are used to store information. The quantum property of superposition means that *n* qubits may be 2^n states simultaneously. This exponential growth could offer virtually unlimited processing power.
Molecular and Nano Electronics	There are several technologies that may replace conventional transistors with equivalents built on the molecular scale. Research areas include Carbon Nanotube Field Effect Transistor (CFET), hybrid mono-molecular electronic circuits, organic molecular electronics, and quantum dots.

DNA Computing

PARTNERING OPPORTUNITES

DNA COMPUTING

- Weizmann Institute of Science
- IBM
- California Institute of Technology

DNA computing is an entirely new computing paradigm that involves computing with biologically-derived matter. It is a form of molecular computing that uses DNA and enzymes for computation. In this computing approach, enzymes are analogous to hardware and DNA is analogous to software. If successfully built, DNA computers would have an enormous capacity for parallel computing. Researchers have demonstrated that DNA computers would be able to solve some problems that are unsolvable by conventional computers.[652]

Current approaches to computing with DNA involve creating a set of all possible solutions to a problem and then filtering until only the optimal solution remains. This is achieved by creating logic rules for membranes that the DNA molecules pass through.[653] The main advantage of DNA computing lies with the four sets of base-pair combinations, which allows trillions of parallel processes to occur at once. Also, because the computing matter is biologically derived, it can self-assemble and self-reproduce, traits which present a number of potential benefits.[654]

There are many technological hurdles that researchers would need to overcome before DNA computing could be useful inside or outside of a laboratory. The most fundamental problem is that a tremendous amount of DNA is required to complete the simplest calculation. There is a debate among experts as to whether or not this technology has any practical applications, and it is widely believed that this technology will only serve a very small and specific role in the future information systems.[655] Also, it is not known how a

DNA computer would withstand space environments. Still, the potential parallel processing capability that DNA computing promises leads many researchers to believe that it will someday provide the world with breakthrough capabilities, even if they impact only a limited number of applications. The experts at TechCast, a forecasting think-tank, estimate that DNA computing will be available in 2025.[656]

Optical Computing[1]

Optical computing is an alternative to conventional computers that involves computing with light instead of electricity (photons instead of electrons). An all-optical computer would have no electrical circuits or wires. Instead it would consist of laser diodes, optical fibers, tiny crystals, micro-optical components, and thin films.[657] Such a computer has the potential to offer many benefits over traditional computers.[658]

The first and most substantial benefit is an increase in processing speed. Using photons instead of electrons offers very fast information processing power and communication, increasing computing speed by more than seven orders of magnitude. This means that an optical computer could perform eleven years of conventional computation in about one hour.[659] Another benefit of optical computing is the potential for parallel processing. Because multiple frequencies of light can travel along the same channel without interfering with one another, an optical computer could easily parallel process. The combination of super fast optical computing speeds with this ability to parallel process could result in staggering computation speeds.

PARTNERING OPPORTUNITES

OPTICAL COMPUTING

- Intel
- MIT, Research Laboratory of Electronics and Microsystems Technology Laboratory
- Georgia Institute of Technology
- Purdue University

Optical computers also have the potential to be lighter and more compact than traditional electric computers, because they are not susceptible to cross-talk, short circuits, and overheating. These traits make insulators, which must be used between electrical components, unnecessary in optical computers.

There is a considerable amount of research going on in academia, government, industry labs, and internationally. Simple optical computers have been built in lab environments, proving the feasibility of optical computing. There have been numerous developments in recent years that, according to experts, indicate that an all-optical computer is likely to be available in as little as five years. All components needed to create a fully functioning optical computer have already been developed and proven as components in electrical computers. There are some technical hurdles remaining, including issues of reducing the

[1] Several near-term photonic materials and optical technologies (including applications in storage and communication) are covered in the report, "Technology Horizons: Game-Changing Technologies for the Lunar Architecture."

size of optical components and integrating optical components onto a single chip.[660] Funding is needed to support development of an all-optical computer. Some believe nano-electronic computers are more promising than optical computers. The experts at TechCast estimate that optical computing will be available in 2018.[661]

Quantum Computing

Quantum computing is a new computing platform in which quantum bits (qubits) are used to store information. The spin of the electron (clockwise or counterclockwise) can be used to represent the logic states 1 or 0. The real promise of quantum computers lies in the property of superposition. The quantum property of superposition means that n electrons may be 2^n states simultaneously. In other words, an electron can coexist in two places at the same time (in this context an electron is often referred to as a qubit). This means that 1 electron could carry 2 logic states, 2 electrons could carry 4 logic states, 3 electrons could carry 8 logic states, and 20 electrons could carry over a million logic states. Every time one electron is added to the computer, the processing power is doubled. This exponential growth could offer virtually unlimited processing power.[662]

PARTNERING OPPORTUNITES

QUANTUM COMPUTING

- National Institute of Standards and Technology, Time and Frequency Division
- Harvard University
- D-Wave Systems
- IBM
- Jülich Supercomputing Center

Researchers estimate that, if successfully built, a quantum computer would take only seconds to solve problems that a silicon computer would take billions of years to solve. One classic example is Shor's algorithm (developed by Peter Shor of Bell Labs), which shows that a quantum computer can quickly factor large numbers. For example, a quantum computer could factor a thousand-digit number in about 20 minutes, a task which would take a conventional silicon supercomputer 10^{24} years.[663]

There are several other capabilities that are related to the development of quantum computers. For example, the quantum property of entanglement theoretically allows for new ways of communication and teleportation. If two atoms are entangled, a change in the state of one causes a change in the state of another, presumably across large distances. Using this property, researchers have transferred information over 1 km.[664] These capabilities would be major breakthroughs, however, they are largely theoretical at this point and not likely to be achieved in the 2050 timeframe.

Stabilizing the qubits so that they store information reliably is one of many technological challenges facing researchers. Currently this technology exists only as small laboratory prototypes, systems that consist of only a few bits. The Time and Frequency Division of National Institute of Standards and Technology, in Boulder, Colorado announced that they developed the world's first programmable quantum processor, which used 2 qubits.[665] Other research prototypes are running at Harvard University, the National

Security Agency, and the Federal Reserve. Commercial companies are working on this technology as well, including D-Wave Systems in Canada and IBM.[666] One approach to stabilizing the qubits is to cool them with liquid helium. This could make quantum computers very large and expensive, and therefore not a good choice for an onboard computer on a spacecraft.

In addition to the many technical hurdles, some experts also believe that this technology would only be useful for niche applications. This belief is difficult to dispel, because developing new algorithms for quantum computing is a very challenging problem. This is due partially to the fact that quantum computers are difficult to simulate on conventional computers, so computer scientists have limited access to test environments for new algorithms. However, there have been several recent developments in this area, most notably at the Jülich Supercomputing Center where scientists set a new world record on March 31, 2010, by simulating the largest quantum computer ever (at 42 qubits).[667] Another concern surrounding quantum computing is that, if successfully built, a quantum computer would have tremendous security implications because of its code-breaking capabilities. These security considerations will affect the development and availability of this technology. Certain advances in molecular and nano electronics (discussed in the following section) could act as enabling technologies for the development of a quantum computer. The experts at TechCast estimate that quantum computing will be available in 2024.[668]

Molecular and Nano Electronics

There are several technologies currently being researched that may replace conventional transistors with equivalents built on the molecular scale. Research areas include Carbon Nanotube Field Effect Transistor (CNFET), hybrid mono-molecular electronic circuits, organic molecular electronics, and quantum dots.

A CNFET is an electronic switching device made from carbon nanotubes. A switch made of a CNFET might use half a million times less electricity than its silicon counterpart and function at clock rates more than a thousand times faster than our current processors. Two other significant advantages are that it could operate at an ambient temperature and would function in a way that is very similar to conventional silicon technology.[669]

A hybrid mono-molecular electronic circuit is an alternative to carbon nanotube technology. This radical approach involves creating a whole circuit, including components and interconnections, out of one molecule.[670]

Organic molecular electronics are another alternative to carbon nanotube technology. This

PARTNERING OPPORTUNITES

MOLECULAR AND NANO ELECTRONICS

- Toshiba
- University of Connecticut, Robert Birge
- IBM
- New South Wales (UNSW), Centre for Quantum Computer Technology (CQCT)
- University of Wisconsin-Madison
- California Molecular Electronics Corporation (CALMEC)
- Purdue University

technology involves extracting photosensitive biological molecules from their natural context and manipulating their photo cycle state to represent the logic state 1 or 0. The photo states are manipulated by colored lasers and detected with an optic system. These molecules are very stable; most are able to hold these states for several years.[671] They potentially have a very low production cost compared to carbon nanotubes, since the molecules can be easily grown and harvested.[672] Researcher Robert Birge, a professor at the University of Connecticut, successfully designed a prototype of a hybrid machine that combined traditional semiconductor circuits with this type of biological circuits.[673] This technology is particularly interesting for storage applications, because the proteins can organize themselves into different 3-D shapes allowing for 3-D data storage. The capacity of such a device is about 1 terabyte per cubic cm and speed of access of 10 Mbits per second.[674] (See Seamless Human-Computer Interaction, "Simulated Reality," page 209, for more information about photosensitive molecules, in the context of optogenetics.)

A quantum dot is a technology that has many exciting near-term applications (such as solar cells and memory storage), but in the future they could also be used as electric transistors. A quantum dot is an artificial construct designed to keep an electron in a quantum state. The quantum dot could allow reading and manipulation of the spin (up or down) of the electron or the electric state of the electron. Both of these properties could be translated to the logic states 1 or 0 to process and store information.

Interconnectivity on this nano scale is the biggest challenge facing the development of these technologies. Even if a carbon nanotube transistor can be made in a lab, producing a chip containing several million of these interconnected devices is very far from being achieved. Interconnectivity is particularly challenging when working with hybrid devices that could include biomolecular, semiconductor, and optoelectronic components. Researchers would also need to develop a method for automated mass production of these integrated circuits, to be economically viable in competition with the conventional silicon industry.[675] Forecasts of maturity dates of these molecular and nano electronic computing technologies are not available, however, the maturity levels of the components discussed in this section are significantly less than those of optical computing components and greater than those of quantum computing. This may be an indication that molecular and nano electronic computing will be commercially available somewhere between 2018-2024 (the respective forecast dates of optical and quantum computing).

There are many research groups and programs currently working on these technologies, and there have been several recent developments in laboratory environments. For example, in August 2009, researchers at IBM announced that they had developed a way to use DNA molecules as scaffolds or miniature circuit boards, enabling them to place nano objects with 6 nm resolution. This could be a major step forward in solving the problem of integrating molecular-scale components. [676] Another recent development was announced in May 2010, when a team from the University of New South Wales (UNSW) Centre for Quantum Computer Technology (CQCT) and the University of Wisconsin-Madison reported that they created the world's smallest precision-built transistor. The transistor is a quantum dot consisting of seven atoms placed in a silicon crystal. It is only

4 nm long and is a fully functional electronic transistor. The research group hopes to ultimately make a quantum computer in silicon.[677]

Technology Trajectory

All computing technologies presented in this section have been demonstrated as being capable of performing computations. However, there are many questions about which approach is best. Some of these technologies may be impractical due to cost of manufacturing and size. Out of the technologies presented in this section, nano molecular electronics enjoy the most funding and research. Perhaps, this is because they are considered by many to be a continuity solution to traditional silicon computers, as opposed to a complete platform shift, as DNA, optical, or quantum computing would be. However, the other technologies (DNA, optical, and quantum) have the potential to provide enormous increases in computing power and their potential should not be disregarded. DNA, quantum, and optical computers would most likely be developed as non-Boolean computers, meaning that new programming and algorithms would need to be developed to run these machines. These computers may be limited to very specific problems.[678] These technologies are too low a Technology Readiness Level (TRL) to predict metrics, such as mass, power consumption, and tolerance of space environments. Some forms of computing, such as those involving carbon nanotubes, may be inherently radiation hardened.

These new computing platforms still need software to be helpful. There are several major hurdles to overcome in the area of software engineering to make that possible. Cost-effective development, reliability, and robustness of software-intensive systems are big concerns. Progress in the following areas is needed: automated verification and validation (V&V), self-writing software, higher levels of automation and artificial intelligence (AI), fault-tolerant software, and software that can efficiently leverage multi-core/parallel-processing computers. These are all difficult problems and ones that are receiving a significant amount of funding and research at all levels of government, academia, and industry. Some of the solutions will likely be specific to terrestrial applications, and therefore the space industry would need to adapt the technologies to its own unique purposes.

Technological advances in the field of Information Technology (IT) tend to speed up further technological advances, creating a ‘virtuous cycle’ of scientific discovery and progress.[679] The term ‘virtuous cycle’ describes a cycle of events that reinforces itself through a feedback loop and has beneficial results. In this virtuous cycle, advancements in IT lead to more knowledge, which in turn leads to innovation and eventually to further advancements in IT. With this exponential increase in speed of technological development and scientific discovery, it is not unreasonable to expect that any of these computing technologies will be available for 2050. The more important question is if and how these computers could be leveraged to support human space exploration.

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SEAMLESS HUMAN-COMPUTER INTERACTION

Virtual, neural, and intelligent interfaces to enable information-rich exploration

SEAMLESS HUMAN-COMPUTER INTERACTION

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Virtual, neural, and intelligent interfaces to enable information-rich exploration

Currently, major mission management operations are carried out by large groups of ground control operators supporting the crewmembers. These ground personnel perform crucial functions such as failure detection, recovery, flight planning and re-planning in event of a failure or unforeseen circumstance. This approach presents several challenges with operational cost, safety, reliability, and communication delays. To address these challenges and support more advanced space exploration, NASA needs to develop technologies that allow the crew a greater level of autonomy. [680] This challenge will increase as space exploration systems become more complex and travel farther from Earth.

> **BREAKTHROUGH**
> Human-computer interfaces enable crew to view data and control machinery in seamless and intuitive ways. Astronauts and mission control personnel enjoy immediate access to data to inform decision-making processes. Complex tasks are negotiated with ease, and vast amounts of data processed and digested rapidly.

This breakthrough capability encompasses a future where sophisticated human-computer interfaces (HCIs) enable crew to view data and control machinery in seamless and intuitive ways. Operators control computers and machines through neural interfaces, virtual environments, and near-to-eye displays. Astronauts and mission control personnel enjoy immediate access to information to aid decision-making processes. Very complex tasks are negotiated with ease, and vast amounts of data are processed and digested rapidly. New interfaces blend virtual and real sensory information and allow hands-free interfaces with speech recognition, eye-gaze detection, and brain-machine interfaces. Intelligent software agents enable these interfaces to act as personal assistants to the crew. These capabilities augment and enhance human exploration of space, and they provide humans in remote locations a virtual presence during robotic exploration. Virtual reality is also used on Earth for training purposes, public outreach, gaming, science, and exploration.

This capability impacts human space exploration in a number of ways. It enables the monitoring and control needed to support increasingly complex exploration systems of the future. This capability increases safety, reliability, and efficiency, because it allows for autonomous or semi-autonomous fault detection, repairs, and missions re-planning. This capability also reduces the crew's reliance on ground control, which reduces the number of ground support operators needed and bypasses problems of communication delays in time-sensitive situations. This benefit would reduce mission overhead cost and improve crew safety. New HCI technologies could also increase the amount and the quality of science that is performed in space by combining the advantages of human and robotic exploration. Virtual exploration could be a powerful public outreach tool. New HCI technologies can also be used to help promote the emotional well-being of crewmembers, by providing a means for entertainment, escapism, and communication with home. HCI can also reduce crewmembers' frustration by facilitating a number of tasks through affective interfaces (interfaces that can perceive, mimic, and respond to human emotion).

HCI is a field that transforms rapidly and continuously. In the next forty years, the development of pervasive sensing networks and smarter machines will change the nature of human-computer interaction, presenting many new challenges. A future of pervasive wireless sensor networks, significantly increased processing power, and more intelligent machines presents tremendous potential for acquiring, processing, and using information in ways we can barely imagine now. Computers and sensors will be much more prevalent and will be involved in many aspects of our daily lives. This future comes with many questions. How will humans interact with such a mind-boggling amount of data? If machines are autonomous or semi-autonomous, how can humans retain adequate control and understanding of our environments? If computers are modeling and simulating complex problems, do we implicitly trust their results? Or have we simply created another problem to understand?[681] We will be living in a complex "computational ecosystem" that could potentially be confusing and unpredictable. As devices are more interconnected, they could act in unintended ways. Will humans be able to understand and navigate this environment?[682] Beyond these questions, there are also many concerns related to security, privacy, and ethics.[683]

Answering these questions will involve a re-imagining of what HCI means. In the future, the computers around us will no longer look like personal computers. We will be changing our definition of what "interaction" means.[684] We will have interactive environments—devices that can sense and compute will be embedded in our environments, we will be able to interact with them, and they will be able to respond to changes and activities going on in the environment.[685] Advances in cognitive psychology as well as technological advances will be needed to address these questions.

Related Capability Areas

This breakthrough capability is related to many of the other breakthrough capabilities in this report. Below are the most closely related breakthrough capabilities.

- **Environmental Omniscience –** Pervasive wireless sensor networks will require interfaces that comprehensively yet clearly depict the output of all data gathered (information) and help the operator respond to the environmental data in the best way possible.

- **Everyday Supercomputing –** Some HCI systems and devices will require more processing power than is currently available onboard.

- **Super Humans –** Some implanted devices overlap the areas of human augmentation and seamless HCI. For the purposes of this report, technologies that enhance human abilities are grouped into Super Humans, but technologies that simply allow a human to have better access to a computer's ability are in HCI.

- **Healthy, Happy Astronauts –** In addition to the increased safety provided by the HCI technologies in this section, these technologies also present many applications that could contribute to the emotional and physical well-being of astronauts. Some example applications include administering therapy, reducing strain, early detection and mitigation of neuropsychiatric conditions, and improving day-to-day happiness and morale.

Supporting Technology Concepts

The following sections describe the supporting technology concepts that may contribute to realizing this capability breakthrough. These technologies are complementary to one another, and a combination of several of these technologies will be needed to achieve the capability breakthrough. Most HCI devices or systems would incorporate more than one of the technology concepts covered in this section. For example, a "smart suit" for EVA missions might combine an augmented reality (AR) display in the visor, a brain-machine interface (BMI) to allow the astronauts to have hands-free access to relevant data, and an intelligent software agent that would analyze the landscape and alert the astronaut to points of interest. The following concepts are based on open-source research, workshops with subject matter experts, and individual interviews.

Supporting Technology Concepts	
Augmented Reality (AR)	The incorporation of virtual elements into a real environment.
Virtual Reality (VR)	The creation of a virtual environment for the user.
Simulated Reality	The creation of a completely immersive virtual environment for the user.
Brain-Machine Interface (BMI)	Monitors the user's neurons and interprets their signals.
Intelligent Interface	Has some level of intelligence in order to assist the user.

Augmented Reality (AR)

In the broadest terms, augmented reality describes the combination of virtual elements and a real environment. Most often, AR describes technologies that augment a person's vision with computer-generated imagery and information. Human vision is overlaid with synchronized computer-generated information in real time (typically on a 2-D screen, head-mounted device, or beamed onto the retina) to improve human interaction with the surrounding environment.[686] This information could be geological information about a planetary surface, maintenance instructions for a piece of hardware, or any other type of data that would help the astronaut with his or her task.

AR is most commonly implemented through a head-mounted display (HMD). HMDs vary in size and weight. Some are built into large helmets like those designed for military pilots, while others are very small and lightweight. [687] For example, AR eyeglasses made by the company Lumus are similar in appearance, size, and weight to standard sunglasses. The glasses use a technology called virtual retina display (VRD) to beam imagery directly onto the retina of the viewer. This creates the illusion of viewing very large, high-resolution displays with a field of view greater than 120 degrees.[688] The displays are see-through to allow the user to retain situational awareness when viewing content.[689] This enables the user to "perform other tasks while maintaining constant hands-free connectivity to critical information."[690] A researcher at the University of Washington is building a similar technology into contact lenses.[691]

PARTNERING OPPORTUNITES

AUGMENTED REALITY

- AR Eye Glasses: Lumus
- AR Contact Lenses: University of Washington
- Geology Smart-Suit: Dr. Patrick McGuire, University of Chicago, the Center for Astrobiology in Madrid
- Haptic Devices for Pilots, BrainPort: Florida Institute for Human and Machine Cognition (IHMC), U.S. Navy, Department of Defense
- Anywhere AR: University of California in Santa Barbara
- Space-Rated AR systems: Boeing and Space Applications
- AR for Car Repair Assistance: BMW

In one example of AR, being developed for space applications, scientists have developed a geology smart-suit in which geological information about the landscape is incorporated into a display on the suit visor. This display allows astronauts to see their environment overlaid with computer-generated geological information.[692] This "smart suit" system also involves the technology of intelligent interface, discussed later in this chapter. (See page 212.)

Traditionally, AR refers to computer-generated visual information being overlaid on human vision. However, there are some forms of AR that leverage haptic technology. Haptics is the science of touch, and the term describes interfaces that allow people to feel virtual objects (such as a touchable hologram, explained in more detail on page 208), as well as interfaces that communicate with the user through touch (such as a system that guides the user through a physical motion, like a brushstroke). Haptic devices currently come in many forms. Gloves and handheld devices are the most common, although haptic technology can be leveraged in many other types of devices, such as steering wheels, clothing, or even flooring.[693] The advantage of using such devices is that they provide alternative or additional modes of communication to traditional audio and visual interfaces.

Organizations such as NASA, the U.S. Navy, and the Florida Institute for Human and Machine Cognition (IHMC) have researched and developed haptic systems to help pilots operate helicopters, fixed-wing crafts, and spacecrafts, and to help crewmembers perform extravehicular activities. These systems usually take the form of a vest that is covered with an array of transducers that deliver haptic feedback to the pilot's body. Research shows that haptic cues about orientation and movement help pilots avoid disorientation and improve their performance. Haptic systems have also been developed to assist people in driving cars[694] and to allow visually impaired people to interact with the environment by feeling objects at a distance, such as a doorway, curb, or furniture.[695] Another haptic system consists of a thimble-like device that can be inserted into a glove and used to communicate alphanumeric characters to the fingertip using a form of tactile illusion.[696]

Haptic interfaces also have a wide range of applications in the commercial world, including virtual assembly, virtual prototyping, maintenance path planning, teleoperation, molecular modeling, surgery, driving, and animation.[697] Haptic devices present great potential as training tools. Researchers are testing systems that train users with a combination of haptic and visual cues. Studies have shown that incorporating the sense of touch into audio and visual training tools decreases learning time and increases the subject's retention of the information.[698]

Another example of a nontraditional AR device is the tongue-mounted device called the "Brain Port," which converts light into electrical impulses that stimulate the tongue. The brain interprets these electrical impulses as visual information, allowing people to see with their tongues instead of their eyes. The Department of Defense is providing funding to the Florida IHMC to adapt this technology to military uses. Researchers hope that the Brain Port may be able to assist soldiers in low-visibility environments by providing 360-degree infrared vision, night vision, and sonar vision.[699] Similar technologies are discussed in greater detail in Super Humans. (See page 82.)

There are several near-term technological hurdles facing AR. Improvements in eye-gaze detection and speech recognition are needed to enable some hands-free AR systems.[700] Improvements in the reliability of speech recognition are needed for that technology to be trusted in mission-critical or life-critical situations. Also, current HMD systems produce unacceptable levels of eye stress.[701] Most commercial developers are concerned with bringing down the cost of AR devices and making AR devices smaller, lighter, more comfortable, and aesthetically pleasing.

Some adaptation of AR would be needed for use in space exploration. Power dissipation would need to be minimized for suit systems.[702] Systems would likely require more processing power than is currently available onboard.[703] For space exploration, all components must be radiation-tolerant and designed to operate in a vacuum environment. Several companies, including Boeing and Space Applications, are working internally on the development of space-rated AR systems.[704]

Another forward step for AR would be the ability to use AR anywhere, including arbitrary environments without preparation. Today, most AR systems rely on environments that have been prepared in some way, either by modeling the environment or by installing markers and instrumentation. However, the prepping processes needed for this type of AR could be costly and time-consuming for large habitats and EVA (increasing mission overhead) and could constrain the use of AR.[705] A team of researchers at the University of California in Santa Barbara is working to solve this problem, by developing a type of AR that they have termed, "Anywhere Augmentation." This form of AR combines wearable computing with AR to create reliable and robust systems that can function in unprepared environments.[706]

With both visual and haptic AR systems, there is concern that the user may become overwhelmed or confused by the information he or she is receiving. This issue is explored more in Technology Trajectory, page 213.

Virtual Reality (VR)

Virtual reality includes a suite of technologies that use virtual sensory information to create an immersive virtual environment for the user. The term "virtual reality" is often applied to systems with greatly varying levels of immersion and sensory integration. VR is often used to describe online worlds such as Second Life, in which the user operates an avatar in a 3-D world, from a traditional 2-D monitor. However, the prevalent understanding of VR describes a system that is more immersive than a 2-D screen and conventional computer speakers. Some VR systems are as simple as a head-mounted device, while others consist of an entire room, or even specialized equipment such as a tank to simulate low-gravity environments. Researchers have also developed technologies that allow the user to physically wander through a virtual room using systems such as an omni-directional treadmill or a rotating sphere.[707]

> **PARTNERING OPPORTUNITES**
>
> **VIRTUAL REALITY**
>
> - VR and Telepresence: Keio University Graduate School of Media Design (KMD), Tach Lab
> - VR for Plant Planning and Operation: Fraunhofer Institute for Factory Operation and Automation IFF, Magdeburg
> - VR for Safety and Training: National Institute for Occupational Safety and Health (NIOSH)
> - Virtual Smells: NTT Com, Japan
> - Haptic Flooring: McGill University, Montreal
> - Airborne Ultrasound Tactile Display: University of Tokyo
> - Virtual Reality Applications Center, Iowa State University

VR has many applications that are relevant to design, training, operations, and maintenance of complex systems that could be analogous to future space exploration systems. For example, safety scientists at the National Institute for Occupational Safety and Health (NIOSH) are using VR to prevent dangerous accidents by studying users navigating a virtual construction site. They also use the virtual construction site to train users how to prevent falls and how to regain their balance if they are about to fall.[708] In another example, a collection of European institutes and vocational schools are using VR to train engineers how to operate complicated machinery for tasks such as turning, drilling, and milling.[709] The VR system both teaches and evaluates the students and allows them to get hands-on experience with complicated machinery without needing access to the real machines. Researchers from the Fraunhofer Institute for Factory Operation and Automation IFF in Magdeburg are also developing a system that uses VR to visualize operations in energy conversion plants. The system visualizes all motion sequences of fluids and gases moving through the plant and can alert users to potential weak points in the system, potential collisions, and inefficiencies. Developers plan to include all plant documentation in the system, so that if a user needs data on a certain component, he or she can simply select the visual representation of the component, instead of searching through instruction manuals. Another benefit of this system is that it allows employees to begin training on plant operations before the plant is even built.[710] These are examples of VR being used to help people maintain and operate complex and potentially dangerous systems. This technology could perhaps be used in similar ways to support training and operations for environments like space stations, habitats, rovers, and crafts.

Most current VR technologies focus on the senses of sight and sound. Integrating all five senses is a challenge but has potential to create a more immersive experience. There are several groups working on this problem commercially and in academia. For example, a team of British academics from York and Warwick universities are developing a head-mounted device called a "Virtual Cocoon" to simulate all five senses. The researchers are incorporating the work of cognitive neuroscientists to deliver the right amount of detail to each sense. [711] Researchers need to be aware of crossmodal effects—how the various sensory input streams affect one another—to create environments that are efficient and immersive.

In Japan, an academic, multi-disciplinary research effort is under way to improve virtual smell technology. Specifically, research is being conducted to develop an olfactory display system that releases specific concentrations of odor molecules to create the illusion that the intensity of the smell changes as the user virtually moves closer or farther from the virtual source of the smell.[712] Also, the Japanese telecom and network services company, NTT Com, is developing a scent system that can produce a variety of smells designed to influence the consumer experience and increase profits. The company is currently testing this product in stores, hotels, movie theaters, and restaurants and has plans to integrate the technology with an internet-based service and cell phones.[713]

Touch is another sensory modality that is being incorporated into VR. Haptic interfaces have already been covered to some extent under the AR section earlier in this chapter. However, there are several more haptic interfaces that have applications within a virtual environment. For example, researchers at McGill University in Montreal, Canada have developed a modular floor tiling system that can simulate the feeling of walking on a variety of different surfaces, such as snow, grass, or pebbles.[714] Another example is a system called Airborne Ultrasound Tactile Display, which is being developed by researchers at the University of Tokyo. This system uses ultrasound to provide haptic feedback from 3-D floating holograms; a user can touch and feel the hologram with his or her bare hands.[715]

Tachi Lab at the Keio University Graduate School of Media Design (KMD) in Japan is using haptics as part of an affective interface for long distance emotional communication. They have developed haptic devices worn on the torso that can simulate the feel of a hug or emit a heartbeat, with different pulses designed to evoke different feelings in the user.[716] (These interfaces are discussed in more detail in Healthy, Happy Astronauts, page 66.)

There are some technological hurdles to overcome in the field of VR. Bringing down the size and the cost of VR systems are perhaps the biggest challenges facing developers. However, the supporting technologies of VR continually improve, and the applications of VR are being explored and refined by industry, academia, and government. The experts at TechCast, a forecasting think-tank, estimate that VR will be used by 30% of the public by 2018.[717]

A space-specific hurdle is that some virtual reality environments may rely on a wealth of data from sensors and cameras. Storing, transmitting, and processing this data may be more difficult in space than on the earth. Advances in processing power, storage, and communications will probably be needed to realize VR in space.

Simulated Reality

Simulated reality goes a step beyond VR by creating a reality that is indistinguishable from real experiences. Theoretically, this simulated reality would be so completely immersive that the user would be unaware that he or she was using a simulated reality interface. The technologies that could achieve this state would work directly on the brain itself, blocking real sensory input and replacing it with simulated input on the level of individual neurons. The candidate technologies for this capability are ultrasound, optogenetics, and transcranial magnetic stimulation (TMS).[2]

PARTNERING OPPORTUNITES

SIMULATED REALITY

- Ultrasound for Entertainment: Sony
- Ultrasound for Diagnostics and Therapy: William "Jamie" Tyler, Arizona State University
- Optogenetics: Karl Deisseroth, Stanford University

In 2005, Sony patented the idea of manipulating neurons using ultrasound to transmit sensory information directly to the brain, creating a simulated reality for entertainment. The patent is based on a theory rather than an invention, and there is no publicly available information on Sony's research in this area.[718] However, some current research in academia suggests that Sony's theory may be valid and that ultrasound may provide a non-invasive alternative to implanted electrodes and fiber optics. This technology is being developed by a team of scientists led by William "Jamie" Tyler, a neuroscientist at Arizona State University. Tyler's team successfully used ultrasound to stimulate action potentials and drive intact brain activity in mice with millimeter spatial resolution and without using any surgery. The procedure appears to be safe for mice and flies, although there has not yet been any human testing. The immediate goal of Tyler's research is to develop ways to use ultrasound to diagnose and treat brain dysfunctions. Ultrasound may also be able to enhance cognitive function and treat cognitive disabilities, such as mental retardation or Alzheimer's disease. Tyler speculates that someday in the future ultrasound may be used as a brain-machine interface for entertainment and communication: "Maybe the next generation of social entertainment networks will involve downloading customized information or experiences from personalized computer clouds while encoding them into the brain using ultrasound. I see no reason to rule out that possibility."[719]

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[2] Some futurists, including Raymond Kurzweil, predict that nanorobotic technology will achieve this capability. However there is no current research on this, and so it is not discussed in this report. For more discussion see: http://www.good.is/post/going-down-the-rabbit-hole/

Another candidate technology for achieving simulated reality is currently emerging in the field of optogenetics. This technology involves putting photosensitive proteins in the membrane of the user's brain cells. These photosensitive proteins are then manipulated by laser beams, which are delivered to the brain through implanted fiber optics. A blue laser causes the proteins to rush positive ions into the cell, turning it on. A yellow light causes negative ions to rush into the cell, turning it off. This process allows scientists to specifically target individual neurons and to control them with millisecond precision. This process is a significant improvement over conventional electrodes, which are not nearly so precise. In the near-term, researchers hope to use this technology to treat depression, narcolepsy, and Parkinson's disease, but in the far-term this technology theoretically could be leveraged to create a simulated reality.[720]

A third candidate technology for achieving simulated reality is transcranial magnetic stimulation (TMS). TMS involves using electromagnetic induction to stimulate weak electric currents in specific areas of the brain. This method is non-invasive and causes less discomfort than the use of direct electric currents. Transcranial magnetic stimulation (TMS) is currently available as a treatment for depression. The procedure is non-invasive, and the immediate side effects are generally mild; however, the long-term effects are not yet known.[721] TMS may not be able to target specific neurons with as much precision as ultrasound and optogenetics, and therefore may not be as likely a candidate for achieving simulated reality. However, some researchers, most notably Michael Persinger (of Laurentian University, Canada), claim that TMS can be used to induce powerful spiritual feelings in patients. Patients undergoing TMS have reported feeling that there was another presence in the room or feeling a unity with God or the universe. These claims have been met with a great deal of skepticism, however, TMS remains an attractive option because of its noninvasive nature and its apparent safety.

Currently all of these technologies are being developed for purposes of diagnostics and therapy. Although no one is yet developing them to create simulated realities, experts are hopeful that they can someday be used for that purpose. In addition to the potential serious health concerns posed by manipulating neurons, there are major ethical and philosophical concerns surrounding these technologies. For example, the optogenetics researcher William Tyler speculates that ultrasound could be used to implant false memories in people.[722]

Brain-Machine Interface (BMI)

Also known as brain-computer or neural interface, this interface monitors the user's neurons and interprets their signals. This provides hands-free control of machinery and software and access to information. Most current BMI technologies can be characterized as either non-invasive devices (such as skullcaps) or invasive devices (such as implanted electrodes). The technologies covered in Simulated Reality also technically classify as BMIs, however, the term "Brain-Machine Interface" is typically only used to refer to nearer-term technologies like skullcaps or implanted electrodes.

BMI technology has improved greatly over the years. Much of the research and development in BMIs is targeted towards helping individuals who have limited motor control (typically from disease, loss of limbs, or spinal cord damage). This technology has allowed amputees to do tasks such as controlling robotic limbs, driving motorized wheelchairs, and typing using only their minds. BMI interfaces are unique in that their operation is independent of the user's physical ability. They have no manual component and therefore could be a very useful technology in space environments, where manual interfaces can be difficult to operate due to factors such as microgravity or bulky suits. BMIs could allow astronauts to perform just as efficiently in space as on earth.[723]

PARTNERING OPPORTUNITES

BRAIN-MACHINE INTERFACE (BMI)

- BMI Games: Neurosky, Emotiv
- BMI-Controlled Limbs with Haptic Feedback: DARPA and University of Florida, Institute for Human & Machine Cognition (IHMC)
- BMI-Controlled Robot: Honda Research Institute
- BrainGate: Cyberkinetics

BMI is beginning to emerge as a technology for entertainment and gaming. Companies such as Neurosky and Emotiv produce and sell computer games and toys that leverage BMI technology.[724] These BMI-powered computer games allow the user to play the game through thought. The Emotiv system can even detect the user's facial expression and therefore infer the user's emotions. This allows the game to respond to the user's emotional state.[725] This type of affective computing could be relevant to promoting crew well-being. BMI can also be used to monitor crew health through the detection of neuropsychiatric conditions before they become problems.[726]

BMI is often incorporated with other technologies presented in this chapter. For example, DARPA is combining a haptic interface with BMI to provide haptic feedback (including temperature, pressure, and vibration) for objects grasped in a BMI-controlled robotic arm.[727] This combination of haptic feedback and BMI could enhance teleoperation.

Research and testing is needed to better understand the applications and requirements of neural interfaces in space environments. Space environments may pose complications that are not present in terrestrial applications. For example, studies on the International Space Station have shown that astronauts' main brain rhythm and main motor cortical rhythm change in response to time spent in space environments. It is unknown how this might affect the operability of BMIs.[728] Also, postural movements that astronauts make to keep a stable position in microgravity produce brain signals that could interfere with the BMI.[729] These are just a few examples of how BMIs may require additional research driven by space requirements.[730]

BMI technologies can be characterized as either non-invasive devices such as skull caps or invasive devices, typically implanted electrodes; however, in the future we can expect a variety of new technologies such as TMS, ultrasound, optogenetics, and nanomachines. These new technologies will probably have greater precision in speed and targeting neurons than traditional electrode technologies. The experts at TechCast estimate that BMI will be commercially available and used to communicate with distant objects and people by 2023.[731]

Intelligent Interface

Intelligent interface is a term that communicates ideas, techniques, and goals, rather than specific devices or software. An intelligent interface has two characteristics. The first is that the interface has some level of intelligence about the task it is intended to perform. It actively assists the user in performing a task, rather than being a mere tool. The second characteristic of an intelligent interface is that it must be intuitive, user-friendly, and effective.[732] An intelligent interface is naturally easy to use through the integration of technologies like natural language processing, gesture recognition, eye tracking, and BMI. An intelligent interface may also have the ability to adapt to the user's needs and capabilities, to interpret user intent, and to respond to the user's emotions. These capabilities could lead to personalized computer assistants for each crewmember. Intelligent interfaces can be used in any type of device. Examples include a software assistant that can assess problems and suggest solutions, a haptic guidance system in a car steering wheel, and a head-mounted display in a spacesuit that suggests to the explorer potential points of interest on the landscape. Intelligent interface technologies have the potential to overlap with all of the other technology concepts in this breakthrough capability.

PARTNERING OPPORTUNITES

INTELLIGENT INTERFACE

- Intelligent/Affective Interfaces: Keio University Graduate School of Media Design (KMD), Tach Lab
- Geology Smart-Suit: Dr. Patrick McGuire, University of Chicago, the Center for Astrobiology in Madrid
- Mission Executive Crew Assistant: European Space Agency

One example of an intelligent interface currently being designed to support space operations is MECA (Mission Execution Crew Assistant), which is funded by the European Space Agency. The goal of MECA is to develop software that acts as an Astronaut's Digital Assistant (ADA), to assist the astronauts and support the collaboration of human-machine teams in space operations. The ADA is intended to function in a ubiquitous computing environment and to communicate autonomously with systems such as Integrated Systems Health Management (ISHM). (For more information on Ubiquitous Computing see page 186 and for ISHM see page 222.) In one example scenario, the ADA learns from ISHM that a piece of equipment is about to fail. The ADA assesses the problem, determines the repair plan, and alerts the crew. If crew intervention is required, the ADA collaborates with the crew to re-plan and reschedule crew operations. MECA would be able to adapt to crewmembers, becoming a personalized assistant. The MECA project is currently in the stage of defining system requirements and developing prototypes for proof of concept. The MECA team plans to implement their requirements using emerging technologies in the areas of artificial intelligence, automated scheduling and planning, and model-based health management.[733] Several other systems similar to MECA have been envisioned and presented in aerospace conferences and journals.

Another example of an intelligent interface for space exploration is the geology smart-suit, which displays geological information about the landscape on the suit visor. This display uses AR to allow astronauts to see their environment overlaid with computer-generated geological information. This system is intelligent enough to identify points of interest on the landscape. The system learns and adapts constantly as the mission is executed.[734] This type of intelligence can also be applied to autonomous or semi-autonomous rovers to help them collect the most interesting images and samples and to prioritize the analysis of data after collection is complete.[735]

The development of intelligent interface technology (or interfaces) is a multi-disciplinary challenge that touches upon the fields of artificial intelligence, user modeling, natural language processing, and cognitive psychology. The experts at TechCast estimate that people will use intelligent interfaces to complete 30% of routine tasks by 2016. TechCast experts also predict that the enabling technologies for intelligent interface (natural language processing, gesture recognition, eye tracking, BMI, AR, and AI) will be commercially available in the 2015-2023 timeframe. Intelligent interfaces will improve and have new capabilities as these supporting technologies mature. AI is perhaps the most challenging component technology, and skepticism about AI may make some wary of placing too much responsibility on intelligent interface. (For more information on AI, see “Intelligent Systems and ISHM,” in Crosscutting Technologies, page 222.)

Technology Trajectory

The future holds unprecedented amounts of data and processing power. This will present new challenges in the field of HCI. Interfaces will need to be able to alert the user to all of the relevant information and make the non-relevant data unobtrusive, so that the user is not overwhelmed. Intelligent and semi-autonomous interfaces will need to support clear, bi-directional communication, so that users can still make their own decisions and not be distracted, confused, or thwarted by autonomous or semi-autonomous interfaces in their environment.[736]

All of the technologies presented in this chapter are being rapidly developed with commercial, academic, and government funding. Key areas of development are defense, entertainment (video games), and medicine. Many of the technologies presented in this section could be used as assistive technologies to people with disabilities. Each technology concept, with the exception of simulated reality, has some product or system that is commercially available.

We can expect many advances and changes in the field of HCI in the 2050 timeline. The history of HCI shows that dramatic paradigm shifts can happen over a 40-year time span. However, specific advances are difficult to predict. Some technologies, such as the graphical user interfaces and touch screens, have enjoyed rapid advancement and widespread acceptance. Meanwhile, other technologies have been stagnant, such as the standard keyboard configuration (QWERTY), which has not changed in many years, despite being challenged several times.

All of these technologies will need to be adapted for use in space exploration. The effects of radiation and microgravity on these technologies are not yet understood. Also, these interfaces are designed for terrestrial application and will need to be adapted to the unique environment and tasks of space exploration. These technologies must also be supported by a higher level of computing power than is currently available onboard spacecraft.

Software is a key hurdle in each of the technologies presented in this section. Challenges and requirements relating to software are discussed in Everyday Supercomputing, "Technology Trajectory," page 199.

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CROSS-CUTTING TECHNOLOGIES

Reaching Across Technological Boundaries

CROSS-CUTTING TECHNOLOGIES

CROSSCUTTING TECHNOLOGIES

Throughout the workshops, interviews, and research that supported this report, technologies were consistently mentioned as potential or even necessary components of multiple breakthrough capabilities. Several technology themes emerged time and again as areas of research that cut across all or most of the breakthrough capabilities. These crosscutting technologies are not capability-specific, but have the potential to dramatically impact each of the breakthrough capabilities. These technologies include components and subsystems of technology concepts that span multiple breakthrough capabilities. Examples of crosscutting technologies include carbon nanotubes; systems to generate and control high-energy-density plasmas; and intelligent software, hardware, and networks. Initial research and development for crosscutting technologies are application-agnostic. Consequently, breakthroughs in these technologies could affect many different systems. It is also difficult to anticipate the magnitude of these breakthroughs. However, the overall importance of these technologies is apparent in the range of applications they may support.

In each of the breakthrough capability chapters, crosscutting technologies were referenced as enabling or enhancing technologies or technology hurdles that need to be overcome to enable the breakthrough capability. This chapter discusses some of the most referenced breakthrough crosscutting technologies, provides insight into how they can affect the thirteen breakthrough capabilities, and highlights some of the current research that could lead to a technology breakthrough.

Crosscutting Technologies	
High-Strength Materials	Includes metals, ceramics, plastics, fibers, cloth, concrete, glass, glues, or other substances that exhibit characteristics such as high specific strength, toughness, hardness, wear-resistance, and durability.
High-Temperature Materials	Materials used for applications that routinely operate at temperatures above 500 degrees C. For space applications, "high temperature" can refer to temperatures within a nuclear reactor, inside of a plasma chamber, during close approaches to the sun, and other extreme thermal environments.
Intelligent Systems and ISHM	Systems that use learning and decision-making capabilities to adapt their behavior to complex, rapidly-changing environments.
Low-Temperature Mechanisms	Mechanisms that can operate reliably and efficiently at temperatures as low as -230 C.
Nanotubes	Hollow, cylindrical structures with small diameters, on the order of a few nanometers, but can have length-to-diameter ratios of more than one hundred million to one; possess a variety of potentially useful characteristics depending on their molecular structure and composition.
Plasma Technologies	Technologies that manipulate, control, and use the fourth

	state of matter, ionized gases known as plasmas. Plasmas have unique characteristics that enable primary systems, including propulsion, energy generation, shielding, and sensors.
Smart Materials	Includes several different classes of materials that have controllable reactive properties, including conductivity, tension, or volume, and respond to specific stimuli such as electric or magnetic fields, heat, or light.
Synthetic Biology	A young field characterized by the use of DNA engineering for the creation of novel organisms and technologies.
Thermal Management	Systems that transport thermal energy from areas with excess heat or to areas that require additional heat. With thermal management, damaging or dangerous thermal energy can be mitigated by either removing it or scavenging some portion for usable energy.

High-Strength Materials

High-strength materials include metals, ceramics, plastics, fibers, cloth, concrete, glass, glues, or other substances that exhibit characteristics such as high specific strength, toughness, hardness, wear-resistance, and durability. High-strength metals and ceramics are designed to combine resistance to deformation with resistance to fracture, while high-strength fibers are developed to minimize tearing or fraying. Other high-strength materials may involve adding components to the fabrication process, including carbon fibers or polymer adhesives, resulting in more durable materials.

High-strength materials (HSM) could be useful in countless space applications, cutting across a variety of elements in an exploration campaign. High-strength, lightweight metals and ceramics are ideal for constructing structural members, fairings, or propellant tanks for spacecraft, while ropes or cables made from high-strength fibers could enable long space tethers. High-strength concrete technologies would be useful in building Lunar or Martian structures from regolith, high-strength glass or polymers might allow for large windows on pressurized spacecraft or space stations, and high-strength cloth could provide protection for satellites and spacecraft against micrometeoroid strikes or allow for stronger, more mobile spacesuits.

One current trend in HSM research is the fabrication of new materials based on biomimetic principles. This involves the study of biological substances that display desired characteristics, and then duplicating or enhancing these structures with synthetic materials. Examples of this practice can be seen in the design of high-strength ceramics that imitate the structure of bone, tooth enamel, or nacre (also known as mother-of-pearl),[737] or fibers with the characteristics of silk.[738] These materials are carefully studied to understand exactly how they are able to exhibit their unusually durable properties, and then the materials are imitated using synthetic components to replace their biological counterparts. For example, instead of replicating the calcium carbonate and protein glue that constitute nacre, a new ceramic might use aluminum oxide or carbon held together with a polymer but arranged in the same structural geometry found in the shell material.

Another current area of research involves the design of materials with nanoscale structures. Ceramics, fabrics, plastics, and paints are being developed using nanoparticles or nanotubes arranged in exacting geometries to impart their strength characteristics from the nano to the macro scale.[739] The process requires extreme precision, as a small number of defects at the nano level can have a disproportionate weakening effect on the larger product, erasing any benefit in structural integrity.[740]

Currently, processes for fabricating materials out of precise nanostructures involve mixing nanoparticles and adherents in a solution and then extracting them chemically or through laborious physical techniques.[741] This requires long timeframes for the production of very small amounts of material. Quality assurance of the final product can also be problematic. Until these issues are resolved, large-scale production of nanoparticle materials is unlikely.

A promising field in the study of HSM involves processing materials, including alloys, ceramics, glass, and composites, in a microgravity environment. The formation of a material that requires heating to a liquid state can be affected by a gravitational pull on fluid flows, causing flaws in the atomic structure of the material as it cools and hardens. Processing such material in a microgravity environment can alleviate uneven flow, reducing the potential for misalignment in the structure. Other materials, particularly ceramics and glasses, may be susceptible to contamination from the containers in which they are processed. A microgravity environment might allow for manipulation of the material without the need for a container.[742]

While the bulk of the work in HSM is conducted within the disciplines of materials science, engineering, physics, and chemistry, contributions have been made from fields as diverse as biology, genetics, and computer science. As a result, there are overlaps of study between high-strength materials and other crosscutting technologies. Examples include synthetic biology, involving self-organizing construction principles, and low-temperature mechanisms, which require materials resistant to shattering under extreme cooling. The study of nanotubes is important in the development of high-strength materials, high-temperature materials, and smart materials technologies, providing further overlap in efforts.

Prominent locations for HSM work in the United States include materials science departments at many research laboratories and universities, including MIT, Northwestern, and Cornell, the Material Science and Technology Division housed at the Oak Ridge National Laboratory, the Structures and Materials Division at NASA Glenn Research Center, The Microgravity Research Program Office at NASA Marshall Space Flight Center, the Materials and Manufacturing Directorate at the Air Force Research Laboratory, the Weapons and Materials Research Directorate at the Army Research Laboratory, and the Materials Science and Component Technology Directorate at the Naval Research Laboratory.

High-strength materials could offer benefits to many technologies within the breakthrough capabilities study:

- **Healthy, Happy Astronauts**
  - HSM could be used to construct a spacecraft that uses artificial gravity.
- **Super Humans**
  - HSM could be used to construct exo-skeletons.
- **Ubiquitous Access to Abundant Power**
  - HSM might be used to produce dense casing material in an antiproton-driven fusion device.
- **Easy Access to Space**
  - HSM could be used in construction of skyhooks and space elevators.
- **Efficient Interplanetary Travel**
  - HSM might be used for tethers.
- **Go-Anywhere Roving**
  - HSM fabric could be used in the construction of mechanical counter pressure suits.
- **Living Off The Land**
  - HSM alloys could provide durable drill bits for autonomous mining technologies.
- **On-Demand Manufacturing**
  - These technologies could be used to manufacture HSM.
- **Self-Sustaining Habitats**
  - The processes needed to make nanoparticle HSM could also be used to produce carbon nanotube membranes.
- **Space Oasis**
  - HSM could be used to produce propellant tanks for in-orbit propellant transfer and storage.
- **Environmental Omniscience**
  - The biomimetic principles used to produce some HSM might also inform the construction of biomimetic sensors.

High-Temperature Materials

High-temperature materials are generally defined as materials used for applications that routinely operate at temperatures above 500 degrees C, though some of these materials operate at temperatures many times hotter. More specific definitions for “high temperature” include temperatures above two-thirds the melting point of a solid, or the point at which extrapolating physical properties from room temperature behavior is not possible.[743] For space applications, “high temperature” can refer to temperatures within a nuclear reactor, inside of a plasma chamber, during close approaches to the sun, and other extreme thermal environments. High-temperature materials often have to operate in harsh, corrosive environments, and the extreme temperatures can accelerate or enable corrosive processes.[744] High-temperature materials usually include solids like stainless steels, superalloys, refractory metals, composites, and certain ceramics, but they can also include liquids like molten salt.

Commonly used high-temperature materials include stainless steels, superalloys, and refractory metals. Stainless steels are steel alloys that include more than ten percent chromium and are extremely resistant to corrosion and oxidation. Some stainless steels, specifically austenitic steels incorporating nickel or molybdenum, retain their high strength at high temperatures but are subject to thermal expansion.[745] Superalloys are metals usually incorporating nickel, cobalt, or nickel-iron; they are particularly resistant to high-temperature creep, or deformation due to the stresses caused by extreme heat. Refractory metals are materials with melting points in excess of 2000 degrees C, including molybdenum, niobium, rhenium, tantalum, and tungsten. The high melting points make these materials particularly resistant to the effects of heat, though it can complicate the fabrication process. These materials are currently relatively mature and are used in terrestrial applications, including nuclear reactors, turbine engines, and piping in heat exchangers. Newer materials that incorporate high-temperature metals include metal matrix composites (MMC)—a composite of metal alloys and reinforcing fibers, potentially including tungsten wires. These composites have improved structural and thermal characteristics over the base alloy.[746] For space exploration, these materials could support technologies including rocket engines, plasma chambers, and components that operate in hot, corrosive environments. Research to develop new steels, superalloys, and applications of refractory metals is primarily limited to incremental improvements for specific applications.

Ceramics are generally inorganic crystalline oxide materials. They often exhibit high strength in compression but are weak in shearing and tension and are resistant to heat and corrosion. Ceramic matrix composites (CMC), which often combine high-temperature ceramic materials with reinforcing fibers, are designed to reduce the brittleness characteristic of monolithic ceramics, potentially allowing them to replace superalloys or refractory metals in many high-temperature applications. Production of CMC involves the addition of reinforcing fibers or nanostructures, often made of carbon, silicon, or aluminum oxide, to a ceramic. CMC provide significant weight advantages over metal alloys (30-50%), while also demonstrating superior resistance to corrosion, increased toughness, and a tolerance for higher temperatures. Current ceramic composites can exceed operating temperatures of 1500 degrees C.[747] However, they are currently prohibitively expensive and do not have the same longevity of metals.[748] In addition, the thermal and structural properties of CMC materials are highly dependent on the microstructural features and consequently the quality of the design and manufacturing processes.[749] The Air Force and NASA are developing CMC materials for use in engine turbines, hypersonic vehicles, reentry heat shields, and rocket nozzles.[750] In addition, there are some commercial applications of CMC materials such as automobile brakes.[751]

New organic materials including resins and composites can also be used for high-temperature applications. NASA has developed a polyimide resin that can operate over a temperature range of about minus 100 degrees C to 1260 degrees C, more than four times hotter than most other polymer resins.[752] This resin can be used in a range of high-temperature applications and is processed as an adhesive, resin molding, coating, foam, thin film, or high-temperature fiber for use in composite materials.

Molten salts tend to have high thermal transfer characteristics and low vapor pressures, which can be beneficial for use as a coolant in a nuclear reactor. Molten Salt Reactors (MSRs) replace water with a molten salt solution, resulting in a system that can run at high temperatures without high pressure requirements. This increases efficiency while reducing risk in operations. Some MSRs mix the fuel source with the molten salt (as uranium tetrafluoride, for example), avoiding the need for any fuel fabrication. The ability to run this fuel/coolant mixture under nominal pressures negates the need for high-pressure pumps and piping, reducing the size and weight of the reactor. Furthermore, the MSR model allows for online reprocessing, which results in much longer fuel life and significantly reduced waste product.[753] Experiments were conducted at the Oak Ridge National Laboratory in the 1950s with MSRs to produce a nuclear aircraft motor,[754] and current MSRs are being planned under several international initiatives, though it is unclear as to whether they will be constructed. Molten salts can also be used in thermal transport systems for other, non-nuclear, applications.

Another thrust of high-temperature materials research is in protective coating for metal, ceramic, and composite parts. These coatings, sometimes called thermal and environmental barrier coatings, provide thermal protection to the bulk material; act as a first stage barrier to radiation; reduce absorbed heat; and can provide corrosion or chemical protection.[755] Some coatings also provide physical protection from high-speed impacts of dust or sand. These coatings are usually ceramic and can either be relatively simple in chemical structure, like boron carbide, or very complex like ZrO_2-Y_2O_3 doped with multiple rare earth oxides. Multiple manufacturing methods for thermal barrier coatings exist, and coating structure, composition, and deposition method can be tailored for specific applications.[756] Current challenges include cost-effective production and depositing even coatings without microstructural defects. Another challenge is selecting coating materials with sufficient protective capabilities that also have good adhesion to the substrate and match its thermal expansion properties. NASA, the Air Force, Oak Ridge National Laboratory, and private companies are developing thermal and environmental barrier coatings for terrestrial and space applications.[757]

In addition to ongoing research, there are some novel high-temperature materials that are commercially available. These include high-end composites and pre-formed engine components, as well as commercial epoxies, adhesives, spray-on coatings, and metal-ceramic putties for bonding or repairing engine components. Advertized operating temperatures for these products range from 200 degrees C to 1650 degrees C.[758]

High-temperature materials offer benefits to many technologies within different breakthrough capability areas:

- **Ubiquitous Access to Abundant Power**
    - High-temperature materials will be instrumental in constructing advanced nuclear reactors.
- **Easy Access to Space**

  - High-temperature materials will be crucial in building air-breathing access to space vehicles, nuclear rockets, and beamed power launch vehicles.
- **Efficient Interplanetary Travel**
  - High-temperature materials will be required for nuclear reactor and nuclear pulse propulsion systems.
- **Go-Anywhere Roving**
  - High-temperature materials will be required to build the rockets on roving hoppers.
- **Living Off The Land**
  - Molten salts may be useful for molten oxide electrolysis.
- **Space Oasis**
  - High-temperature materials may be required for components of in-orbit propellant transfer and storage devices.

Intelligent Systems and ISHM

Intelligent systems use learning and decision-making capabilities to adapt their behavior to complex, rapidly changing environments. Intelligent systems may act autonomously or semi-autonomously, requiring human interaction in some situations. Intelligent systems are currently used in industrial environments where humans and robots collaborate to complete a task. Intelligent systems reduce the workload on humans by solving simple tasks without human interaction or by helping humans identify the best solution in complex problems. This capability is attractive for space applications because of the complexity of systems and operations of space exploration missions, because communication delays could prevent the crew from receiving assistance from earth, and because a system failure could pose risks to astronaut health and safety.

Spaceflight missions collect massive amounts of sensor data, and, in current architectures, monitoring for fault detection requires that all usable data be transmitted to ground control, where a large team of experts can analyze the data. When this team of experts detects a fault, they then have to diagnose it and decide on the best course of action to restore system functionality.[759] The recovery action is either executed remotely by flight controllers on the ground or communicated to the astronauts so that they can perform the action to restore system functionality.[760] This system is enough to sustain human spaceflight in orbit or even to the Moon, but beyond these locations, data transmissions will have speed-of-light communication delays. For example, in a trip to Mars, the communication delay can last for up to 40 minutes.[761] Some faults require relatively quick responses, and those will have to be detected, diagnosed, and managed onboard, without any support from ground control.[762] A crew of a few astronauts will not have the same expert knowledge of spacecraft systems as a room full of engineers in ground control, and balancing a lack of time with a lack of sufficient knowledge could prove dangerous to the crew and the mission.[763] This challenge will be exacerbated in future space exploration missions, which will be more complex and have more sensors collecting more data requiring more instant, expert analysis.

An intelligent system can address these challenges, especially one that supports integrated systems health management (ISHM), which autonomously performs the tasks of monitoring, detecting, diagnosing, and managing system faults. While current ISHM systems exist, future ISHM systems could receive data from every sensor in the pervasive sensing network of the spacecraft or habitat.[764] This data would be continuously monitored by the ISHM system, which would intelligently analyze the data to detect, diagnose, and predict the progression of faults.[765] Some faults could be within the capabilities of the ISHM system to manage itself, and for other faults, the ISHM system would instantly alert crew or ground control to perform the correct recovery action.[766]

This crosscutting technology provides increased autonomy from ground support, allowing space exploration missions to go farther from earth, taking pressure off of the crew, and increasing safety and reliability. ISHM and other types of intelligent systems would enable some of the complex systems described in several of the breakthroughs in this report. Examples include space oases, on-demand manufacturing, reconfigurable robots, self-sustaining habitats, and autonomous or semi-autonomous rovers. Eventually, the automated operation of computers, vehicles, and habitats could eventually allow for independent design, construction, experimentation, operation, or error detection.

There are many challenges facing researchers in the field of intelligent systems. It is difficult to ensure operational success, as systems are designed to deal with unpredictable events. Also, abilities such as learning, creativity, or planning for future events are extremely difficult to replicate in artificial systems.[767] There are several major hurdles to overcome in the area of software engineering to make this technology possible. Cost-effective development, reliability, and robustness of software-intensive systems are major concerns.[768] Progress in the following areas is needed: automated verification and validation (V&V) and certification, self-writing software, radiation-hardened hardware, fault-tolerant software, automated transformation of Computer Aided Design (CAD) models into diagnostic models, long-duration machine learning, automated diagnosis and prognosis using physics-based models, automated planning and scheduling for recovery, and new interfaces to allow humans to interact with intelligent systems.[769] These are all difficult problems and are receiving funding and research on multiple levels of government, academia, and industry. Some of the solutions will likely be specific to terrestrial applications, and therefore the space industry would need to adapt the technologies to its own unique purposes.

This is a multidisciplinary field including artificial intelligence, cognitive science, computational perception, robotics, and other disciplines. Key research facilities include NASA Ames Intelligent Systems Division, JPL, NASA JSC, Stanford, Carnegie Mellon, Penn State, Georgia Institute of Technology, PARC, Boeing, Honeywell, and MIT Computer Science and Artificial Intelligence Laboratory (CSAIL).[770]

This technology is potentially applicable to any system or capability where humans, habitats, vehicles, or robots are involved, and it is enabled by the three capability areas related to information technologies:

- **Everyday Supercomputing**
    - The operation of intelligent systems and advanced ISHM requires massive

amounts of in-space computing and processing power.

- **Seamless Human-Computer Interaction**
  - HCI devices, particularly intelligent interface, are the medium through which humans interact with intelligent systems.
  - As the uses of HCI become more complex and variable, an advanced ISHM system will be necessary to monitor all electronic interfaces and ensure that everything on the network is communicating properly.
- **Environmental Omniscience**
  - Intelligent systems will enable sophisticated analysis of data by sensing networks.
  - ISHM requires the use of a pervasive sensing network to collect and transmit data for the analysis and detection of faults in any system.
- **Self-Sustaining Habitats**
  - To be completely self-sustaining, a habitat needs ISHM to enable a constant state of self-diagnosis and fault prevention.
  - Intelligent systems would enable self-regulating life-support systems.
- **Go-Anywhere Roving**
  - Intelligent systems are necessary for all autonomous vehicles and robots.
  - ISHM could monitor uncrewed rovers on EVA.
- **Space Oasis**
  - Performing repairs on an orbital depot will be costly, and losing an orbital depot to a systems failure would be even costlier, especially if human life is involved. Therefore, using ISHM to prevent failures will be necessary for both crewed and uncrewed space oases.
  - Other types of intelligent systems will also be necessary, for example, to enable self-repair robots.
- **Healthy, Happy Astronauts**
  - ISHM could be linked to sensors embedded in the human body, to monitor crew health and lower health risks. For example, if a biosensor detects that an astronaut's serotonin levels are low, affecting the astronaut's mood and ability to sleep, the ISHM system could automatically adjust the lighting and atmosphere of the habitat to increase the astronaut's sense of well-being.
- **Living Off The Land**
  - Intelligent systems will be necessary to enable autonomous mining technologies.
  - Uncrewed mining expeditions will benefit from ISHM, to monitor operations and prevent failures.

Low-Temperature Mechanisms

Space exploration often involves operating in extremely cold environments. For example, robotic missions and outposts may have to withstand extremely low temperatures on permanently shadowed regions of the lunar surface, distant planets and moons, and during interplanetary travel. These areas have temperatures around –230 C to –190 C.[771] Such extremely cold environments present engineering challenges. Solids become brittle at low temperatures, because the bonds between atoms lose flexibility. As these bonds become more rigid, they are more likely to break. Liquids also play an important role in many space exploration systems and can turn to solids in extremely low temperatures.

The area of low-temperature mechanisms involves developing mechanisms that can operate reliably and efficiently at temperatures as low as -230 C. Because of the temperature extremes of space, there is also a need for mechanisms that can operate in temperature ranges from -230 C to 120 C. Current spacecraft systems can operate at temperature ranges of -115 C to 0 C.[772] Technological advances are needed in low-temperature mechanisms such as motors, drive systems, actuators, bearings, sensors, control electronics, and cabling.[773] In addition to these mechanisms, advances are also needed in materials that can operate at extremely low temperatures, such as lubrication for joints or drive motors, heat rejection fluids to enable thermal management in power systems, low-temperature electrolytes to enable power storage, and liquids to enable lunar- or space-based liquid mirror telescopes.

One of the technologies being developed to meet this need for low-temperature mechanisms and materials is advancement in ionic liquids. Scientists are exploring the possibility of manipulating the chemical and physical properties of ionic liquids to tailor them to specific temperature ranges and operating conditions. This could result in ionic liquids that are specially designed and optimized for specific tasks. This is a challenging problem and requires scientists to understand the structural properties of ionic liquids.[774]

If the necessary technological advancements are made, ionic liquids could have many applications, including use as heat transfer fluids, lubricant fluids, solvent replacement, electrolytes in batteries, plasticizers, solvents in the controlled synthesis of nanomaterials, homogenous and heterogeneous catalysts, matrices for mass spectroscopy, liquid lens in a lunar telescope, and operating fluid for oxygen compression.[775] Ionic liquids can also assist in the purification of gases and act as gas absorption agents.[776]

Currently, NASA centers JPL, LaRC, and GRC are collaborating to develop low-temperature mechanisms to enable space exploration. NASA also collaborates with the companies Aeroflex and Phytron.[777] Key research facilities outside of NASA include the University of California, Santa Barbara, and the Naval Research Laboratory (NRL).

Because this technology enables any system or device that needs to operate in extremely cold environments, it could be related to all of the breakthrough capabilities in this report. It is most closely related to the following breakthrough capabilities:

- **Ubiquitous Access to Abundant Power**
    - Heat transport fluids that remain liquid at low ambient temperatures as well as high temperatures of a reactor core enable thermal management for advanced nuclear reactors.
- **Easy Access to Space**
    - Extremely reliable, long-life, low-temperature turbo pumps enable reusable air-breathing access to space.

- **Efficient Interplanetary Travel**
  - Rugged, dependable, low-temperature actuators may enable precise control of solar sails.
- **Go-Anywhere Roving**
  - Low-temperature materials for batteries and other energy storage systems will enable roving hoppers.
  - Flexible, low-temperature, structural materials will enable shape-changing rovers, boats, and sailboats and other rovers that operate in cold environments.
- **Living Off The Land**
  - Low-temperature mechanisms enable mining in extremely cold environments, such as permanently shaded areas of the lunar surface, and can enable robotic and mechanical systems to withstand extreme temperature ranges of day-night cycles.
- **Environmental Omniscience**
  - Low-temperature sensors could be important in realizing this breakthrough capability, especially for planetary mapping of sensors.
- **Space Oasis**
  - In some locations, low-temperature mechanisms are required for robots to operate in space. In these locations, low-temperature mechanisms would enable assembly robotics, maintenance robots, and swarm robotics.

Nanotubes

Nanotubes are hollow, cylindrical structures with small diameters, on the order of a few nanometers, but can have length-to-diameter ratios of more than one hundred million to one. Most nanotube research is conducted on carbon nanotubes, though other substances, including boron nitride, can be used to fabricate them. Nanotubes display a variety of potentially useful characteristics depending on their molecular structure and composition, particularly high-performance strength, electrical, and thermal properties.

Carbon nanotubes (CNT) can be produced in a variety of configurations. Single-walled nanotubes consist of a single layer of carbon atoms forming the tube wall. Multi-walled nanotube variants include tube-within-a-tube configurations, in which smaller tubes are nested inside of larger tubes, or parchment configurations, in which a sheet of graphene is rolled to form a spiraling tube. The properties of both single- and multi-walled nanotubes also depend upon their bandstructure, or chirality, the manner in which the hexagonal arrangement of carbon atoms composing the wall surfaces is aligned.

The ability to consistently produce nanotubes of specific configuration and chirality is one of the primary challenges facing nanotube technologies. It is compounded by another fundamental challenge: the difficulty of achieving industrial levels of nanotube production at a nominal cost. Current production methods include pulsed laser vaporization, which tends to produce the highest quality CNT (of specific configuration and chirality), as well as arc discharge and chemical vapor deposition, which produce higher quantities of material.[778]

Carbon nanotubes exhibit tensile strength characteristics that exceed those of diamond and are also remarkably resistant to deformation. These properties, in combination with the comparatively low mass of CNT materials, result in a superior building material for spacecraft, satellites, or any components with high-strength and low-weight requirements. However, small defects in the molecular structure of nanotubes can result in significantly reduced structural integrity, as the tensile strength of the material is only as strong as its weakest component. Therefore, high product quality is essential, though extremely difficult to achieve at this point in the technology's development.

CNT in the correct configurations and environmental conditions also offer interesting electrical conductivity characteristics, with nanotubes behaving variously as insulators, conductors, semiconductors, or superconductors. Current research involves mixing CNT with polymers to form conductive plastics that could be used in antennas, anti-static materials, or sensors for spacecraft,[779] while other CNT materials are being examined for use as lightweight electromagnetic shielding for satellites.[780]

Mimicking the hairs on the feet of gecko lizards, nanotube materials might also be used to construct reusable adhesive materials. Weak intermolecular forces between the nanotubes and a surface provide adhesion, which could be broken and reconnected repeatedly. As this process is not temperature dependent, nanotube adhesives could be used to connect satellites for in-orbit refueling or other spacecraft rendezvous activities.[781]

Nanotubes also present applications in power generation and storage. Solar cell technologies involving CNT are being developed; these technologies could enable printable solar panels or paints containing nanotubes to act as solar cells.[782] Nanocomposite paper could be used as a lightweight, high-energy battery or supercapacitor, capable of operation in extreme temperatures. The basic components are carbon and cellulose, so the paper would be biodegradable.[783] Such batteries could be used on spacecraft, allowing for battery placement virtually anywhere, or in astronauts' clothing or EVA suits, providing a low-mass power source.

Nanotubes demonstrate excellent thermal conductivity along the hollow length of their structure, while providing strong thermal insulation laterally. The insulating properties could be useful in the construction of lightweight thermal blankets for spacecraft, but the thermal conductivity of nanotubes offers another possibility—development of thermal rectifiers, devices that can direct the flow of heat. Thermal flow in most materials is random, but using nanotubes allows the direction of heat to be controlled. This property could be used to avoid overheating in microelectronics, to distribute heat from one area of a spacecraft to another very efficiently, or potentially to develop thermal diodes, which may led to new thermal components and possibilities of computing with heat.[784]

One other potential challenge to the use of nanotubes in space applications is the question of their possible toxicity. Due to the incredibly small size and the needle-like structure of nanotubes, there is concern that they may present dangers similar to that of asbestos if inhaled. The ability of nanotubes to penetrate cell walls is already well documented, for it is one of the reasons they are being investigated as drug delivery mechanisms for anti-cancer agents.[785] However, there is evidence to suggest that CNT may be carcinogenic if absorbed into lung tissue,[786] which would require a reassessment of the methods of their manufacture and use in space technologies.

Nanotube technologies offer benefits to many technologies, at least one in every breakthrough capability in this study:

- **Healthy, Happy Astronauts**
  - Nanotubes may provide excellent drug delivery characteristics for nanomedicine.
- **Super Humans**
  - Nanotube materials could be used to construct stronger exo-skeletons.
- **Ubiquitous Access to Abundant Power**
  - Nanotubes would be essential in the design of multifunctional photovoltaic materials.
  - Their electrical properties could be used in developing high-temperature superconducting (HTS) wires.
- **Easy Access to Space**
  - Advances in CNT materials are likely required for advances in skyhooks and space elevators.
- **Efficient Interplanetary Travel**
  - Solar cells or thermal materials incorporating nanotubes could be used in conjunction with solar-powered propulsion.
- **Go-Anywhere Roving**
  - Strong, low-mass materials made with nanotubes would be useful in the construction of extraterrestrial balloons, Montgolfiere-Curie airships, and tumbleweed rovers.
- **Living Off The Land**
  - High-strength nanotube materials used to build mining vehicles would be advantageous for autonomous mining technologies.
- **On-Demand Manufacturing**
  - Nanotubes are already being used in early nanobots, a precursor to self-replicating nanomachines.
- **Self-Sustaining Habitats**
  - CNT are required for carbon nanotube membranes.
- **Space Oasis**
  - Nanotube adhesives might be useful for orbital rendezvous during in-orbit propellant transfer and storage.
- **Environmental Omniscience**
  - Nanopaper batteries and nanotube wires could be used extensively in equipment for ubiquitous computing.
- **Seamless Human-Computer Interaction**
  - Nanotubes might prove useful in constructing biomedical equipment necessary for brain-machine interface (BMI).
- **Everyday Supercomputing**

- Nanotubes would be essential for molecular and nano electronics.

Plasma Technologies

As the fourth state of matter, ionized gases known as plasmas, display a diversity of properties dependent on their composition, temperature, and environment. Their gaseous nature allows for great versatility in shape and size, but the electromagnetic characteristics of plasmas offer the greatest potential. Plasma is electrically conductive and, unlike typical gases, reacts to electromagnetic fields. As a result, plasma can be manipulated in a variety of ways, allowing for a wide range of applications. These may include use as a propellant, a fuel source, or even as various types of barriers.

Plasma technologies can be divided into those that use low-temperature plasmas (near zero Kelvin to ambient temperature) or high-temperature plasmas (roughly five hundred to tens of thousands Kelvin). Another differentiator of plasmas is their density. Dense plasmas (roughly 10^5 electrons per cubic centimeter or higher) have increased energy and can support a variety of applications that cannot use less dense plasmas, including manufacturing, fusion, and shielding. Plasma density (the number of free electrons per unit volume) is not necessarily reliant on the temperature of a plasma. The energy expenditure required to make a dense plasma, either hot or cold, is extremely high by the standards of today's space applications. The mass of current power-generating equipment, therefore, stands as a significant barrier to many plasma technologies in space.

High-temperature, or hot, plasmas are already in use as propellants for spacecraft, having flown in various motor configurations for several national and international space organizations. Current ion engines create high-thrust velocities but low levels of thrust, resulting in motors that are only useful for exo-atmospheric applications, such as satellite maneuvering or interplanetary flight. Plasma engines are considerably more fuel efficient than chemical propulsion engines, creating a much higher specific impulse, and are restricted more by their electrical consumption than their propellant.[787] As increasingly efficient power generators are coupled with this technology, the capabilities of plasma engines will expand, with the potential for use in long-distance human spaceflight applications or the redirection of an Earth-bound asteroid. Other trajectories in the technology of plasma engines include magnetoplasmadynamic thrusters, which offer the potential to match thrust levels of chemical motors while maintaining a high level of efficiency,[788] and magnetic sails capable of using plasmas generated by the sun (or other stars) to "push" a craft, eliminating the need to carry propellant.[789]

Hot plasmas are also currently used for research into nuclear fusion. This research involves immense facilities for terrestrially-based operation, but the potential for fusion as a clean and highly-efficient power source could fundamentally alter the way power requirements are viewed in space exploration.[790] Plasma fusion technologies are still being investigated and require a far greater scientific understanding of plasma dynamics in order to realize their full potential, particularly regarding the containment of a plasma hot enough to sustain a fusion reaction.

Low-temperature, or cold, plasmas by contrast offer a very different array of potential benefits. Plasmas can be used as semi-permeable barriers through which some materials may pass. Dense plasmas are already used in electron-beam welding as barriers to separate a vacuum from atmosphere. In this application, an energetic particle beam is created in a vacuum before passing through a small plasma window to weld materials too large for conventional vacuum chambers.[791] This technology could be adapted to space exploration in a variety of ways, including large windows and airlocks on spacecraft through which materials and astronauts could pass, or barriers for remote sensing equipment with particular temperature or pressure requirements. It is also possible to use a plasma barrier as a valve or pump to transfer atmosphere to a contained vacuum or vice versa. Currently, plasma windows are restricted in size and shape to ten-inch diameter circular openings, a result of the high power requirements (some 20 kilowatts per inch). As mentioned before, the energy necessary to generate a dense, cold plasma is substantial and presents a distinct challenge for this technology.

Another possibility involves the use of cold plasmas as shielding for spacecraft, deflecting either radiation or debris. Cosmic radiation, which poses serious health risks to astronauts over time, could be repelled by surrounding a craft with a wire mesh that runs a current through a cloud of plasma, inducing a magnetic field.[792] If the plasma were made dense enough, it could potentially ward off micrometeorites or debris.[793] Both of these applications would negate the necessity of heavy shielding materials, such as metals or liquids, the only current viable options. Additionally, if a spacecraft was using plasma propulsion, it is feasible that the plasma cloud surrounding the craft for protection might be generated through some process by the motor, further reducing volume and mass requirements.

As with plasma fusion technologies, development of cold, dense plasmas still present an extreme challenge due to the fact that plasma dynamics are not fully understood. Fundamental scientific research is necessary for the advancement of most plasma-based technologies, which will require continued efforts on several fronts. Considerable energy is also necessary for the creation of dense plasmas, and the challenges presented in generating the requisite power will need to be overcome both for advancement in some areas of plasma research and also for the realization of many dense plasma technologies in space.

Development of plasma-based propulsion is being conducted at NASA Glenn Research Center and the Jet Propulsion Laboratory, as well as several other national and international space organizations. Plasma fusion research is being conducted at the U.S. National Ignition Facility, the International Thermonuclear Experimental Reactor in France, and many tokamak reactor sites throughout the world, including U.S. reactors at Princeton and MIT. Cold plasma research is taking place primarily in academia, with some financial support from the Air Force. Cold plasma research groups currently reside at Stanford, Princeton, Ohio State, University of Wisconsin, New York Polytechnic, and Old Dominion, among others. Plasma window technology was developed at the Department of Energy's Brookhaven National Laboratory.

Plasma Technologies offer benefits to many technologies within different breakthrough capabilities:

- **Healthy, Happy Astronauts**
  - Cold plasma could be used for sterilization in a trauma pod or robotic surgery.
- **Ubiquitous Access to Abundant Power**
  - Hot plasmas could be used in a fusion process for advanced nuclear reactors.
- **Easy Access to Space**
  - Hot plasmas would be essential in fusion nuclear rockets.
- **Efficient Interplanetary Travel**
  - Ion thrusters are integral to solar-powered propulsion.
- **Go-Anywhere Roving**
  - Plasma fusion reactors might eventually power small crewed or uncrewed submersibles.
- **Living Off The Land**
  - Plasmas might be useful in molten oxide electrolysis.
- **Self-Sustaining Habitats**
  - Plasma barriers might serve as containment for a bioregenerative life-support environment.

Smart Materials

Smart materials include several different classes of materials that have controllable reactive properties, including conductivity, tension, or volume, and respond to specific stimuli such as electric or magnetic fields, heat, or light. These substances can be glasses, ceramics, metals, polymers, and fluids. Current smart materials include chromogenic materials that can change colors, electroactive polymers that expand or contract with tunable electric properties, ferrofluids with controlled magnetic properties, piezoelectric materials that convert electrical energy to mechanical energy, self-healing polymers that can regenerate their physical structures, and shape-memory materials that allow for efficient transition between multiple shapes. Research in the field is ongoing and quite active, and new materials with new properties are in development.

Chromogenic materials react to a stimulus, usually light, heat, or electricity, by changing color. This is generally a result of a change in the electron density of the molecules constituting the material, induced by external stimuli. Current chromogenic materials include glasses that darken in response to light, and other glasses that will reflect light or heat (infrared wavelengths) when exposed to an electrical charge.[794] These materials might be useful for windows on spacecraft or habitats exposed to varying degrees of light.

Electroactive polymers (EAP) respond to electrical stimuli by expanding or contracting, depending upon the polarity of the charge in an electric field between two voltage terminals. Due to their toughness, high degrees of actuation under strain, and resistance to vibration, EAP have become known as "artificial muscles."[795] They are lightweight and react very quickly to applied voltage, but currently cannot provide a great deal of force to their movements. Work is underway involving new structural arrangements of EAP, using accordion-like molecular designs to maximize strength and load-bearing capacity, with the potential to surpass the abilities of human muscle tissue.[796] Possible space uses include mechanical counter pressure suits for astronauts or a wide range of uses in robotics.

Ferrofluids are fluids that contain small, magnetically-responsive particles in suspension. Appearing as an opaque, slightly viscous liquid, ferrofluids react strongly in the presence of a magnetic field. Developed by NASA, ferrofluids are commonly used as liquid gaskets in computer hard drives but have also been tested for use in attitude control systems on some spacecraft. They could potentially be used to adjust the shape of a liquid mirror on a microgravity telescope.[797] Another family of ferrofluids, called magnetorheological (MR) fluids, contains larger magnetic particles (micrometer scale) and respond to magnetic fields by partially solidifying. These fluids are currently used in high-performance shock absorbers but have potential in a variety of hydraulic applications. Their ability to regulate hundreds of watts of mechanical power with only tens of watts of electrical input offers an energy-efficient option, though the weight of high-powered magnets needed to control MR fluids may be restrictive for space use. Possible applications include use in resistance suits for astronauts to combat muscle atrophy[798] or for mobility systems in robotics.[799] Ferrofluids are addressed in more detail in the report, *Technology Horizons: Game-Changing Technologies for the Lunar Architecture*.

Piezoelectric materials accumulate an electrical charge when subjected to pressure or increase in size in response to an electrical charge (though these size changes are generally on the order of tenths of a percent). This effect is the result of a change in polarization in response to mechanical stress, which is manifested as a variation in charge density in the electrical field between the faces of the crystal structures within the substance. First used in sonar applications, piezoelectric materials are currently found in technologies such as touch-screen devices and automobile airbag sensors. Most piezoelectric materials are crystalline in structure, including some metals and ceramics, and the mechanics of their properties are fundamentally well understood. As charge efficiencies increase and sizes of materials are reduced even to the nano level, piezoelectric materials could potentially be used to harvest electrical energy from nearly any mechanical source. Vibrations produced by rover tires moving across terrain or by an accelerating spacecraft might be sources of electricity, as could the movements of astronauts inside environment suits or walking across the floors of a habitat.[800] If generators were made small enough, the hydrodynamic forces of the human circulatory system could even be used as an energy source.[801]

Self-healing materials are polymers, glasses, and ceramics that are capable of automatically repairing damage they sustain. This is accomplished either intrinsically, where the structure of the material is capable of reconstituting itself, or extrinsically, where a healing agent is embedded in the material.[802] Intrinsic materials rely on their molecular composition for self-healing properties, with novel molecular shapes or chemical attraction resulting in local re-adhesion in damaged areas.[803] Extrinsic materials involve small capsules filled with a resin distributed through the material, or capillary pathways allowing resin to flow into the material, with a catalyst agent to harden the resin activated upon damage. Extrinsic materials are limited in the number of times they can repair themselves by the amount of resin available.[804] Self-healing materials could be useful for construction of spacecraft encountering micrometeorite strikes or for habitats subject to adverse weather conditions, such as the intense dust storms common on Mars. Equipment prone to micro-cracks due to operational vibration or exposure to radiation might also benefit from self-healing materials.[805] Additionally, incorporating conductive nanotubes into resin could allow for the repair of electrical pathways on microcircuits, potentially eliminating the need for redundant electronics in satellites and robotic vehicles.[806] Self-healing materials were addressed in detail in the report, *Technology Horizons: Game-Changing Technologies for the Lunar Architecture*.

Shape-memory alloys (SMA) are metals that can be "programmed" to a specific shape. If the material is then subjected to deformation, it can be restored to its original shape through exposure to an external stimulus, usually heat or an electromagnetic field. Some SMA have two programmed states, one at a high temperature and one at a low temperature. The material will transition between its two shapes as its temperature changes.[807] Other SMA are capable of pseudoelasticity, meaning they can be deformed to an extreme degree but return to their original shape as soon as the deforming stress is removed. Most SMA combine quantities of copper, zinc, nickel, or titanium, and are currently cost-prohibitive. They could be used in the construction of shape-changing vehicles or spacecraft or for the deployment of solar arrays. Thermally-activated SMA could also be used in radiators to replace liquid coolants.[808]

Shape-memory polymers (SMP) are similar to SMA, but offer a different array of shape-memory properties. SMP currently change shape in only one direction, due to their structure. The outer portion functions like a wax, while the core acts as a spring. The material can be deformed, and the wax-like coating will retain the deformed shape. When activated, the wax-like portion softens, allowing the spring core to revert to the original shape.[809] Activation methods for SMP include not only heat, electricity, and magnetism, but also light or chemical solutions.[810] Some SMP can be programmed to three, four, or five separate shapes, which are accessed by heating the material to specific temperatures.[811] Uses for SMP in space might include construction of shape-changing vehicles, the manufacture of compact parts for assembly in hard-to-reach areas,[812] or nanoparticle SMP for use in terabit-capable, miniature, memory devices.[813]

Smart materials offer benefits to many technologies within different breakthrough capabilities.:

- **Healthy, Happy Astronauts**
  - Shape-memory alloys and polymers are already used extensively in medicine and could be of great use in robotic surgery.
- **Super Humans**

  - Chromogenic materials might be useful in constructing visual prosthetics.
  - Electroactive polymers could provide muscle power to exo-skeletons.
- **Ubiquitous Access to Abundant Power**
  - Self-healing materials would reduce the maintenance required on aspects of extraterrestrial wind or geothermal power plants.
- **Easy Access to Space**
  - Shape-memory alloys and polymers could be used for developing air-breathing access to space vehicles that might require different exterior configurations at various speeds and altitudes.
- **Efficient Interplanetary Travel**
  - Shape-memory alloys or polymers could be used to deploy large solar arrays required for solar-powered propulsion.
- **Go-Anywhere Roving**
  - Shape-memory alloys and polymers would be required for construction of certain shape-changing rovers.
  - Electroactive polymers could be used in mechanical counter-pressure suits or to move the wings on flapping wing vehicles.
- **Living Off The Land**
  - Electroactive polymers could provide artificial muscles for mining vehicles.
  - Ferrofluids may provide suspension systems for large construction vehicles.
- **On-Demand Manufacturing**
  - Shape-memory alloys and polymers, or perhaps magnetorheological fluids, would be useful in constructing self-reconfigurable modular robots.
- **Self-Sustaining Habitats**
  - Self-healing materials might keep antimicrobial materials from breaking down over time, while reducing potential maintenance issues.
- **Space Oasis**
  - Shape-memory polymers would be useful for manufacturing parts required for autonomous robotic assembly.
  - Electroactive polymers or magnetorheological hydraulics could provide the muscles for service and maintenance robots.
- **Environmental Omniscience**
  - Piezoelectric micromotors could provide power to smart dust particles.

Synthetic Biology Technologies

Synthetic biology is a young field characterized by the use of DNA engineering for the creation of novel organisms and technologies. The term itself was first used in 1980 and more permanently in 2000.[814] In some ways, synthetic biology could be seen simply as an outgrowth of genetic engineering or of biomimetic chemistry. The difference between the two fields is of approach; synthetic biology distinguishes itself in its passion for large-scale manipulations. Rather than simply splicing one desirable gene into an existing organism, adherents envision wholesale redesign of living systems.[815] Commonly, DNA proteins are seen as analogous to lego blocks, and standard DNA "parts" are composed of smaller units called "BioBricks."[816]

One of the goals of synthetic biology has been to create artificial life, and this goal was accomplished in May of 2010 when researchers at the J. Craig Venter Institute created a self-replicating synthetic bacterial cell.[817] What is new about this demonstration is the creation of the genome from individual components, rather than the manipulation of an existing genome to create a modified being. The team was able to reconstruct the genome of Mycoplasma mycoides and transplant it into a new cell, which then took on the properties of the organism and began replicating. This activity, which is not entirely unique and uses many accepted and even older methods, proves the possibility that known or novel genomes can be constructed from component parts to form a living being.[818]

Synthetic biology has research and engineering applications.[819] Research applications generally attempt to reconstruct naturally occurring DNA sequences to generate basic knowledge of how DNA works and how natural systems behave. Research along these lines has been very beneficial in understanding viruses, such as HIV—by modeling behavior, new diagnostic tests can be conceived. Engineering applications manipulate the genome for new technologies.

The larger thrust of synthetic biology is the design and creation of new organisms that do not currently exist in the world. The general paradigm is to classify genomic "parts" that can be assembled into a custom organism. Each "part" is a sequence that performs a particular function. The "Registry of Standard Biological Parts" is an attempt to catalog and build knowledge on parts to aid further design. Students and researchers upload gene sequences and characterize the function those sequences perform. By its own account, the quality and reliability of these parts cannot be guaranteed. Still, the vision is that a system like this can create a toolbox of functional approaches for engineering and construction.

The analogy of building organisms like legos is, in point of fact, a gross oversimplification of the process moving forward. The synthetic life that was created at the Venter Institute copied, with minimal modification, an existing organism.[820] The process of combining DNA is fraught with several critical barriers that are part of the overall problem that genomes present enormous complexities that researchers are still in the early stages of understanding. DNA circuitry is not simple and predictable like electronics. Parts may function differently when assembled together than they do in isolation, or they might be completely incompatible. Parts may also be affected by variability in how they are grown, excessive noise, and seemingly random variations that confound design.[821] Overall, synthetic biology is a very complex, nonlinear field whose expansion and development will have to evolve with its underpinning basic science.

Nonetheless, the field is often titled as the most important field of research for the 21st century and has applications across the economic spectrum.[822] Relatively near-term applications include batteries, solar cells, biotechnologies, pharmaceuticals, biomaterials, transportation fuels, and waste disposal.[823]

Synthetic biology is an international field with substantial contributions from U.S. organizations and research institutions. Academic institutions hosting research include the MIT Department of Electrical Engineering and Computer Science, Stanford University, Boston University, California Institute of Technology, Duke University, Princeton, University of California, Berkeley, University of California, San Francisco, University of Texas, Austin, Vanderbilt University, Georgia Tech, Northwestern University, and Virginia Tech.[824] Other institutions include New England Biolabs, Ginki BioWorks, the J. Craig Venter Institute, and Synthetic Genomics Inc.

Space applications have a wide range of possibilities. NASA performs a small amount of research in the field and is currently in the process of defining the research agenda through workshops with NASA and external experts.[825] Examples of spaceflight applications include:

- **Healthy, Happy Astronauts**
    - Plants could be engineered for greater yields, hardiness in space, and survival in foreign environments.
    - Genes for countless antibiotics and a number of host cells could allow a very-low-mass, complete pharmacology to be accessible to astronauts during missions.
- **Ubiquitous Access to Abundant Power**
    - Solar cells enabled by organisms using processes like photosynthesis may outperform existing technologies in terms of efficiency.
- **Living Off The Land**
    - Bio-mining—the development of microbes or plants that are able to concentrate metals and compounds—requires advances in synthetic biology. A long-term example is a flower that pulls and concentrates gold from regolith.
- **On-Demand Manufacturing**
    - Organisms that can break down existing materials into new materials, allowing for the repurposing and recycling of old equipment, has terrestrial and in-situ applications, with the former emphasizing the creation of novel materials.
    - Biomimetic materials, like the underwater adhesives used by barnacles, could improve operations in challenging environments.
- **Self-Sustaining Habitats**
    - Plants and microbes could be developed to process and recycle waste into other assets.
    - Bacteria could be developed to process waste gases into oxygen.
- **Environmental Omniscience**
    - Biosensors enabled by custom organisms could increase the fidelity and resolution of many sensing systems.

Thermal Management

Thermal management is the transport of thermal energy from areas with excess heat or to areas that require additional heat. With thermal management, damaging or dangerous thermal energy can be mitigated by either removing it or scavenging some portion for usable energy. Alternatively thermal management can include the transport of heat or targeted heating systems to provide heat to vital systems in cold environments, like batteries in space. Efficient thermal management can protect personnel and equipment that might be adversely affected by excess heat and can reduce power generation requirements. Thermal management may include technologies such as heat exchangers, thermoelectrics, electrocaloric devices, or thermal rectifiers.

Heat exchangers are devices that transfer thermal energy from one medium to another, such as radiators and heat pipes. They have been in use for decades, with space applications ranging from cooling microelectronics to regulating temperatures of spacecraft (to cope alternately with the vacuum of space and unfiltered solar radiation). Most radiators for current spacecraft applications transfer heat using the thermal conductive properties of a liquid traveling through an exposed pipeway, absorbing heat from one point and radiating it at another. A heat pipe is similar to a radiator, but uses a phase transition in its liquid to convey thermal energy. A liquid under low pressure absorbs heat and vaporizes at one location, then condenses into liquid as the heat is dissipated at another location. Due to the phase transition, this is accomplished with little change in temperature. Both radiators and heat pipes are able to operate in a wide variety of thermal environments, depending primarily on the thermal conductive properties of the fluid used and, in the case of heat pipes, the pressure under which the fluid is maintained.

Significant research is underway to develop options for various liquids used in these devices. There is particular interest in liquid metals due to their thermal conductivity and higher heat capacity. Some liquid metals also allow electromagnetic manipulation, negating the need for a mechanical pump. Metals that remain liquid in temperatures as low as -10 degrees C are currently under development, allowing the transfer of greater amounts of thermal energy at lower temperatures.[826] Other solid metals, known as thermoelastic shape-memory alloys, could replace liquids in some heat exchanger applications, allowing far greater energy efficiency than a compressor-based liquid system due to their expansion and contraction properties.[827] Future uses in space include the incorporation of heat exchangers with nuclear reactors for supplying power to a lunar or Martian outpost[828] or powering interplanetary propulsion systems. They might also be used as cooling devices on the leading edges of wings for hypersonic aircraft used to boost payloads to low orbit.[829]

One other use for liquid metals with high thermal conductivity is in the construction of extremely concentrated photovoltaic cells. Normally, highly concentrated light causes the photovoltaic material to overheat, resulting in melting or vaporization. Placing the material on a metal heat sink can reduce the thermal effect, but imperfections on the surface area of the metal and the cell cause a reduction in contact and result in inefficient thermal transfer. By using liquid metals at the interface, this inefficiency is nearly eliminated, allowing for a tenfold increase in the concentration of light on the photovoltaic cell.[830] If such a technique could be developed for use in space, it could vastly increase the power generation capabilities of solar arrays.

Another method of thermal transfer involves the use of ceramics or polymers called electrocaloric materials, which consist of chains of molecular dipoles. These molecules are randomly oriented until exposed to an external electric field, which causes them to align in the direction of the field. This alignment reduces thermodynamic entropy in the substance, similar to a phase change, causing a rise in temperature. Removing the electrical field causes the material to cool. Covering a battery in electrocaloric material could enable heating or cooling in response to changing thermal environments, while combining electrocaloric materials with a liquid or metal heat sink could result in a refrigerating device far more efficient than mechanical vapor-compression cycle or magnetic cooling devices.[831] The lack of moving parts in such a system would make it desirable in space applications, as the risk of failure would also be reduced. Electrocaloric polymers have a greater range of temperature change (up to 12 degrees C) and can absorb more thermal energy than electrocaloric ceramics, which often contain hazardous materials like lead. Currently, electrocaloric polymers can only be produced in thin sheets, limiting their utility.[832]

The properties of thermoelectric materials, which generate electrical voltage in response to a temperature difference, have been known for two centuries, but most materials that conduct electricity also conduct heat, drastically reducing efficiency. There are more efficient thermoelectric materials that are used in radioisotope thermoelectric generators for deep space applications, but they are prohibitively expensive. Nanoscale materials are being examined in an effort to develop substances with high electrical conductivity but low thermal conductivity, combining components of differing size and thermal characteristics to increase the internal surface area of the material. This would slow heat transfer without impeding electron flow.[833] Another area of research deals with reducing the cost of thermoelectric materials, focusing on the recent discovery of organic compounds that function as thermoelectrics. Organic materials are generally more abundant and cheaper to manufacture than their inorganic thermoelectric counterparts, inviting a broader application of this technology.[834] Inexpensive and efficient thermoelectric materials could allow for the scavenging of thermal energy in numerous space applications, from plasma propulsion systems and nuclear power plants to the inner lining of an EVA suit.

Heat rectifiers are conceptual devices that control the flow of thermal energy in a single direction in much the same way that a semiconductor diode can control the flow of electrons. The process involves using three (or more) substances with differing phonon bandwidths. The first segment conducts heat vibrations at high frequencies, while the third segment conducts them at low frequencies. The middle segment has nonlinear characteristics dependent on temperature; it conducts large heat vibrations at high temperature and low heat vibrations at low temperature. With the first segment at high temperature and the third segment at low temperature, heat travels through the first segment and easily transfers to the middle segment. As the temperature gradient cools over the middle segment, heat can flow into the third segment. If the temperature gradient is reversed, however, with the first segment cold and the third segment hot, heat cannot travel in the opposite path.[835] Early experimentation seems to have proven the concept of heat rectifiers.[836] Eventually, this technology (or similar advances involving nanotubes, see page 226) might be used to construct computing devices that utilize thermal instead of electrical energy. This could be useful for construction of spacecraft components that need to avoid electromagnetic interference.

Thermal management technologies offer benefits to many technologies within the breakthrough capabilities of this study:

- **Ubiquitous Access to Abundant Power**
  - Ceramic bricks in an insulated container could be used as a thermal capacitor to store heat,[837] which could then be converted to electricity using thermoelectric materials.
- **Easy Access to Space**
  - Heat exchangers could be used for cooling leading-edge surfaces on air-breathing access to space craft.
- **Efficient Interplanetary Travel**
  - Heat exchangers could be used on nuclear-powered propulsion systems.
  - Radiators may be necessary to cool solar cells for concentrated photovoltaic power systems on solar-powered propulsion systems.
- **Go-Anywhere Roving**
  - Heat exchangers could be used to keep components warm in mobile ice probes.
- **Living Off The Land**
  - Heat exchangers would be necessary on mining equipment for autonomous mining technologies.
- **On-Demand Manufacturing**
  - Thermoelectric and electrocaloric materials would be useful in the design of self-reconfigurable modular robots.
- **Self-Sustaining Habitats**
  - Thermal rectifiers designed on biomimetic principles could aid in the development of biomimetic architectures.
- **Space Oasis**
  - Heat exchangers would be used in the design of craft for in-orbit propellant transfer and storage.
- **Environmental Omniscience**
  - Thermoelectric materials could power implantable biosensors, using the temperature difference between the skin surface and subsurface.
- **Everyday Supercomputing**
  - Thermal rectifiers incorporating nanotubes might be useful for heat mitigation in molecular and nano electronics.

NEXT STEPS

NASA's flexible approach to human space exploration will require the development and infusion of innovative technologies across all elements of future exploration missions. While evolutionary technology advancements will support some of the future activities, truly ambitious human exploration programs that are possible within the next forty years require breakthroughs in many areas to maximize potential.

This study investigates the major challenges for human exploration between now and 2050, while detailing opportunities to address those challenges with technical innovations. The thirteen breakthrough capabilities, which form the basis of this report, define a set of futures where exploration challenges are solved. Humans are launched into space and move to exploration destinations quickly, easily, and reliably. Once they arrive, exploration is enhanced with near perfect knowledge of the environment, advanced sensing technologies, and the ability to easily explore the destination. Astronauts are comfortable and safe; protected from the risks of space travel; in communication with their families on Earth; and able to communicate the firsts of exploration with virtual explorers on Earth, who support and engage in the exploration along with the astronauts. Exploration is sustainable. Outposts create building materials, consumables, and fuel from in-situ resources; grow their own food; and make their own spare parts.

This report addresses nearly one hundred specific technology concepts that could help make these futures a reality. Each concept includes details on how it works, who is currently researching it, the biggest hurdles for using this technology for exploration, and who are likely targets for NASA to partner within this area. Some of these technology concepts address breakthroughs in advancing current technologies and adapting them for use in space; examples include virtual reality and virtual communications, robotic surgery, and 3-D printers. The majority of the technology concepts represent breakthroughs in the fundamental science or engineering required for the concept. Examples include biomining technologies that use bacteria to turn regolith into usable inputs, robots that can reconfigure themselves to address the job at hand, dust-sized sensors that can provide a complete picture of a new environment, small and efficient nuclear power stations that are safe and easy to use, computers that interact directly with the human brain, launch concepts that do not use propellant, and many others. Some of these breakthroughs will be achieved and in wide use by 2050, while others will not be able to surmount the technology hurdles necessary for technology adoption.

The analysis and information in this study provides NASA, and other exploration organizations, with a resource for planning long-term exploration missions and technology investments. The breakthrough capabilities, technology concepts, and crosscutting technology areas will help clarify technology pathways to achieve long-term human exploration goals. This knowledge can feed into NASA's technology development efforts, such as those underway within the Office of the Chief Technologist. The technology concepts in this study can feed into mission planning efforts going on today. The detailed information on technology trajectories will help NASA identify the most promising concepts and the most opportune times to invest so that NASA may identify and prioritize investment strategies. In addition, this report could help NASA respond to questions from Congress and NASA’s Senior Management Council regarding NASA's approach to innovative technology development.

Partnership opportunity information in this study will help guide the development of partnerships with external organizations. Commercial and academic entities and other government agencies with similar technology goals or advanced technical knowledge are identified as potential partners in the report. Partnership opportunities could be as simple as a memorandum of understanding or more integrated, such as joint technology development activities. The level of partnership will depend on the complexity of the technology, the similarities in requirements between agencies, the relative funding requirements, and the timing required for technology advancement. The nature of the partnering organization is very important as well. Military agencies may come with clearance requirements. Commercial organizations may come with privacy, intellectual property, or public relations concerns. International partners, whether commercial or government, will bring trade restrictions.

This report is designed to serve as a companion document to a previous report, *Technology Horizons: Game-Changing Technologies for the Lunar Architecture (2009).* The *Game-Changing* report and this report complement each other to identify innovative technologies that will produce a significant impact on human exploration in the near, mid, and far terms. Understanding the trajectories of near-, mid-, and far-term technologies will enable NASA’s exploration missions to go further and achieve more with less resources. Continual technology intelligence is critical for NASA’s planning, technology investment, and partnering activities. These reports are designed to keep NASA’s technology intelligence current, with an alternating two-year cycle for refreshing and updating the technologies in each of the reports. An update for the *Game-Changing* report is scheduled for 2011, and it is planned that this report will be refreshed in 2012. These reports will help NASA align itself with cutting-edge technology developments, which will foster NASA’s position as a global innovation leader. These reports and other efforts will enable NASA’s vision of “*fanning out across the inner solar system, exploring the Moon, asteroids, and Mars nearly simultaneously in a steady stream of ‘firsts.’*”

APPENDIX A: BREAKTHROUGH SCENARIO WORKSHOP PARTICIPANTS — MARCH 19, 2010

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