National Aeronautics and Space Administration

Technology Horizons:

Game-Changing Technologies for the Lunar Architecture

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1.0 EXECUTIVE SUMMARY

NASA is currently designing a plan to return to the Moon by 2020 and sustain a human presence. While still in evolution, the current lunar architecture includes the vehicles and systems to travel to, explore, build, and sustain an outpost on the Moon. A lunar outpost mission will require technology from across the spectrum of human activity, including health, automobiles, electronics, information technologies, energy generation and storage, materials science, manufacturing, and propulsion, to name a few. Unlike relatively specialized space activities, such as interplanetary probes, the broad base of activities and capabilities required for a human presence on the Moon draws from capabilities across the economy.

Goals

This report was conceived with the goal of identifying the emerging and external technologies across the economy that could have the most game-changing effects on NASA's lunar architecture. This includes technologies being developed specifically for space applications, as well as those in other areas that could be adapted for use in space. The study focused on technologies that could be infused within the timeline currently planned for the architecture, 2020 to 2030. Selected technologies are at the intersection of two important forces. First, broad participation across the economy lends significant interest and investment to their development. Secondly, their impact on NASA's lunar architecture is substantial, affecting multiple system areas.

The definition of "game-changing technologies," for the purposes of this study, is given as:

> *"A game-changing technology is an emerging technology area that, if infused into the lunar architecture, will provide benefits that extend beyond its adopted system area. These technologies will benefit architecture elements beyond their own, and they will foster NASA's leadership in innovative technology use."*

Process

Under the direction of NASA's Exploration Systems Mission Directorate (ESMD), Directorate Integration Office (DIO) The Tauri Group compiled a list of over 260 emerging external technologies that could be useful to NASA in implementing the lunar architecture. These technologies were grouped into NASA-relevant technology areas. Through several rounds of analysis from NASA technology and architecture experts, nineteen emerging technology areas were identified as the most game-changing to the 2020 to 2030 lunar missions.

Game-Changing Technologies

This report includes a synopsis of each of the nineteen technology areas that incorporates basic information on what is driving the market for each technology, who is performing the research, profiles of example technologies, a description of the impact this technology area could have on the lunar architecture, and some information on how this technology might be infused into the architecture as a whole. In rank order, the nineteen technology areas are:

Energy Storage Technologies Page 17

Game-changing highlights:

- Receiving substantial investment across industry and government, with hybrid vehicle markets a major driver of innovation
- Critical components of outpost capability for surface mobility, and for surviving eclipse periods
- Could expand exploration range and vehicle performance, increasing exploration and enabling greater science return
- Will require component-level trades to evaluate new storage technologies

Anti-Radiation Drugs Page 22

Game-changing highlights:

- Under development to counteract the toxic effects of exposure to radiation, in medical, military, and industrial applications
- May be traded against mass requirements and technology development resources for radiation shielding materials and structures
- Could provide practical solution for radiation protection during extravehicular activity (EVA)
- Infusion could mean substantial mass savings and decreased health risk levels

In-Situ Resource Utilization (ISRU) Manufacturing Page 26

Game-changing highlights:

- Could enhance supportability, especially for consumables
- Longer term, in-situ manufacturing techniques (including free-form manufacturing) reduce launch costs by producing equipment on-site
- Has high extensibility to missions beyond the Moon

Radiation Shielding Page 29

Game-changing highlights:

- Being advanced by military, nuclear, and medical sectors
- Could provide improved shielding with lower mass, to reduce risk of radiation exposure with minimal impact on architecture
- Potential to trade against 5 cm water wall currently in the architecture or to provided enhancements to habitat or EVA suits

Advanced Pressure Garment Technologies Page 34

Game-changing highlights:

- Advanced full suit concepts under development by MIT and University of North Dakota, related component technologies development in military and healthcare sectors
- Could make suits that are easier to wear and longer lasting, enabling more exploration and lower logistics burden
- Components could improve safety of astronauts during EVA, with radiation and rip/tear protection
- Provide extensibility to Mars

Nuclear Power Technologies Page 39

Game-changing highlights:

- Could supply substantially more power than currently planned solar cells
- Reduction of restrictive low-power requirements reduces development costs across the architecture

Advanced Nanotube-based Materials Page 43

Game-changing highlights:

- Researched by government and commercial organizations for hundreds of applications
- Could improve performance across the architecture: biotechnologies, ultracapacitors, structures, windows, radiation shielding, and solar cells
- Could have a large impact on the total mass of the lunar architecture

Next Generation Fuel Cells Page 47

Game-changing highlights:

- Significant investment from the military, and declining but strong interest from the Department of Energy and industry
- Important applications in power storage throughout the architecture, especially in increased range of surface mobility assets

Next Generation Solar Cells Page 51

Game-changing highlights:

- Significant investment in development across industry, military, and other government agencies
- Fast growing markets and diverse technology solutions means high probability of improved performance and surprise innovations
- Next generation technologies may change solar power concept of operations, i.e., integrated structures rather than deployed

Advanced Cryogenic Technologies Page 55

Game-changing highlights:

- Enable low-temperature storage, management, and transfer of cryogenic fuels
- Could increase sustainability of the architecture, providing more mass and volume devoted to payloads
- Are transformational to the architecture, providing new capabilities and requiring system-level technology trades

Printing Manufacturing Page 59

Game-changing highlights:

- 3D Printing is used in rapid prototyping, and could develop towards free-form manufacturing
- Printed electronics reduces the cost of semiconductor manufacturing and enable flexible electronics
- Could enhance supportability or enable in-situ, free-form manufacturing

Advanced Coatings, Adhesives, and Self-Healing Materials Page 62

Game-changing highlights:

- Being developed by government and industry around the world
- Augment lunar elements, adding dust mitigation properties, maintenance capacity, ruggedness, and reliability
- Could lower overall maintenance and repair concerns, improving sustainability and decreasing maintenance related costs and mass

Advanced Electric Propulsion Page 66

Game-changing highlights:

- Could provide a higher thrust, reducing the fuel requirements for lunar cargo transport
- Could support ongoing logistics requirements of the architecture
- Potential for Mars missions, providing decreased travel time, lower mass, and lower mission cost

Heat Transfer Materials Page 70

Game-changing highlights:

- Driven by industrial, military, and international investments
- "Supertubes," developed in China, push the limits of heat transfer physics
- Integration reduces mass and volume in thermal control, and can be used to recycle heat in ISRU processing applications

Autonomous Systems and Vehicle Control Page 73

Game-changing highlights:

- High level of interest in government, academic and commercial organizations
- Reduce or remove the need for human controllers
- Can provide self-aware systems that can control, monitor, and repair themselves

Long Distance Power Transmission Page 77

Game-changing highlights:

- Provide power beaming and space solar power could enable constant power on the surface of the Moon at major power levels
- Could beam power for habitats, science experiments, ISRU operations, and rovers, obviating the need for most batteries
- Wired solutions work with the current architecture to transmit power, while wireless solutions could supplant current architecture designs

Advanced Chemical Propulsion Page 81

Game-changing highlights:

- Provide improved performance, storage capabilities, or environmental impact of rocket engines
- Greater energetic performance increases lift mass, could increase the capabilities of the architecture and extend the time between resupply flights
- Requires significant design changes to current launch systems

Massive Online Collaborative Environments Page 86

Game-changing highlights:

- Maximize the utility of available data through an immersive collaborative environment
- Could improve performance by enhancing collaboration between people on the ground and astronauts in space
- Could provide virtual access or exploration of the Moon to the public

Emerging Communications Systems Page 90

Game-changing highlights:

- Increase bandwidth and throughput for data between systems, and from the lunar surface to Earth
- Greater availability of bandwidth allows new applications, such as more sophisticated user interfaces
- Could improve data transfer between robotic systems, such as the rover, and the lunar habitat, increasing the science and exploration conducted

Technology Watch List

This report also includes an additional Technology Watch List, which identifies 28 fast-moving technologies whose advance is not necessarily contingent on NASA funding and research. These are areas of rapid innovation that NASA can monitor for future developments with game-changing impacts. Some examples include adaptive communications technologies, advanced data storage, and human-computer interaction technologies. The complete Watch List can be found on page 94.

Next Steps

Awareness of emerging technology areas and economic forces driving investment bring several benefits in strategic planning, including planning flexibility into the architecture, determining the best technologies to address particular requirements, and informing investment and partnering decisions. In addition, should the architecture be reconceived, whether due to changes in political forces, major cooperation commitments from international partners, changes in expected transportation system performance, or external economic events, the identification of dynamic game-changing technologies across the economy could be a valuable tool to inform the trade space in future assessments.

This report is the first in a two-part series of documents on game-changing technologies. The forthcoming companion document will address longer-term technologies, focused on those that enable conceptual transformations of space architectures; those that are "extremely" game changing. The report, due to be completed in mid 2010, will include a broader set of technologies and will use an approach to identify technologies appropriate to the changes in subject matter and scope.

2.0 INTRODUCTION

NASA is currently designing a plan to return to the Moon by 2020 and sustain a human presence. According to the NASA Authorization Act of 2008:

> *"Congress hereby affirms its support for--*
> 1. *the broad goals of the space exploration policy of the United States, including the eventual return to and exploration of the Moon and other destinations ...*
> 2. *the development of technologies and operational approaches that will enable a sustainable long-term program of human and robotic exploration of the solar system;*
> 3. *activity related to Mars exploration, particularly for the development and testing of technologies and mission concepts...*
> 4. *international participation and cooperation, as well as commercial involvement in space exploration activities."*[1]

While still in evolution, the current lunar architecture includes the vehicles and systems to travel to, explore, build, and sustain an outpost on the Moon. The transportation architecture includes the human-rated Ares I rocket, the Crew Exploration Vehicle for orbital travel, and the Ares V for cargo transportation. The architecture also includes buildup of an outpost on the lunar south pole with modular habitat elements to accommodate multiple crew members, and pressurized vehicles, such as the Lunar Electric Rover (LER), for exploration of the surface. Solar panels provide electricity, ISRU modules extract oxygen from the regolith, and science modules collect and analyze data. Cargo unloading and some minor construction tasks, like berm building, are performed robotically. Human return will begin with an initial sortie lasting seven days with a crew of four. After the first sortie, the duration crew are on the lunar surface will increase as additional cargo is delivered, reaching 180 days.[2]

A lunar outpost mission will require technology across the spectrum of human activity, from health, to electronics and information technologies, energy generation and storage, materials science, manufacturing, and propulsion, to name a few. Unlike relatively specialized space activities, such as interplanetary probes, the broad base of activities and capabilities required for a human presence on the Moon draws from capabilities across the economy. The potential for applicable technology development from areas normally outside NASA's scope is real. When the long development timeline for space hardware is contrasted with rapid innovation in some other technology areas, it is clear that potential partnerships and opportunities for technology infusion may exist in surprising areas.

This report was conceived with the goal of identifying the emerging and external technologies across the economy that could have the most game-changing effects on NASA's lunar architecture. This includes technologies being developed specifically for space applications, as well as those in other areas that could be adapted for use in space. The study focused on technologies that could be infused within the timeline currently planned for the architecture, 2020 to 2030. A companion document to this one, to be released mid-2010, will look at game-changing technologies with a longer horizon. Identifying game-changing technologies can help NASA:

- Plan flexibility into the architecture to accommodate promising new technology areas
- Inform technology investment decisions, including decisions to monitor rather than invest
- Identify areas for partnership, ranging from memorandums of understanding (MOUs) to joint technology development
- Give a timeline for potential technology infusion
- Augment established NASA-internal technology development efforts
- Enable a more capable lunar architecture system

Under the direction of NASA's Exploration Systems Mission Directorate (ESMD), Directorate Integration Office (DIO) The Tauri Group compiled a list of over 260 emerging external technologies that could be useful to NASA in implementing the lunar architecture. These technologies were grouped into lunar architecture-relevant technology areas. The technology areas were reviewed and rated by three separate groups of experts: NASA architecture experts, NASA domain system engineers, and a technology expert panel, which included senior-level representatives from NASA and external technology development organizations. This report details the nineteen highest rated technology areas and example technologies within those areas.

What is Game-Changing?

The term 'game-changing technologies' is often used in the trade press, and there are related concepts and terms, like 'emerging,' 'disruptive,' and 'surprise' technologies. While these terms have different original meanings, overuse and misuse can distort their associations. To avoid confusion and to provide a clear basis for the assessments that followed, the study team developed a specific definition for the term "game-changing technologies" as it applied to NASA in this context:

> *A game-changing technology is an emerging technology area that, if infused into the lunar architecture, will provide benefits that extend beyond its adopted system area. These technologies will benefit architecture elements beyond their own, and they will foster NASA's leadership in innovative technology use.*

Game-changing technologies can have a dramatic effect on figures of merit, can enable new capabilities, and can enhance exploration and science. Examples of improvements to figures of merit include:

- decreasing development costs by using technologies that are advancing more quickly in the commercial sector
- decreasing mass by leveraging lighter, stronger materials with enhanced performance
- improving reliability with technologies that have well documented performance characteristics
- improving crew health and safety with advanced medical technologies
- increasing system power by leveraging developments in commercial and military energy storage.

In addition to improvements in figures of merit, game-changing technologies can also expand or add to exploration capabilities. For example, a technology could allow citizens to directly interact with lunar sensors, thus adding capability (public outreach, in this instance) to the exploration mission. Similarly, technology could transform the exploration and science plans for the lunar surface by improving the quality, quantity, or ease of the science and exploration that is planned.

Over the course of the study, the team carefully communicated this definition of game-changing technologies during review sessions to ensure all potential technologies were measured against a consistent idea. The nineteen technology areas that were selected as the most game-changing fit the definition well. They each have potential for dramatic and extensive effects on the architecture. Some technologies promise significant improvements in figures of merit, while others promise enhancement or transformation of the capabilities of the lunar architecture.

Types of Technologies

In the course of researching technologies for this report, the team classified technologies according to three distinct types, based on the impact they have on the lunar architecture. The impacts were identified and formalized into three technology categories: Transformational, Revolutionary, and Rapidly-evolving. These categories help explain how each technology would affect the architecture, and they guide the process for future infusion.

Transformational technologies are system level technologies that cause major changes in the accepted way of doing things. A transformational technology will cause a fundamental change in the way a technology solution is approached.

- The technologies require a system change
- Example: Change power systems from energy storage to power beaming

Revolutionary technologies are component level technologies with highly improved performance or capability, and will eventually replace currently dominant technologies.

- The technologies require significant modifications at the component level
- Example: Change from batteries to fuel cells

Rapidly-evolving technologies are technologies with rapid incremental improvements in the performance of established products.

- The technology is the same but will have far superior performance to current technologies
- Example: Solar cells with increased efficiency

These technology types help categorize the effects on the architecture and guide the process for future infusion. The final selection of the most game-changing technology areas includes all three types, reflecting different integration opportunities. Of the nineteen selected technology areas, seven are considered Transformational, seven are Revolutionary, and five are Rapidly-evolving. The identification of the technology types in this report enables NASA to consider the trade-offs of infusing one of technology area over another. It also helps NASA to consider the trade space between existing technology solutions for the lunar architecture and these game-changing technologies. A graphical depiction of the trade-offs in technology infusion is shown in Figure 1.

Transformational technology areas require the most flexibility in terms of accommodating changes across elements. As an example, the current architecture uses wired power transmission from power generated by solar cells deployed from the habitat, or nuclear reactors a safe distance afield. Switching to power beaming, from arrays in lunar orbit would require design changes, with implications throughout the architecture. It would also be expected that NASA would not make such a switch without anticipating higher levels of capability from that system and the consequences of those capabilities would ripple as well.

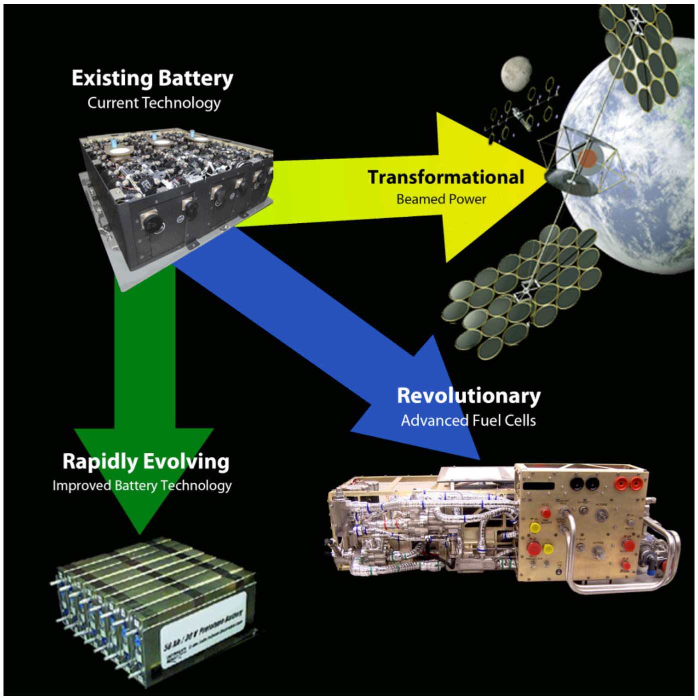


Figure 1: Types of Technologies

The infusion of revolutionary technology areas, which represent substantial changes to subsystems of the architecture, will be different. For these technology areas, NASA must have flexible system design. An example would be trading out traditional vehicle controls for autonomous controls. The shape, volume, and driveshafts on the LER would be unaffected, but the vehicle control element and operations would have undergone a revolution.

Rapidly-evolving technology areas require the least design changes to infuse into the architecture. However, they may require the most attention to and coordination with external forces in investment decisions, to assure that resources are not wasted on redundant development, or on a component that will rapidly become obsolete. These technology areas result in capability gains, but generally work according to the same principles of existing technologies. Because of this, these technology areas can be infused later in the process, allowing more of these types of technologies to be used.

3.0 METHODOLOGY

The study team was initially requested by NASA to analyze existing trajectories in emerging technologies across the economy, and identify fast-moving and dynamic technology areas that may support NASA operations. The study team reviewed all available reports focusing on disruptive, game-changing, or transformational technologies relating to national economy, defense, and space applications. This top down approach allowed the team to identify potential technology solutions that NASA is currently seeking, as well as to identify technologies on the horizon that could displace, augment, or make obsolete established NASA technologies and approaches.

The methodology employed by the study team to identify the most game-changing technologies was broken into four major steps.

1. Develop, research, and group technologies
2. Review technology areas to identify the most game-changing
3. Characterize selected technology areas for report
4. Create a technology watch list

1. Develop, research, and group technologies

A diversity of sources was used to populate the initial technology list. Comprehensive open-source research surveyed recent un-classified reports and studies on disruptive, transformational, and emerging technology trends and areas. These include those with a military focus, space focus, consumer focus, and more general studies. Each of the technologies from these reports was captured. In addition, emerging (low-TRL) technologies were taken from a data set that is a component of DIO's MATCH (Mapping Applicable Technologies to Exploration Challenges) database, the External Government Technologies data set, which tracks non-NASA government technology programs that may have NASA applications. Representative sources included:

Emerging Technology Sources
Disruptive Civil Technologies: Six Technologies with Potential Impacts on U.S. Interests Out to 2025 – National Intelligence Council, 2008
SRI Consulting Business Intelligence, Technology List, 2008
MIT-NASA Workshop: Transformational Technology, 2005
The Future Operational Environment, Mad Scientist Future Technology Seminar – U.S. Army Training and Doctrine Command, 2008
MIT Technology Review, Special Report: Ten Emerging Technologies – 2006, 2007, 2008
Avoiding Surprise in an Era of Global Technology Advances – Defense Intelligence Agency, 2005
NATO Assessment of Possible Disruptive Technologies for Defense and Security
CNES, 1st International Symposium on Disruptive Technologies, 2005
Advanced Space Systems Concepts and Technologies: 2010-2030 – The Aerospace Corporation, 2003
DTIC 5th Annual Disruptive Technologies Conference, 2008
MITRE Emerging Technologies
Technology Strategy Board, Technology Area
MATCH External Government Technologies Data Set

In the end, a list of 260 entries was compiled for initial review; this list is shown in Appendix C: Initial List of Technologies. This list was then sorted using NASA's Small Business Innovative Research (SBIR) program taxonomy, which characterizes each technology by its application in a NASA context:

NASA SBIR Categories	
Avionics and Astrionics	Materials
Bio-Technology	Microgravity
Communications	Power and Energy
Cryogenics	Propulsion
Education and Training	Robotics
Electronics	Sensors and Sources
Extravehicular Activity	Structures
Information	Thermal
Manufacturing	Verification and Validation

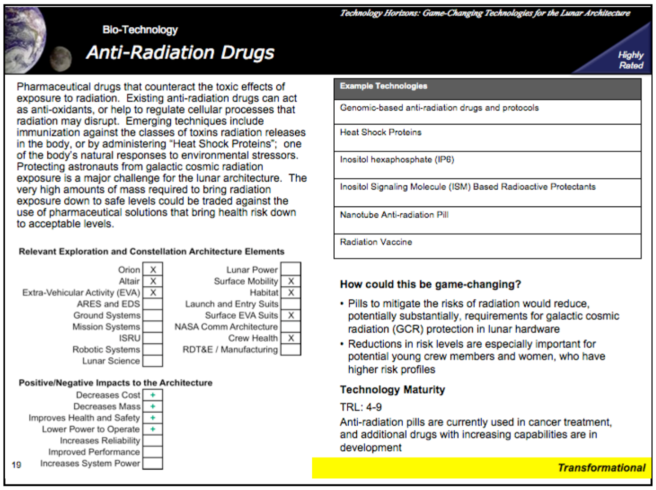
Since the initial technology list was compiled from diverse sources, and not just the space industry, some of the technologies had little or no applicability to NASA. Each technology was rated for its applicability to NASA; technologies with little or no applicability were eliminated from further analysis. Examples of eliminated technologies include green buildings and digital money. The remaining technologies were grouped into technology areas, to ensure even comparisons across proposed technologies. Some of the listed technologies were specific, while others were included as technology areas (i.e. specific medical sensors verses a large area like printed electronics). The technologies were grouped into 84 technology areas, with the original technologies that make up each of these technology areas maintained as examples under each area. The technology areas were characterized according to technology readiness level, development complexity, level of interest, benefits to the architecture, and relevance to architecture elements. Each of these measures analyzed different aspects of the technologies.

- Technology Readiness Level (TRL) gives a measure of technology maturity. This study uses Department of Defense (DoD) TRL definitions in order to assess each technology in its intended context. A technology is at TRL 9 if it is proven terrestrially; this does not measure maturity for the space environment.
- Development complexity is a measure of how difficult it is to complete development of this technology area to TRL 9.
- Level of interest illustrates the amount of research being done in different sectors such as academia, military, other government, and commercial sectors. A low level of interest denotes a technology area that is only of interest to one or two sectors while a high level of interest denotes a technology area being developed in four or five sectors.
- Benefits to the architecture rates the technology area on the positive and negative impacts the technology has on figures of merit including cost, mass, reliability, performance, power, and health and safety.
- Relevance to the architecture illustrates which architecture elements (i.e. Orion, Altair, Extra Vehicular Activity (EVA)) could be affected by the technology area.

The ratings were used to develop an internal ranking of technology areas, which the study team used to develop a preliminary prioritized list to guide the discussion in the first review panel. In addition, each of these measures was used to communicate the comparative benefits of each technology area to the review panels.

2. Review technology areas to identify the most game-changing

Summary quad charts were created for the initial 84 technology areas, including a description of the technology area, a listing of example technologies, tables showing relevant architecture elements and benefits to the architecture, brief descriptions of how the technology area is game-changing, and the technology area maturity (given as the range of TRLs for the example technologies along with a qualitative description of maturity). These charts were used to describe the technology areas in a series of reviews to downselect to the final nineteen technology areas. (Figure 2 is a sample of a technology quad chart, the full set of quad charts used in the expert review panel is included in Appendix A: Technology Area Quad Charts.)



Technology Horizons: Game-Changing Technologies for the Lunar Architecture

Bio-Technology

Anti-Radiation Drugs

Highly Rated

Pharmaceutical drugs that counteract the toxic effects of exposure to radiation. Existing anti-radiation drugs can act as anti-oxidants, or help to regulate cellular processes that radiation may disrupt. Emerging techniques include immunization against the classes of toxins radiation releases in the body, or by administering "Heat Shock Proteins"; one of the body's natural responses to environmental stressors. Protecting astronauts from galactic cosmic radiation exposure is a major challenge for the lunar architecture. The very high amounts of mass required to bring radiation exposure down to safe levels could be traded against the use of pharmaceutical solutions that bring health risk down to acceptable levels.

Example Technologies
Genomic-based anti-radiation drugs and protocols
Heat Shock Proteins
Inositol hexaphosphate (IP6)
Inositol Signaling Molecule (ISM) Based Radioactive Protectants
Nanotube Anti-radiation Pill
Radiation Vaccine

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU		Crew Health	X
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improves Health and Safety	+
Lower Power to Operate	+
Increases Reliability	
Improved Performance	
Increases System Power	

How could this be game-changing?

- Pills to mitigate the risks of radiation would reduce, potentially substantially, requirements for galactic cosmic radiation (GCR) protection in lunar hardware
- Reductions in risk levels are especially important for potential young crew members and women, who have higher risk profiles

Technology Maturity

TRL: 4-9

Anti-radiation pills are currently used in cancer treatment, and additional drugs with increasing capabilities are in development

Transformational

19

Figure 2: Sample of Technology Quad Chart

Three reviews were conducted to identify the most game-changing technology areas.

- NASA Langley Research Center review (April 21, 2009) -The purpose of this review was to focus and prioritize the list of technology areas in preparation for the architecture team review and expert review panel. This small review panel was chosen for their expertise in the lunar architecture, to review these technologies from the viewpoint of the architecture. The results of this review eliminated about one-third of the technology areas; 59 moved forward.
- Review cycle with the Constellation lunar surface system (LSS) project office and targeted design system element engineers (April – May, 2009, via email) – Initiated with a presentation on April 27th at the DIO Strategic Analysis Face-to-Face Meeting. The purpose of this review was to allow domain system element engineers, with expertise in the LSS elements including Altair, power, habitation, surface mobility, and others, to rate and comment on technology areas within their expertise. The results of this review were used to refine the quad charts for the next review cycle and to identify highly rated technology areas.
- NASA expert review panel workshop (May 28, 2009) – This review invited a focused team of senior-level representatives from throughout NASA and some participants from external technology development organizations. This review identified the final list of prioritized game-changing technology areas, which is included in this report.

3. Characterize selected technology areas for report

After the expert panel workshop identified the top game-changing technology areas, the study team further researched the selected technology areas to create detailed profiles of each area.

The result is a synopsis of each technology area that incorporates basic information on what is driving the market for the technology area, who is performing the research, profiles of example technologies, a description of the impact this technology area could have on the lunar architecture, and some information on how this technology might be infused into the architecture as a whole. Each profile contains:

- Basic market and research data - speaks to the environment for the technology outside of NASA, in terms of what other government agencies, commercial entities, and international bodies are investing in the technology area and why. Certain technology areas, particularly space specific, advance within communities where NASA's involvement is critical. In these instances (e.g. liquid rocket engines) the value of looking at research and development outside the space community is minimal. In other instances (e.g. information technology) a multitude of players advance technologies in a number of directions, pulled by market forces. Awareness of these forces is important to tracking the context of the technology area. A global approach is important to understanding the full breadth of technology development.

- Example technologies – brief descriptions differentiating technical approaches from one another, and speaking to the original applications of these technologies. These straightforward sections flesh out the technology area with specific examples of the technical challenges and innovations at the technology level.

- Game-Changing Impact to the Architecture - discusses the impact the technology would have on the lunar architecture. A table of checkboxes depicts which lunar architecture elements and figures of merit the technology areas would affect and the likely figures of merit the technology area would impact.

- Technology Trajectory - assesses the maturity of the example technologies, and provides projections of the technology development timeline, with an eye to the timeline of the lunar missions.

- Integration - discusses major integration issues both in terms of whether this particular technology is qualified for the environmental challenges of space, as well as the systemic effects on other functional elements within the architecture.

4. Create technology area watch list

The outputs of this kind of study may not be investment decisions, but rather a directive to pay particular attention to an area of the economy in anticipation of an imminent capability. A technology may be identified as potentially game-changing to the lunar architecture, but may become available independent of NASA involvement. Examples include energy storage and information technologies, which are being rapidly advanced for commercial and government applications outside of NASA. These areas with broad industrial support will continue to develop quickly without intervention from NASA. For these technologies with broad industrial support, it was decided that NASA should keep a technology watch list to track the progress, and reassess periodically.

The technology area watch list was generated from the list of 59 technology areas submitted for consideration to the expert review panel on May 28th and is shown in section 5.0 of this report.

4.0 TOP GAME-CHANGING TECHNOLOGY AREAS

Nineteen technology areas were identified as the most game-changing to the lunar architecture. For each technology area, a description of the area and specific technologies that comprise this area are detailed. The impact to the architecture is discussed, as well as how this technology area is game-changing to the architecture. Finally, the technology maturity and trajectory is profiled, and a brief discussion of integrating this technology area into the architecture is provided. The technology areas are shown in rank order as rated by the senior-level expert review panel, with energy storage technologies cited as the top game-changing area.

Energy Storage Technologies

Revolutionary

Energy storage technologies store energy in a variety of forms, including chemical fuel, electric charges, rotating mass, magnetic fields, and compressed gas. This category specifically includes batteries, hydrogen storage technologies that support fuel cells, capacitors, and magnetic energy storage, but excludes fuel cell systems. The need for portable, high-density energy sources pervade the economy, with important drivers in military operations, transportation, and personal electronics. New technologies and concepts for energy storage include new batteries and battery materials, flywheels, superconducting magnetic energy storage, ultra capacitors, and materials that are able to hold gaseous fuels in a solid state.

Technology Name	Description
Advanced Flywheel Technology	A form of mechanical storage, where a rotating disk or rotor stores energy as rotational energy.
Energy Storage Materials	Materials that can store energy in a useful form, thereby including natural materials, such as coal or uranium, but also including batteries, capacitors, and synthetic hydrogen storage materials.
Genetically-Engineered Functional Fibers	Fibers built from self-aligning viruses, genetically engineered to contain functional elements that work cooperatively when spun into a macroscopic fiber (a few centimeters long by approximately 50 micrometers). These fibers can be engineered for conductivity or energy storage.
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-ion Polymer Battery with Microporous Gel Electrolyte	A lithium-ion battery with gel suspended in a polymer matrix as an electrode. The resulting microporous gel electrolyte (MGE) can operate over a wide range of temperatures; it has high ionic conductivity and good adhesion to the electrodes at low temperatures, and maintains a high mechanical strength at high temperatures.
Lithium Sulfur Rechargeable Batteries	An alternative to typical Lithium-ion battery chemistries, using sulfur in the cathode. It has a very high specific energy that can be used in all portable and transportation applications.
Metal-Doped Carbon Nanostructures	Nano-scale formations of carbon, like carbon nanotubes, that have metal atoms added to the carbon substrate. It is theoretically feasible to bind hydrogen molecules to these metal-doped structures in a stable solid.
Metal Organic Frameworks	Porous, crystalline compounds with record-breaking surface area, potentially used for solid state hydrogen storage.
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.
Ultracapacitors	A rechargeable energy storage device that physically separates positive and negative charges on opposite sides of a very thin substrate (as opposed to opposing plates in a normal capacitor), allowing for very high energy densities.

Energy storage technologies are critical for a number of industries and government agencies, and thus receive substantial investment across industry. Outside of NASA, the military, the automobile industry, and the renewable energy sector have critical energy storage needs. The U.S. military has provided research and development funding for new and innovative batteries and novel battery chemistries.[3] The military has extensive needs for batteries in aircraft, communications equipment, robotics, and portable electronics generally. Battery research has become critical for the automotive industry in recent years with the rising demand for hybrid vehicles, and increasing investment in electric concepts.[4] This has led to research within the large automobile companies, and has seeded a market that has attracted many start-ups. Ultracapacitors have become associated with hybrid vehicles, as this application is one of the major drivers of development for these vehicles, along with power management and consumer electronics[5]. Battery storage is also important for many renewable energy concepts and the development of smart grids.[6] Whereas power plants continually adjust output based on demand, renewables, such as wind and solar energy, generate electricity according to uncontrollable events and situations. This makes storage of energy for future distribution an essential concern that is driving technology development such as the liquid battery.

Energy storage solutions include those for solid-state storage of hydrogen for fuel cells; flywheels; advanced concepts like superconducting magnetic energy storage (SMES), ultracapacitors, and genetically-engineered functional fibers; and novel battery chemistries.

Carbon-nanotube-doped carbon nanostructures and metal organic frameworks are technologies for storing hydrogen in a solid-state container, rather than in a cryogenic liquid or pressurized gas form. Metal organic frameworks are mixtures of metal oxides and organic materials that result in exceptionally high surface areas, and hydrogen adsorption at around -0.62 wt%, and up to 1.5wt% with an H2 dissociating catalyst.[7] These and similar hydrogen storage technologies generally do not apply to lunar missions, because NASA can store hydrogen more efficiently in liquid form. However, in surface mobility applications, rugged terrain could be a threat to pressurized gas tanks, and therefore may be a driver of solid-state storage. Technologies developed by the Department of Energy (DOE) are generally for transportation applications, and are willing to trade mass for ruggedness and safety. These technologies could have overlapping requirements with the Lunar Electric Rover.

Advanced batteries use structurally or chemically improved anode and cathode materials. Silicon nanowire lithium ion batteries use silicon nanostructures that can absorb more lithium than conventional carbon anodes. The anode nanostructuring increases the surface area of silicon in contact with battery electrolytes (increasing energy density as a result of higher surface area) and allows the silicon anode to swell from lithium absorption without damaging the battery, thereby increasing safety. Lithium ion polymer batteries with microporous gel electrolytes (MGEs) are designed specifically to operate over a wide temperature range through innovations to electrolyte material. Liquid batteries are designed for rapid recharge and very low cost, using molten metal electrodes and molten salt electrolyte. The technology is highly scalable, and the innovators envision the technology to be used for storing energy generated by renewable sources.[8] The lithium sulfur battery, in development by the U.S. military, would replace lithium ion batteries in many applications, with a significantly higher energy density.

Advanced storage concepts include ultracapacitors, superconducting magnetic energy storage (SMES) systems, and genetically-engineered functional fibers. Ultracapacitor technology meets requirements for rapid charge and discharge. Ultracapacitors address the traditional capacity limitation of capacitors by separating physical charges on either side of a thin substrate, rather than opposing plates. They have a low specific energy, compared to batteries, but long shelf life, and very long cycle life.[9] They also have the benefit of operating well in the cold, a challenge for batteries.[10]

Superconducting magnetic energy storage systems store energy in magnetic fields created by direct current in a coil of superconducting material. These systems have a very high cycle life, are ~97% efficient, but require immersion in cryogenic fluids to maintain their properties. They have been slow to move in the market due to expense, parasitic losses, and low energy density.[11] These technologies are typically used in power management systems.[12]

Genetically-engineered functional fibers are a low-TRL technology that uses genetically-engineered viruses to produce fibers with customized properties. Tests show promise for fibers with energy storage properties, among others. While an advanced concept, these fibers may hold considerable promise in the future.

Flywheels store energy in spinning rotors that can be charged and discharged rapidly. They have been used and investigated by NASA in the past as a replacement for batteries in some applications.[13] Flywheels are often used in grid management; terrestrial markets for the technology are driven by the increasing need for uninterruptible power systems.[14]

Game-changing Impacts on the Architecture

Energy storage is one of the critical components of outpost capability for its necessity in mobile operations, for surviving eclipse periods and other operations and scenarios. Some potential outpost locations on the lunar south pole can experience extended eclipse periods. NASA references 122 hours for maximum eclipse periods, during which the outpost will have to operate on stored electricity, assuming the use of solar power, whose panels will generate no electricity when dark.[15] Mobile applications, particularly pressurized rovers, are the other major beneficiary of energy storage technologies. Energy storage capability will directly influence exploration range. Better batteries and fuel cells could serve this role, as would the use of ultracapacitors to leverage the energy lost in braking. Fuel cells are cited as having a longer range than batteries in architecture documents.[16] With greater range comes increased exploration, and a greater science return.

Within the quickly advancing energy storage technologies profiled here, some of the technologies are far reaching, and some are more appropriate for use on specific applications within the architecture. For example, ultracapacitors and metal organic frameworks support mobile applications, while SMES and liquid batteries support electric grid management. Many of the battery technologies have wider applications throughout the architecture, where batteries could be used to power any number of applications from electronics to rovers. Fuel cells and batteries are, generally, applicable for the same range of applications, though fuel cells scale up more efficiently.

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Benefits to the Architecture

Decreases Cost	+
Decreases Mass	+
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	+

Technology Trajectory

NASA's energy storage needs require a minimum specific energy of 150-200 Wh/kg with a goal of 600 Wh/kg, while current state of the art batteries for space systems provide about 100 Wh/kg.[17] Additional technology development is therefore necessary to support these requirements. Given the investment flowing into developing and advancing energy storage technologies in both government and commercial sectors, there are many opportunities for NASA to leverage these emerging technologies to help support this requirement.

Ultracapacitors and SMES systems are available commercially, but are immature in the context of commercial technologies; they can be expected to continue development in the coming years. Genetically-engineered functional fibers have been demonstrated, but particular applications are at a low TRL and in the concept phase.

The DoD funds all three lithium batteries profiled here, which stand at TRL 6 for the lithium sulfur battery, TRL 5 for the lithium nanowire battery, and TRL 4 for the lithium polymer with MGE. Prototypes of the liquid battery exist, but they are not yet in production.

Metal organic frameworks are also at a low TRL and are among a large number of materials under investigation for hydrogen storage. However, as emphasis is moving away from hydrogen for use in the energy infrastructure of the near future, progress in researching and developing hydrogen storage technologies may slow.[18]

Integration

Energy storage is a revolutionary technology area that will affect space systems on a component level, but are unlikely to affect the technical and design aspects of integration beyond the additional capability they produce. Different technologies will have different performance variations, lifetimes, and monitoring and maintenance considerations. However, they are all wired into an element or grid the same way, and provide the same service.

Batteries used in space are susceptible to radiation effects and must be protected or designed to minimize damage. Battery performance and operations in the temperature extremes of the lunar environment present a challenge. The operating temperature range for batteries on the lunar surface is around 123 C to -88 C, while standard lithium-ion batteries operate between 80 C and -50 C.[19] The DoD is designing batteries with wide operating ranges that could be employed in either the arctic or the desert. It is highly likely that the infusion of the DoD battery technology development will require further development for lunar operation.

SMES technologies, which are normally suspended in cryogenic fluid in terrestrial applications, benefit from the cold temperatures in permanently shaded regions of the lunar surface. The relative cold also benefits ultracapacitors. These technologies would be most beneficial for the pressurized rovers, but they are unlikely to yield the range that is possible with fuel cells. They serve the system best as part of a regenerative breaking system.

The use of batteries or fuel cells on the lunar electric rover is one important area of technology selection that will depend on technology development. Currently, NASA’s Surface Architecture Reference Document (SARD) mentions that the rover can use rechargeable batteries, and carry fuel cells for longer range.[20]

Anti-Radiation Drugs

Transformational

Anti-radiation drugs are pharmaceutical solutions to counteracting the toxic effects of exposure to radiation from cosmic rays, solar flares and neutrons. Existing anti-radiation drugs can act as anti-oxidants, or help to regulate cellular processes that radiation may disrupt. Emerging techniques include immunization against the classes of toxins radiation releases in the body, or by administering "heat shock proteins," one of the body's natural responses to environmental stressors. Protecting astronauts from galactic cosmic radiation exposure is a major challenge for the lunar architecture. The mass penalties to mitigate radiation exposure could be traded against the use of pharmaceutical solutions to mitigate that risk.

Technology Name	Description
Amofistine (Brand name: Ethylol)	A cytoprotective adjuvant used to protect from radiotherapy, especially in head and neck cancer.
Bio 300	A radiation countermeasure whose affects include stimulation of hematopoietic cell growth and differentiation, inhibition of protein tyrosine kinase-triggered apoptosis, and potent antioxidant activity.
Five (5)-Androstene Steroids	A naturally occurring adrenal steroid hormone that increases the number of circulating platelets, and cells of the innate immune system, shown to be effective against radiation exposure.
Genomic-based Anti-radiation Drugs and Protocols	Future DNA-based medical interventions to reduce the health risks associated with radiation exposure, or the identification of astronauts based on their genetic radiation tolerance.
Granulocyte-macrophage Colony-stimulating Factor (G-CFS)	A protein secreted by macrophages, T cells, mast cells, endothelial cells and fibroblasts that functions as a white blood cell growth factor, and is often used following cancer treatment.
Heat Shock Proteins	A class of anti-radiation treatments based on heat shock proteins (HSPs); those naturally expressed in cells to counteract environmental stressors like heat, hypoxia, and ionizing radiation. In the lab with rats, administering gene-altering compounds (adenoviral vectors) to increase production of heat shock proteins had radiation-protecting effects.
Inositol Hexaphosphate (IP6)	An antioxidant that can protect DNA from the harmful effects of radiation by reducing free radicals. Cells treated with IP6 have an extended period of DNA repair before cell division, reducing the probability of cell death.
Inositol Signaling Molecule (ISM) Based Radioactive Protectants	A proprietary class of molecules developed and investigated by the Seattle Biopharmaceutical firm, ISM Therapeutics, that regulate many cellular processes, including actin cytoskeletal dynamics, apoptosis, cell division, and intracellular-membrane trafficking. A drug that leverages these molecules to protect from and repair radiation damage is in development.
Nanotube Anti-radiation Pill	Single-walled carbon nanotubes (CNT) coated with two common food preservatives, butylated hydroxyanisole and butylated hydroxytoluene, which absorb free radicals.
Radiation Vaccine	Vaccinations against the specific systematic toxins that radiation exposure induces in the body, referred to as Specific Radiation Determinant (SRD). SRD toxins are specific to different kinds of radiation exposure; the vaccine can be customized for nuclear power workers, commercial and military pilots, cosmonauts/astronauts, nuclear-powered engine vessel operators, and as protection against nuclear terrorism.

Drugs to mitigate the effects of radiation are under development in the medical, military, and industrial sectors, in the United States and internationally, and there are several approaches to their application. Medical interest in the technology largely stems from the need to protect cancer patients from the harmful effects of radiation therapy. Radiation therapy targets malignant tumors with radiation exposure, but can have extensive collateral damage on other parts of the body that would ideally be mitigated by these drugs. In general, research and development (R&D) funding for medical technologies comes from agencies like the National Institutes of Health (NIH) and National Science Foundation (NSF), or through in-house R&D at pharmaceutical companies. Military interest in radiation protection is in protecting soldiers from the potential fallout of a nuclear attack and other radiation sources—soldiers may be exposed to fallout from "dirty bomb" attacks, uranium artillery, reactors used in propulsion, or other non-nuclear offensive weapons.[21] The U.S. Armed Forces Radiobiological Institute in Bethesda, MD, anchors much of this research, and often leverages work done for broader medical applications, as is the case in Inositol hexaphosphate (IP6), for instance. There are also industrial applications for these technologies for employees exposed to ionizing radiation at, for instance, nuclear facilities.[22]

Anti-radiation pills either work to prevent radiation from causing damage, or work to quickly repair and normalize the negative effects of exposure. Anti-oxidants, which neutralize free radicals, are one common form of radiation protection. One of the damaging consequences of radiation exposure is the creation of free radicals—atoms and molecules with unpaired electrons that can react with other molecules and cause disruption in cells, preventing healthy cell repair.[23] Nanotube anti-radiation pills, Inositol hexaphosphate, and Bio 300 are examples of drugs that use antioxidants to counter radiation damage. Bio 300 also has compounds shown to directly inhibit cell death and contribute to cell growth.[24]

Granulocyte-macrophage colony-stimulating factor (G-CFS), heat shock proteins (HSPs), radiation vaccines, genomic solutions, and inositol signaling molecules also work to prevent damage, repair damage, or strengthen the body's natural ability to repair damage caused by radiation. G-CSF stimulates the growth and development of white blood cells to recover from cancer therapies, and is the current standard for treatment of acute radiation syndrome.[25] Five (5) androstenediol are naturally occurring steroids that stimulate the immune system, and have shown positive results in the treatment of radiation exposure.[26] Heat shock proteins are a naturally occurring substance that protects organs in times of stress. Therapy leveraging these proteins increases their production in anticipation of radiation exposure, offering natural protection from radiation exposure.[27] Genomic solutions are a projected future technology based on the use of gene therapy for radiation protection. It has been observed that susceptibility to radiation damage can vary from individual to individual—that some humans are inherently "rad-hard". Future interventions could identify and work with this underlying genetic disposition, or DNA mechanisms. Alternatively, identifying those individuals accurately could give a far more precise analysis of the risks associated with each flight, or aid in crew selection in the nearer term. Vaccines, developed by Russian scientists, do not protect against radiation per se, but provide inoculation against the particular toxins that different forms of radiation will create in the body.[28] Inositol signaling molecules (ISM) regulate particular cellular processes that radiation will disrupt; the signaling molecules themselves are simply delivery molecules that deliver therapeutic substances on the correct pathways. In anti-radiation drugs, ISM-based drugs offer regulation of cell repair and division mechanisms.[29]

Game-Changing Impact on the Architecture

The potential importance of radiation drugs to the lunar architecture stems from the amount of radiation astronauts are exposed to in space and on the lunar surface. While solar particle event (SPE) radiation can be largely predicted and prevented with water walls within habitat enclosures, galactic cosmic radiation (GCR) is not only more persistent and prevalent, but also requires massive amounts of protection for shielding. Pharmaceuticals could help reduce risk to acceptable levels and enable 180-day stays on the Moon, while maintaining habitat-shielding requirements at levels where the architecture can still function acceptably. Of particular concern is protection during EVA, where astronauts are essentially unprotected—the mass required to protect from GCR particles is well beyond the point at which it could be practically integrated into an EVA suit. Anti-radiation drugs would be particularly important to reducing the risks of EVA, and enable greater use of EVA throughout the architecture.

Missions to the lunar surface offer novel challenges to NASA due to their length and the relatively high amounts of radiation to which astronauts will be exposed. NASA's protocols are based on protection from radiation and limiting the overall exposure. Anti-radiation medications are an alternative approach that mitigates the damages caused by this exposure. This could get NASA to within acceptable risk limits for 180-day missions, and have the further benefit of reducing the risks for those within acceptable limits. The amount of mass required to protect habitat spaces from radiation is enormous, and, as mentioned, there is no practical method of protection during EVA missions. Anti-radiation pills may be essential for making the architecture work.

Relevant Exploration and Constellation Architecture Elements

Orion	X
Altair	X
Extra-Vehicular Activity (EVA)	X
ARES and EDS	
Ground Systems	
Mission Systems	
ISRU	
Robotic Systems	
Lunar Science	
Lunar Power	
Surface Mobility	X
Habitat	X
Launch and Entry Suits	
Surface EVA Suits	X
NASA Comm Architecture	
Crew Health	X
RDT&E / Manufacturing	

Benefits to the Architecture

Decreases Cost	+
Decreases Mass	+
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	
Improved Performance	
Increases System Power	

Technology Trajectory

These anti-radiation pills are in varying states of development. Near term or available medications, those developed by or with assistance from the Armed Forces Radiobiological Institute, include Amofistine, Bio 300, CBLB502, Five (5)-Androstene Steroids, G-CFS, IP6, and Inositol Signaling Molecule (ISM) Based Radioactive Protectants. These approaches use generally established mechanisms and molecules. Nanotube anti-radiation pills use a well-known approach, but are at a lower TRL, partially due to the use of carbon nanotubes in development. Heat shock proteins and radiation vaccines are being investigated internationally, in South Korea and Russia, respectively. Genomic-based therapies are more of a speculative technology based on observed effects rather than specific ongoing research.

Integration

Anti-radiation drugs are a transformational technology. Integration of these technologies trades against eliminating or replacing portions of other radiation protection systems such as radiation shielding and protective garments. Alternatively, NASA could decide to use this technology as a secondary protection. The benefit of anti-radiation medications is the simplicity of their integration into the architecture. Their mass is essentially negligible, pills or minor equipment, and could trade against either substantial mass savings in shielding systems or decreased health risk levels in the architecture. Integration would likely occur in the human health and monitoring operations. As with all oral and intravenous medications, safety and efficacy testing on Earth may be a substantial effort.

In Situ Resource Utilization (ISRU)

Revolutionary

ISRU manufacturing technologies and processes can be used on the lunar surface to harvest resources and manufacture components or structural elements. These technologies will need to function in the lunar environment or within a small, self-contained volume. ISRU manufacturing includes low temperature/low energy construction techniques, transformation of regolith into useful building materials, resource extraction and production, and manufacturing of complex architecture components from lunar materials. The outputs of these technologies will be consumables, propellants, and structural materials.

Technology Name	Description
Low-temperature Joining Processes	Manufacturing techniques such as laser or friction welding and S-Bond soldering that bind materials with less energy and heat than traditional joining technologies.
Mechanical Soil Stabilization	Polymers, synthetic fibers, or foamed asphalt additives to soil for hardening, waterproofing, controlling dust, or compensating for weather conditions.
Photochemical Splitting of Water	Uses sunlight and a chemical catalyst to split water into H2 and O2 for use as fuel and oxidizer.
Projectile Excavation	A low cost electric launch system and projectiles that are accelerated to high velocities to penetrate and crush rock. The system is compatible with vacuum, and the projectiles can be tailored for different types of rock, ore, or other materials.
Smart Motors for Resonance Sifting	Sifting with smart electromagnetic motors and specially designed hampers to establish a resonance frequency in the screen. At resonance the screen can be induced into a vibrational mode with minimal energy and no hopper vibration.
String Ribbon Manufacturing of Silicon Solar Cells	Solar cell manufacturing using high temperature resistant filaments to draw thin-film silicon ribbons from a pool of molten silicon; uses fewer raw materials than traditional crystalline silicon manufacturing; could be scaled down for manufacturing on the lunar surface with in-situ materials.

ISRU is an interdisciplinary technology area that is needed to accomplish a diverse set of tasks. It includes the use of natural materials indigenous to the Moon (regolith, solar radiation) and discarded materials retired from their original use (descent stages, propellant tanks, and residuals). ISRU aims to support site preparation, consumable production, propellant production, and outpost build-up, and self-sufficiency.[30] Although site preparation activities like berm building or trench digging for nuclear reactors are ISRU operations, they will be done with surface mobility hardware, and are not addressed in this list of technologies. NASA technologies developed to support ISRU include the Oxygen Production Plant and the Excavation Tool Kit.[31] The production plant refines regolith to produce oxygen, and the excavation tool feeds regolith into the plant.

Because ISRU is very specific to NASA, there are no directly equivalent systems-level technologies terrestrially or in the private sector. One potential exception, mechanical soil stabilization, is ground preparation polymers and foams used by the military to stabilize soil in wet conditions, or eliminate dust in areas with substantial sand.[32] On a component level, however, there are manufacturing analogs that contribute some lessons learned or conceptual approaches that may have value for future development of ISRU systems. Smart motors for resonance sifting is an innovation in sifting that may be appropriate to NASA regolith processing. The technology uses electromagnetic motors to establish a resonance frequency with the sifting screen, so that it can be vibrated using much less energy than traditional systems.[33] Projectile excavation is an alternative to drilling and blasting that uses small projectiles fired with electrical energy. The process is purported to be safer, more precise, and consume less energy than conventional mining techniques.[34] Photochemical splitting of water uses catalysts to directly split hydrogen from oxygen in an aqueous solution when exposed to sunlight.

Other industrial innovations may support future in-space manufacturing. Strong ribbon manufacturing of silicon solar cells is a very simple process for manufacturing solar cells out of molten silicon. Two strings are dipped into molten silicon and pulled out, creating a thin film between them that hardens, and can be easily cut and adapted into a photovoltaic cell.[35] Low temperature and low energy joining processes such as laser and friction welding and S-bond soldering could provide manufacturing benefits to enable in situ fabrication of lunar base elements. Laser and friction welding are established, but innovative welding/joining techniques may be beneficial for free-form manufacturing. S-Bond, an innovation of S-Bond Technologies LLC, a commercial company, is an activated solder that uses titanium and rare earth metals to remove or adhere to oxides or nitrides on the surface of the joined materials. These metals eliminate the need for high-power, focused ultrasound to clean surfaces before soldering.[36]

Game-Changing Impact on the Architecture

The production of oxygen reduces the need for consumables and propellant, potentially reducing mass across the system, but the long-term benefits of ISRU could evolve the concept of operations for buildup and maintenance. Consumable and propellant production is a move towards self-sufficiency. New mining techniques and technologies could increase the amount and kind of resources available on the Moon. Manufacturing techniques using additional resources further reduce the upmass requirements for the outpost, or expand usable assets. The more that ISRU processes are able to accomplish on the surface, the greater and more sustainable the impact of the lunar outpost will be, and the more extensibility to further destinations the base will have.

The current concept of outpost buildup includes some ISRU activities. For example, ISRU plants will extract oxygen from the lunar soil, which can be used as atmospheric gas input into the environmental control and life support system (ECLSS), or combined with scavenged hydrogen to create water, or used as an oxidizer. ISRU technologies reduce the amount of consumables needed for transport from Earth to the lunar surface, potentially reducing cost or mass.

Relevant Exploration and Constellation Architecture Elements

Orion		Lunar Power	X
Altair		Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science			

Benefits to the Architecture

Decreases Cost	+
Decreases Mass	+
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	
Improved Performance	
Increases System Power	

Technology Trajectory

The technologies listed are at varying states of TRL. With the exception of photochemical splitting of water, the remainder of the technologies listed are available or near term. Photochemical splitting has been under investigation for over 40 years, and continues to be studied in laboratory environments, with novel and nanoengineered enzymes under development and testing.

ISRU also shares a long-term trajectory with printed manufacturing. As mentioned on page 59, an integrated ISRU module that was able to separate and refine materials from raw inputs, and print out finished products, is an advanced concept that could support free-form manufacturing—the autonomous manufacture of complex machinery. The timeline for this kind of game changing effect is beyond that of the lunar architecture.

Integration

These are revolutionary technologies, components of larger systems that require integration into customized ISRU systems. As with all systems, radiation and temperature ranges are critical considerations. Mechanical soil stabilization technologies would need investigation, as they are all likely to react with air when hardening to form a rigid surface. The need for air is a similar concern with forms of welding and soldering.

Radiation Shielding

Revolutionary

Radiation shielding materials block solar particle events (SPEs), galactic cosmic radiation (GCR), and radiation trapped in planetary magnetic belts, with either physical barriers, or electric and magnetic fields. This technology area includes lightweight radiation shielding materials and functional materials that provide radiation shielding through electrostatic and magnetic forces. Radiation shielding technologies perform differently for SPEs, GCRs, photons, and neutron sources. Consequently, complete radiation shielding solutions could require a hybrid approach.

Technology Name	Description
Carbon Nanotubes with Adsorbed Hydrogen	Currently being researched for energy storage applications. These materials also have radiation shielding properties for high-energy particles.
Electrostatic Radiation Shielding	Uses repulsive forces to deflect charged particles away from a location.
Isotopically Enriched Boron Nitride Nanotubes	Have similar properties to carbon nanotubes and increased resistance to oxidation. These nanotubes can absorb neutrons.
Superconducting Magnetic Radiation Shielding	A strong magnetic field created by current in superconducting wires. The magnetic field deflects charged particles away from the crew.
Multifunctional Polymeric Nanocomposites for Radiation Shielding	Incorporates atoms and molecules with radiation shielding properties into a lightweight polymer matrix.
Lunar TexShield	A blanket designed for use in lunar surface systems, developed by North Carolina State University, made of layers of a nylon polymer containing radiation-absorbing metal compounds.

Aerospace, military, nuclear, and medical markets use radiation shielding materials. Military agencies rely on radiation shielding materials to protect soldiers from nuclear fallout, low-level contamination from dirty bombs, or depleted uranium munitions.[37] Chemical, biological, radiation, and nuclear (CBRN) protective equipment primarily provide radiation protection by preventing particle inhalation and adhesion to skin.[38] Nuclear power plants use concrete and steel to absorb radiation. Medical applications provide protection from penetrating radiation, but solely for small doses such as radiation from x-ray machines.[39] The amount of radiation that astronauts are exposed to over long duration missions outside the Earth's magnetic field require protection beyond the low mass solutions used in these markets and solutions that are more manageable than large amounts of concrete.

The ideal shielding material for charged particles from SPE or GCR is hydrogen, preferably as a dense liquid or solid.[40] However, liquid hydrogen is heavy, energy intensive to maintain, and provides no structural benefit to most habitat and spacecraft designs. For high-energy photons, heavier materials like lead perform better.[41] A number of technologies can provide partial protection by using lightweight, hydrogen-rich or embedded materials; electromagnetic fields; or by using other elements that are good neutron and gamma ray absorbers.

Electrostatic radiation shielding technologies deflect charged particles with electric fields. One example technology would use strong fabric balloons with a conductive coating, such as gold. A charge would be loaded onto the balloons on the lunar surface, inflating them through electrostatic forces. Negatively and positively charged balloons would be arrayed to provide a barrier to charged particles, though the overall system maintains a net electrostatic potential of zero.[42]

Carbon nanotubes with adsorbed hydrogen materials have been reported to store 3-10% hydrogen by weight at room temperature; however, there is controversy over the validity of these results.[43] Experimental success with storing hydrogen in doped carbon nanotubes has been shown at the National Renewable Energy Laboratory (NREL).[44] Other solid hydrogen storage technologies are currently being researched.[45] The concentration of hydrogen in these materials makes them attractive for radiation shielding. In addition, carbon nanotubes with adsorbed hydrogen could be used as a multi-purpose material for structural elements or energy storage, making them attractive for use on the lunar surface.

Isotopically enriched boron nitride has a higher concentration of the isotope boron-10, a stable, naturally occurring isotope of boron. Boron-10 is an efficient neutron absorber, yielding boron-11, the more common stable isotope.[46] Boron nitride nanotubes are very strong and can be used in structural elements, in addition to providing radiation protection from fusion sources or neutron scattering from impacts of GCRs.[47]

Superconducting magnet systems can create intense magnetic fields with little electrical power loss, and maintain these fields for long durations. Current challenges to this technology include developing a lightweight system that can create a magnetic field large enough to protect a habitable spacecraft. Another challenge is keeping the system at cryogenic temperatures, which gives the materials their superconductive properties. However, recent advances in superconducting technology and materials permit superconductive properties to exist at temperatures higher than 120 Kelvin (−153° C).[48] Superconducting magnetic shielding would provide protection against charged particles, but not photons or neutrons.

Polymeric radiation shielding comes in multiple forms, and there are several technologies in various states of development, including Demron, a commercially available technology.[49] Multifunctional polymeric nanocomposites include a hydrogen-rich monomer that is polymerized with metallic nanoparticles. The resulting nanocomposite can protect against low-energy protons and electrons from SPEs; high-energy, high Z number radiation from GCR; and high-energy gamma and x-rays.[50] Other elements such as boron or rare earth elements can be incorporated for additional GCR and neutron shielding. A specific example of polymeric shielding is the Lunar TexShield, developed by textile engineering students at NC State University. Lunar TexShield has layers of radiation shielding materials including lead sulphide, boron oxide, barium sulphate, and Demron fabric. In addition, the outer layer of the Lunar TexShield blanket is made of flexible solar panels that can generate electricity.[51]

Game-Changing Impact on the Architecture

In the current architecture, four astronauts can be protected from SPE radiation by using a five-centimeter water wall that encloses a small portion of the habitat element.[52] However, this design does not provide enough protection from GCR. GCR is a constant radiation source and potentially requires massive amounts of radiation shielding throughout the architecture. This mass requirement would be prohibitive to the lunar architecture and is currently not part of the design.[53] Effects of GCR on astronauts are being further studied.

Finding cost-effective, low-mass radiation protection is necessary to allow long duration stays on the lunar surface. All the technologies listed here are being developed to provide improved shielding with lower mass. Additionally, nanotube technologies and polymeric fabrics are multifunctional, so they could possibly be used as a replacement material for other architecture components.

Electrostatic and magnetic shielding can provide protection over larger areas, potentially over the entire outpost with lower mass than current shielding options. Electrostatic shielding balloons are lightweight and can be folded for transport, but challenges associated with discharging and electrostatic attraction of lunar dust could be an issue.[54] Superconducting magnetic radiation shielding has the potential to reduce the mass of shielding required by an order of magnitude, providing it can use lightweight cryogenic cooling technologies.[55]

New radiation shielding materials technologies such as nanotubes and polymeric fabrics can provide radiation shielding comparable to current shields with dramatically less weight. Nanotube structures and polymeric fabrics can both provide multiple functions to the architecture. Nanotube structures whether made from carbon or boron nanotubes can provide both low-mass radiation shielding and energy storage. Similar to nanotube structures, polymeric fabric shields are lightweight and could provide a dual use for the lunar base. The TexShield has been designed to collect solar energy as well as protect from radiation.[56] The multi-functional polymeric nanocomposites technology provides structural integrity for flexible and rigid structures and habitats, and electrical conductivity for electrostatic control for dust mitigation during lunar missions.[57] Because there is no one technology that provides complete protection for all types of radiation, combining radiation shielding materials into a hybrid solution that incorporates elements with different radiation shielding properties may provide the best options for protection throughout the architecture.

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU		Crew Health	X
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	
Improved Performance	+
Increases System Power	

Technology Trajectory

Most radiation shielding system technologies described here are at low TRLs or in the conceptual phase. Demron is an exception and is currently commercially available. Electrostatic shielding has been studied and analyzed conceptually, but development does not appear to be moving forward past the conceptual phase. Nanotubes are being studied for a myriad of applications and carbon nanotube materials for radiation shielding were identified by a 2005 NASA workshop for further study.[58] The use of magnetic fields for radiation shielding is not a new technology, however, the ability to produce magnetic fields strong enough to enable magnetic shielding around a habitable volume on the lunar surface is just being developed. Magnetic field shielding will require further study before it can be considered for the lunar architecture.[59] With the exception of Demron, multifunction polymeric fabrics for lunar systems are in the conceptual stage of research and development. Polymeric fabrics are being studied as an SBIR for NASA, at North Carolina State University and by BAE Systems for Marshall Space Flight Center (MSFC).[60]

Integration

Radiation shielding to protect from SPE's and GCR's is a necessary aspect of long-duration stays in space. The technologies shown here are primarily revolutionary in that they are components of larger systems, such as the habitats and clothing. Nanotube and polymeric fabric technologies could be incorporated into other systems in the architecture, such as part of the structures for habitable volumes. These technologies are also flexible and can be designed into clothing. These lightweight solutions could be used to replace or enhance the water shields currently planned. Any multifunction technologies that can provide energy collection or storage would also require integration and design with those systems. The exceptions to these component technologies are electrostatic and magnetic shielding technologies, which are whole systems that must be designed with the lunar base and would eliminate the need for other types of shielding.

Advanced Pressure Garment Technologies

Transformational

Advanced pressure garment technologies support EVA surface suit capabilities. Long-duration lunar EVA missions require EVA suits that are lighter, mitigate dust damage, and protect from radiation, if possible. The game-changing technologies identified to support this mission include next-generation suits, such as the Bio-Suit concept designed at MIT and the North Dakota Experimental-1 (NDX-1), a next generation suit that is light enough to also be used on Mars. Additional technologies support component capabilities of EVA suits. Advances in visual visors increase comfort and productivity. Intravenous perflourocarbon is under development to treat decompression sickness and could be used to reduce prebreath protocols. Additional related technologies include self-healing materials, radiation shielding materials, and energy scavenging technologies.

Technology Name	Description
Bio-Suit	A skintight pressure garment that maintains internal pressure through mechanical force.
Digitally Enhanced Night Vision Goggle (DENVG)	A helmet-mounted night vision system that enables real time image enhancement and generates a digital output.
Demron	A lightweight, fabric-like material for radiation shielding.
Intravenous Perflourocarbon	A nonpolar liquid capable of dissolving respiratory gasses for treating decompression sickness, or intravenous oxygenation.
North Dakota Experimental-1 (NDX-1)	A next generation space suit designed and tested for the specific challenges of exploring the surface of Mars.
Power-Generating Backpack	A suspended-load backpack that converts mechanical energy from walking into electricity up to 20 Watts.
Self-Sealing Protective Garment	Uses advanced materials, like a laminate or a sealing polymer coupled with a containment fabric, to fill new holes or tears in a garment.

Spacesuits are a specialized technology used solely for living and working in space. The market for these garments is limited to governmental space programs and the limited and future commercial human spaceflight market. However, some components of these garments could be enhanced through the use of technologies developed for other purposes. These external technologies could provide radiation protection, improved EVA operations' performance and length, and provide power for hand tools. The DoD and the Department of Homeland Security (DHS) use Demron suits and blankets for protection against nuclear, chemical, and biological attacks. The military is also developing self-sealing fabrics that provide protection to soldiers and first responders in the event of a breach in contamination suits. The U.S. Army has developed enhanced night vision goggles, while the Office of Naval Research has developed power-generating backpacks that can power handheld devices. Perflourocarbon is being developed to eliminate decompression sickness (DCS) for divers, and could also aid astronauts, who can experience DCS while conducting EVAs.

The bio-suit system is a next generation suit concept designed at MIT. It is a hybrid technology that combines wearable electronics, information systems, and biomedical technologies.[61] The suit is a skintight pressure garment that maintains internal pressure through mechanical counter-pressure force rather than gas pressurization. Life support is provided through a helmet with a breathable atmosphere, and by suit layers that control temperature and skin respiration. The functional components can be embedded in the inner layers, and an external layer can be applied separately from recyclable materials to help mitigate dust contamination.[62] The entire suit is flexible and lightweight, which could relieve some of the physical strain that astronauts endure when using the current EVA suit design.[63] Another benefit of the BioSuit is that it can be designed to different resistance levels. This would enable astronauts to exercise against the suit, helping to maintain their muscle strength for long-duration stays in space. This application could also be used terrestrially for athletic training and physical therapy.[64]

The NDX-1 suit was designed specifically for use on Mars. It is a pressurized suit with six layers of protective fabric and weighs only 50 pounds (excluding life support and communications). It has a removable covering that protects against dust and extreme temperatures, and it has soft fabric joints that improve mobility. The NDX-1 has been tested in Mars analog studies.[65]

Demron is a polymer fabric of polyurethane and polyvinylchloride that incorporates embedded heavy metals with radiation-shielding characteristics. The material has the consistency of heavy, dense rubber. It is effective against alpha and beta radiation, and reduces but cannot completely block gamma radiation. For gamma radiation, Demron is comparable to iron and is significantly less effective, by thickness, than lead. However, due to Demron's lower density, it is more effective than a lead shield 150% its weight for high-energy gamma radiation.[66] Although Demron is more expensive than lead, it is lighter and can be treated like fabric for cleaning. Demron radiates heat and can be used for full body suits.[67]

Research and development is underway to produce protective garments that are able to continue providing protection after a breach is made in the garment. These garments could be used in pressurized space suits and for chemical and biological protection for the military and first responders. One material currently under consideration is a laminate of a sealing polymer coupled with a containment fabric. The fabric holds the polymer in place, and the sealing polymer moves between the fabric fibers to fill a breach in the material.[68] This self-sealing pressure barrier technology is also being considered for use in inflatable structures and shelters with space and terrestrial applications.

The digital enhanced night vision goggle (DENVG) is a helmet-mounted night vision system. The goggles use both image intensification and uncooled thermal imagers to "provide a multi-spectral image during day, night, and obscured battlefield conditions." DENVGs have custom electronics that digitize sensor data, manipulate the images, and fuse the sensor data into a single visual output. These electronics enable real time image enhancement and generate a digital output, which is intended to interface with other electronics via a USB port. DENVGs will be hardened against environmental conditions, although not to electromagnetic radiation. These goggles are designed to work with lithium AA batteries.[69]

Perflourocarbon (PFC) is a non-toxic, nonpolar liquid capable of dissolving significantly more respiratory gasses (O2, CO2, N2) than polar solutions like water or other aqueous solutions, such as blood plasma.[70] It has been investigated for the treatment of decompression sickness (DCS), as it can dissolve significantly more nitrogen than blood, reducing N2 gas bubble formation.[71] PFC may be used to reduce prebreathe time before EVA. It has also been tested as a way of intravenously oxygenating blood, as a substitute for breathing. Intravenous oxygenation is a much longer-term application.

The suspended-load backpack is a rigid frame pack where the sack carrying the load is suspended from the frame by vertically oriented springs. The vertical movement of the backpack contents during walking provides the mechanical energy to drive a small generator mounted on the frame. The pack can generate up to 20 Watts of electricity, more than enough energy to power a number of portable electronic devices at once.[72]

Game-Changing Impact on the Architecture

The ability to explore the lunar surface with frequent EVAs is a cornerstone of the lunar architecture. The primary impact of these technologies is to increase duration and frequency of EVAs by significantly enhancing astronaut productivity during EVA, increasing the duration of EVAs, improving durability of the suit, providing radiation protection, and supporting crew health during EVA.

If both radiation exposure and the physical demands of current suit designs were decreased, EVA durations could be lengthened. Next generation suits are lighter weight, more maneuverable, and have been designed to alleviate dust. New fabrics like Demron could be incorporated into suit designs to provide radiation protection. Self-sealing garments would allow astronauts to continue an EVA even if their garment is torn. These technologies could create suits that would last much longer and provide enhanced protection to astronauts. Additionally, self-sealing garment fabric could be used to improve the reliability and sustainability of inflatable structures.

Other technologies that can impact the design of the suit are EVA suit components: night vision goggles and power-generating packs. Night vision goggles can improve performance in low light conditions. Suspended-load backpacks increase astronaut mobility and comfort by alleviating the strain of the PLSS. Additionally, these packs could supply power for the PLSS or handheld devices.

Intravenous perflourocarbons could reduce prebreathing times. Long-term potential applications of this technology include chemically oxygenating the blood, eliminating the need for respiratory gasses in the suit. This would decrease mass by reducing consumables used on EVAs.

Relevant Exploration and Constellation Architecture Elements

Orion		Lunar Power	X
Altair		Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	X
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU		Crew Health	
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improves Health and Safety	+
Lower Power to Operate	+
Increases Reliability	+
Improved Performance	+
Increases System Power	+

Technology Trajectory

Advanced pressure garment technologies currently range in maturity from TRL 2 through 9. Prototypes of the BioSuit and NDX-1 have been developed, and some terrestrial testing has been completed.

Component technologies are more mature and could be incorporated into future generations of existing suits. Digital night vision goggles and suspended-load backpacks are currently in use by the military and consumers. However, power-generating variants of suspended-load packs are still being developed. Researchers are still developing the interface for connecting the backpack to the various electronic devices. Options under consideration include charging the gadgets directly from the backpack using cables or creating standardized batteries for the various electronics.[73]

The first generation intravenous perfluorocarbons entered the market in 1989, but were recalled in 1994. The current second generation drugs are under phase II and III evaluation by the Food and Drug Administration (FDA) for their application with patients at risk of hypoxia, or lack of oxygen in the blood, while undergoing procedures like transplants.[74] The application for prebreathing is in lower, preclinical stages of development.[75] Use as an alternative to breathing is theoretical.

Integration

Advanced pressure garments, such as the BioSuit and NDX-1, are transformational technologies that would require replacement of the current suit. Other technologies would require redesigning portions of the suit. For example, the current EVA surface suit could be reconfigured to replace the original material with the self-sealing protective garment. Integrating perflourocarbons does not require a change to the current design, but it could allow for changes in operations, to the size of oxygen tanks, and to the overall PLSS.

Nuclear Power Technologies

Rapidly Evolving

Non-propulsion nuclear space systems generally use either fission systems or radioisotope generators (RTGs) as alternatives to solar power.. Fission systems convert the heat generated from a controlled fission reaction into electricity, generally by using thermoelectric materials, or a combination of heat pipes and Stirling or Brayton engines. Fission reactors have the potential for very high power output. RTGs convert the decay of a radioactive substance into electricity using thermoelectric or thermophotovoltaic systems. These systems are often used on interplanetary missions for their long life and energy density, but they provide a relatively limited amount of power. Nuclear power could provide an energy-rich, centralized power source for a lunar outpost. It could also serve individual elements, from sensors networks to mobility platforms.

Technology Name	Description
Fission Reactors	Captures the energy release from a large nuclei (such as uranium 235) for conversion into electricity.
Fusion Reactors	Captures the energy released when two atoms fuse to create a larger element.
Structural Bond Energy Release (SBER)	Materials that release substantial energy in solid-solid phase change transitions.
Low Energy Nuclear Reactions (LENR)	Nuclear reactions occurring at near room temperature.
Microisotope Power Source	A very compact radioisotope generator that would be able to replace batteries in some applications, bringing order of magnitudes greater energy density.
Radioisotope Power Generation	Conversion of the heat released from radioactive decay, such as plutonium 238, into electricity.
Stirling Radioisotope Generators (SRG)	A radioisotope generator that uses a Stirling engine to convert heat sources into electricity.

The DoD and DOE are heavily tied into nuclear technologies. The two departments work closely with all concerns related to nuclear weapons. The U.S. Navy has extensive experience with nuclear reactors for propulsion. The military also conducts research and development in advanced innovative nuclear concepts like Low Energy Nuclear Reactions (LENR), with funding in 2010 under defense research sciences. NASA has traditionally been active in nuclear technologies as both a developer and consumer. Due to its strategic importance, governments tightly control nuclear technologies.

Fission systems are the most common and mature form of nuclear energy, splitting large nuclei and converting the released energy into electricity through steam generation or other methods. These systems are used extensively; supplying about 21% of the electricity used globally, and powering many military ships.[76] Several fission reactors, mostly Russian, have been used in space. The United States flew the SNAP-10A (System for Nuclear Auxiliary Power) in 1965, and Russia flew over 30 reactors in reconnaissance missions between 1967 and 1988.[77]

NASA and the DOE are currently developing fission surface power technology for potential human missions to the moon and Mars under the Exploration Technology Development

Program. The reference concept generates 40 kWe and uses a liquid-metal-cooled, fast-spectrum reactor with Stirling power conversion.

Fusion reactors work with a well-established mechanism of fusing the nuclei of small atoms into larger atoms, releasing substantial amounts of energy. Fusion reactors pose a more difficult engineering challenge than fission. The primary challenge faced with fusion reactors are temperatures in excess of 100 million degrees Fahrenheit, beyond the point at which material containers can be used.[78] Experimental reactors exist, but there are no current plans for reactors that would generate electricity commercially. ITER (originally the International Thermonuclear Experimental Reactor), a large-scale demonstration reactor, is in the early stages of construction in the south of France, with experiments scheduled to commence in 2018.

LENR is a controversial form of nuclear power, colloquially known as cold fusion, which ascended to infamy in the late 1980s and then became taboo in subsequent years. Despite the respite, LENR is launching a modest comeback. SRI International conducted extended research into the phenomenon in the 1990s with positive results, even while the US patent office continued to refuse applications for the process. Most recently in 2009, a major U.S. government entity, the Space and Naval Warfare System (SPAWAR) Center in 2009 claimed visual and replicable evidence of the phenomenon.[79] The SPAWAR's experiment worked by electrolyzing a solution of palladium chloride and heavy water with a nickel or gold electrode. In LENR, there are brief periods in which the power output of a given cell is greater than the power supplied to it. The physical process of how this occurs is still not well understood, but may indicate a nuclear reaction.[80] One theory indicates that the anomalous power is the result of deuterium-deuterium fusion, although the idea has attracted rival explanations and no consensus. Regardless of the theory, the mechanism is not well established, and is in the early stages of research.[81]

Radioisotope generators (RTGs) are a relatively simpler technology. A decaying radioactive material releases heat, which is then converted to electricity using thermoelectric materials, or thermophotovoltaics. These are commonly used on interplanetary missions. Microisotope power generators are developmental technologies that miniaturize this process for small, mobile applications. Next generation radioisotope generator technology uses Stirling engines to create mechanical energy from heat. Stirling Radioisotope Generators (SRG), in development at NASA for a number of years, have several times the efficiency of RTGs, (20 to 30 percent efficient verses 6 to 7 percent) saving cost in plutonium procurement and in lower mass.

Game-Changing Impact on the Architecture

Energy is a critical consideration for all aspects of lunar operations. Abundant power increases capabilities on the surface, introduces scalability into operations and concepts, and reduces the need to spend astronaut time for power-saving activities (i.e., astronauts can "leave the lights on"). Solar power is the predominant option in the architecture. The level of energy provided by solar power is sufficient, but requires planning with regards to when the power units are flown during buildup, and it requires technology development across the architecture to conserve power usage.

The abundant power possible with nuclear reactors could be an important resource. Perhaps most critically, having nuclear power baselines moving forward saves upfront design resources across the architecture, as all technologies do not need to be designed for low-power operations. Apart from reactor technology, RTGs and SRGs could be used instead of batteries in mobile or remote applications, such as in distributed sensor networks, or to provide auxiliary power to surface vehicles.

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)		Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems		NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Benefits to the Architecture

Decreases Cost	-
Decreases Mass	
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	+

Technology Trajectory

Fission reactor systems are very mature; nuclear reactors have been in operation in Navy vessels since the 70s. A space-qualified version of these reactors would be among the options with the lowest development costs. Radioisotope generators are also mature, and have flown in space extensively. However, the industrial base for the fuel commonly used in these systems, Plutonium 238, is very weak. It is no longer produced internationally, the U.S. supply is dwindling and mostly accounted for, and the global supply, entirely in Russia, is reported to be only around 10kg.[82]

Fusion systems and advanced concepts are highly unlikely to be available within the 2030 timeline. A very large, 30-year, $14 billion project called ITER, a collaboration between China, EU, India, Japan, Korea, Russia, and the United States to demonstrate the feasibility of a large fusion reactor, began construction in 2007.[83] There are no operational reactors. Structural Bond Energy Release (SBER) and LENR are advanced concepts that would take many years to develop if they ever advance beyond theoretical stages.

Integration

Nuclear power technologies are rapidly evolving. A reactor for the Moon can be developed with mature existing technologies. With development funds, the size and mass could be reduced. As mentioned above, operating the lunar outpost with abundant power enables enhanced operations and development cost savings across the architecture. This comes at the expense of cost risk for the reactor, and political risk overall. Emission of radiation is a further concern to astronauts operating on the surface. For this reason, some nuclear architecture concepts bury the reactor in lunar regolith. Overall, however, the amount of radiation exposure from the reactor is minimal compared to normal levels of galactic cosmic radiation throughout the surface. It should also be noted that LENR technology is desirable because of its potential to produce power on the scale of nuclear fusion with none of the harmful radiation side effects.[84]

Nuclear power technologies present political challenges. Launching radioactive material poses a risk that draws political attention, even when radioactive isotope generators are involved. Nuclear reactors may draw even more consideration.

Advanced Nanotube-Based Materials

Rapidly Evolving

Nanotubes are long, thin, nanometer-scale cylinders. Nanotubes are commonly made from exclusively carbon atoms, or boron and nitrogen lattices; however, other materials including silicon, metal oxides, and DNA have been used to manufacture nanotubes. Their nanostructures have a length-to-diameter ratio unequalled by any other materials. These cylindrical molecules are extraordinarily strong and have a broad range of electronic, thermal, and structural properties that change depending on the nanotube. The novel properties make them potentially useful in many applications in nanotechnology, electronics, optics, and other fields of materials science, as well as potential uses in architectural fields.

Technology Name	Description
Boron Nitride Nanotubes (BNNTs)	Nanotubes of Boron and Nitrogen similar in shape to carbon nanotubes, with very similar strength and encapsulation properties; are thermally stable; are more resistant to oxidization and have better electrical properties than carbon.
Carbon Nanotubes (CNTs)	Nanometer-scale tubes of carbon in a hexagonal lattice; often added to other materials to increase strength without increasing mass.

Carbon nanotubes (CNTs) are nanometer-scale tubes of carbon in a hexagonal lattice. Nanotubes can have a single, one-atom-thick wall, similar to graphene, or multiple walls. The number of walls and lattice structure of CNTs change their physical properties.[85] CNTs can have high electrical conductivity, tensile strength, flexibility along the axis, thermal conductivity, and can emit electrons. CNTs are often added to other materials to increase strength without increasing mass. Applications can include additives for concrete and sports equipment; artificial muscles; ribbons for a space elevator; and electrical components such as transistors, diodes, and resistors.[86] CNTs are being research throughout the world with a broad range of potential applications, including nanoelectronics, composites, chemical sensors, biosensors, microscopy, nanoelectromechanical systems, and many more.[87]

Boron nitride nanotubes (BNNTs) have similar properties to carbon nanotubes due to their structural similarities.[88] Graphene and hexagonal boron nitride have similar structural properties and can be easily manufactured as a rolled tube. In bulk crystals, graphene and hexagonal boron nitride have different layering properties, however the interface between layers and the distance between atoms within a layer is similar for both materials, about 6.6A and 2.5A respectively.[89] BNNTs are thermally stable and are more resistant to oxidization than carbon. These properties make BNNTs more suited for high temperature applications or in corrosive environments, such as batteries, fuel cells, and ultracapacitors.[90] They have a wide bandgap and are predicted to perform well in semiconducting and optoelectronic applications.[91]

BNNTs offer several advantages over CNTs.[92] BNNTs have better electrical properties, which are not solely dependent on the specific nanotube geometry (i.e. tube diameter and number of layers).[93] BNNTs could conceivably be doped to make electrical devices on a single nanotube.[94] Metallic boron nanotubes, nanotubes constructed exclusively of boron, could be better conductors than carbon and may be superconducting at high temperatures, which theoretically would enable a superconducting nanocomputer.[95]

Game-Changing Impact on the Architecture

Both carbon and boron nitride nanotubes can provide large mass savings for the lunar architecture. Their high strength and low weight could potentially decrease the mass of structural materials, and if widely deployed, could have a large impact on the total system mass of the lunar architectures. In addition, isotropic enriched boron-10 nanotubes adsorb neutrons and could provide radiation shielding.

Applications of carbon and boron nanotubes can affect every element of the lunar architecture. They can provide improved performance in a number of space systems including biotechnologies, transistors, ultracapacitors, structures, windows, radiation shielding, and solar cells. Research for this study identified many technology areas leveraging developments in nanotube technologies:

- Anti-radiation drugs
- Emerging therapeutics
- In-situ medicine
- Nano-electronics
- Quantum computing
- Nano-manufacturing
- Advanced coatings and adhesives
- Artificial muscles
- Power-generating materials
- Radiation shielding
- Transparent composites
- Energy storage
- Next generation solar cells

In addition to these areas, nanotube technologies have promise for longer-term future space applications. In some potential space systems, such as space elevators, nanotubes are being considered as a possible enabling technology.

Relevant Exploration and Constellation Architecture Elements

Orion	X
Altair	X
Extra-Vehicular Activity (EVA)	X
ARES and EDS	X
Ground Systems	X
Mission Systems	X
ISRU	X
Robotic Systems	X
Lunar Science	X
Lunar Power	X
Surface Mobility	X
Habitat	X
Launch and Entry Suits	X
Surface EVA Suits	X
NASA Comm Architecture	X
Crew Health	X
RDT&E / Manufacturing	X

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	-
Improved Performance	+
Increases System Power	+

Technology Trajectory

Due to their useful properties and applications, CNTs and BNNTs are of interest to the scientific community. There have been hundreds of potential applications and products articulated for these materials, which are in various states of development, from TRL 2 through 9. They are currently being used as bulk nanotubes for material additives in applications like high-performance bicycles. However, commercial applications have been gradual, due to high production costs and issues concerning reliability. When exposed to oxygen or a natural atmosphere, carbon nanotubes degrade within a few days.[96]

Nanotube applications are limited by the lack of bulk manufacturing techniques.[97] This is true for both carbon and boron nitride nanotubes.[98] The Australian National University is currently studying mass production methods for boron nitride nanotubes.[99] Nanocomp Technologies is the only commercial producer of carbon nanotube yarns and mats. They can produce CNT yarns up to 10 km and mat up to 4ft by 8ft, currently the largest in the world.[100] NASA has also made advances in manufacturing single-walled CNTs without the use of a metal catalyst that are enabling less expensive and more robust products using simpler and safer methods that are producing a higher yield.[101]

Integration

Nanotube technologies, both carbon and boron nitride, are primarily rapidly-evolving technologies that can be integrated into the architecture by switching from current technologies to a similar nanotube-based technology. An example would be changing from current electronic components to nanoelectronics. However, some applications of nanotube materials may require system redesign to take advantage of performance improvements of nano-components.

Integration of nanotube structures would require system-level changes to the architecture. Because nanotubes are being integrated into so many technology areas, it may even be possible that NASA would unintentionally infuse nanotubes into the architecture simply by pulling in other advanced technologies that are taking advantage of the benefits of nanotube technologies.

Next Generation Fuel Cell Technologies

Rapidly Evolving

Fuel cells are electrochemical energy conversion devices that generate electricity from chemical energy. Fuel cells are differentiated from batteries because of the external source of fuel and oxidants. In a basic hydrogen fuel cell reaction, a catalyst splits hydrogen gas into two ions and two electrons at the anode. The electrons conduct through the anode to provide a direct current for an external circuit. On the cathode side, a catalyst splits oxygen gas into two oxygen atoms. The oxygen, hydrogen, and electrons combine at the cathode to form water. Fuel cells can be continuously operated as long as the fuel feeding the cell is replenished. Hydrogen is not the only type of fuel that can be used, but it is the most common. In some cases, reformers strip hydrogen from a hydrocarbon fuel such as methane, or alcohol such as ethanol (alcohols and hydrocarbons being, generally, the two categories of fuels used in fuel cells). In other cases, an alcohol like methanol can be used directly. Because the fuel is stored externally, only the storage element needs to be increased if a fuel cell is scaled up for greater energy density of the overall system. For this reason, fuel cells have the potential for higher energy densities than batteries for larger systems.

Technology Name	Description
Micro-scale Fuel Cells	Fuel cells specifically designed to power small electronic devices.
Nitrogen-doped Carbon Nanotubes Catalysts	Vertically aligned carbon nanotubes on a substrate that can catalyze oxygen reduction reactions at a fuel cell cathode.
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.
Core-Shell Catalysts for Proton Exchange Membranes	An alternative catalyst for proton exchange membranes that reduce the amount of platinum used.
Innovative Hydrogen Liquefaction Cycle	A helium-based refrigeration cycle employing Reverse-Brayton turbomachinery.

The potential importance to many different application areas makes fuel cell technology dynamic and fast moving across the economy—improvements can be expected over the next several decades. Research and development spending is estimated to increase 15% annually through 2013.[102] As the technology evolves, it is not finding one dominant application but many; fuel cells can be used in consumer electronics, appliances, power tools, auxiliary power units, watercraft, and weapons systems.[103] Research advancing fuel cells covers all components of the devices: research into more effective or less expensive catalysts, catalysts and microbes to enable different fuels, membrane materials, bi-polar plates, and fuel storage material and concepts. Advances in fuel cells would have impacts across the lunar architecture, in terms of lower mass, higher capability, or greater range on mobile assets. Innovations in the technology may increase the types and power levels of applications for which fuel cells are efficient.

Major sources of non-NASA funding for fuel cell technologies include the DOE, the military, and some commercial sources. Fuel cell research was a major part of the DOE hydrogen initiative, begun in 2003. Research into platform technologies to enable a hydrogen infrastructure was a major part of this initiative. The program's budget was cut by about 60% in 2009, but several programs remain active.[104] DoD interest in fuel cell technologies range from advanced aerospace applications to human portable, miniature solutions. Portable energy is always a critical component for the military, where logistics are central to forward operations. The military thus shares mass efficiency requirements with NASA operations. On the commercial side, funding for fuel cells has waned after much enthusiasm and investment in the first half of the decade, as mass markets have yet to materialize.[105]

DoD research includes development of proton exchange membrane (PEM) fuel cells, fuel cell miniaturization efforts, and novel catalysts. PEM fuel cell research includes optimizing design of membranes for humidity, temperature, and high performance. Catalyst research includes nitrogen-doped carbon nanotubes. These catalysts are vertically aligned carbon nanotubes that can catalyze oxygen reduction reactions at a fuel cell cathode, with similar performance to platinum with a few advantages. This avoids the high cost, limited supply, and degradation of platinum-based catalysts.[106] Micro-scale fuel cells are a Defense Advanced Research Projects Agency (DARPA) effort to reduce the size and efficiency of fuel cells to be able to compete with batteries in portable electronics. Related programs miniaturize the fuel cell, the catalytic combustor, and the reformer. The goal is to be able to refuel the miniaturized cells with methane or gasoline, reducing the logistics load. Large global markets for miniature fuel cells exist in the electrical bicycle market—19 million of which were sold in 2008.[107]

Nano-capillary network proton conducting membranes and core-shell catalysts address humidity and catalyst cost, respectively. These technologies are in development through the DOE.[108] The nano-capillary membrane technology is a novel high performance membrane material for high temperature and low relative humidity PEM fuel cell operation.[109] In tests in 2008, the nanofiber network membranes demonstrated 0.07 S/cm proton conductivity at 30 degrees Celsius and 80% relative humidity. Core-shell catalysts are catalysts for PEM fuel cells in which platinum is only present on the surface, reducing the amount of the material used in the fuel cell.[110]

Game Changing Impacts on the Architecture

Advances in fuel cell systems increase the efficiency, lower the cost, and in some cases customize the size of the systems. With the exception of microscale fuel cells becoming competitive for portable equipment, most fuel cell innovations will not change the general trades with batteries for energy storage. Mobile applications for fuel cells have the greatest potential to be affected by advances in fuel cell technologies. Fuel cells are also important to the habitat modules. Smaller fuel cells may have a similar effect on EVA equipment.

Advances in fuel cell systems could increase the energy storage capability available across the lunar architecture. The relatively smaller fixed mass by percentage of the system for regenerative fuel cells offers savings over batteries for large energy storage systems. On an architecture-wide level, the impact would be a savings in mass. The area where fuel cell advances could have the greatest potential impact is in surface mobility, where increases in efficiencies directly increase the range of rovers, and other mobile elements. Current state of the art fuel cells could extend exploration range in vehicles over batteries. Increased range brings flexibility and increased capabilities to these missions. Micro-scale fuel cells, designed to replace portable, handheld batteries, may save mass in small or portable devices used in the habitat or on EVAs.

Microbial and enzymatic fuel cells that are able to convert organic waste steams into electricity may have some application as an auxiliary power source and waste disposal mechanism, but the amount of power generated would likely be small.

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Benefits to the Architecture

Decreases Cost	+
Decreases Mass	+
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	+

Technology Trajectory

Fuel cells are a mature technology undergoing rapid evolutionary innovations. Fuel cells were first "invented" in the1880s in Germany. They were not used, however, until the 1950s—and it was in NASA and space applications where they found their first markets.[111] They are currently used in a number of commercial applications. They are used as backup power systems in large facilities, or as backup and primary power systems in telecom switching stations and cell towers. Landfills, treatment plants, and breweries that generate substantial amounts of methane in production, capture and use this gas as an input for fuel-cell-based auxiliary power sources. Fuel cells are being integrated into a number of vehicles, including buses, cars, planes, forklifts, trains, and boats, where they either reduce direct emissions over and against hydrocarbon fuels, or increase capability compared to battery power.[112]

Integration

Fuel cells are a rapidly-evolving technology area that can be expected to increase in capability, but not present itself in a different form, or with unknown integration challenges. Fuel cells developed for terrestrial applications require space qualification before flight, due to sensitivity to electromagnetic pulse (EMP), radiation effects, thermal environments, and micro gravity.

Fuel cells used in mobility applications on Earth would likely be advantageous due to ruggedness and vibration tolerance.

One of the main challenges to fuel cell use in the United States exists outside of the technology: the network effects and infrastructure required for refueling and maintenance. Technologies aimed at commercial markets require a major mass market to warrant the change in infrastructure. NASA does not face similar integration problems, and will be able to incorporate advances in catalysts, membranes, and integrated systems as they become available.

Next Generation Solar Cells

Rapidly Evolving

Photovoltaic solar cells use semiconductor materials to convert sunlight into electricity. There are a number of different photovoltaic technologies. Crystalline silicon cells are often considered first generation solar technology, still have the highest efficiency of any technology when stacked in multi-junction cells, and are commonly used in space systems. Thin film solar cells, with semi-conductor material deposited on a thin, and often flexible substrate, are considered second-generation technology. However, beyond thin film cells, the number and kind of solar technologies are proliferating rapidly. Third generation technologies include organic, nanocomposite, and quantum dot photovoltaics, among others. There is substantial private sector investment and innovation in this field, and public funds have been increasing as well. Future technologies may work and operate in a number of different ways, from improvements in current silicon technologies, to quantum dot and nanostructured approaches.

Technology Name	Description
Inorganic Semiconductor Nanorods / Quantum Dot Solar Cells	Solar cells crafted from semiconducting inorganic crystals (nano-crystals) with adjustable sizes and tunable band gaps.
Nano Composite Solar Cells	A class of solar cells with nano-engineered semiconductor materials for high efficiency.
Thin-film Solar Cell Technology	A solar cell made by depositing one or more thin layers of photovoltaic material on a thin substrate.
Dye-sensitized Solar Cells	Solar cells that use natural dyes (sometimes extracted from plants) to create a photo-sensitive anode.[113]
Solar Concentrators	Devices that focus light on a solar cell, increasing the efficiency of the solar cell.
Organic Photovoltaics	Nano-enabled polymer photovoltaic materials, normally more lightweight, flexible, and versatile than traditional solar materials.

Solar cell technology has received substantial investment in the private and public sector, domestically and internationally. Germany is by far the largest market, accounting for over 40% of global demand.[114] Japan has been an important market historically, driving the technology since the 1980s, but it was surpassed by the United States between 2007 and 2009 in terms of the number of installations. China is beginning to make major investments in solar energy as well.[115] These markets are growing rapidly—global PV installations grew by 110% in 2008, after growing by 68% in 2007.[116] These very high levels of growth spur major investments in the private sector, which has surpassed the amount of public investment since 2005.[117] (A DARPA program investigating nanocomposite solar cells was cancelled in 2007 due to superior technologies available in the private sector.) U.S. government investment includes, funding through DOE (largely at the National Renewable Energy Laboratory), NSF, and military funding, in a number of technologies.

Just as the industry is growing rapidly, so is the number of photovoltaic technologies offered and in development to serve the market. Crystalline silicon cells have been used for decades, and thin film cells have been used increasingly in residential installations. Within these two technology areas, a number of different chemistries are used to optimize cost, efficiency, bandgap, and physical properties. Emerging technologies include concentrator systems, nanocomposite solar cells, organic photovoltaics, and quantum dot cells. Concentrator systems focus light on the semiconductor, increasing the efficiency of the overall system. The semiconductor material is often the most expensive part of the system (especially for crystalline cells) and concentrators can optimize cost. Nanocomposite solar cells encompass a number of technologies that use manufactured nanopatterning in material design. Among these nanocomposite cells are organic photovoltaics, which include, both polymer photovoltaic materials and dye-sensitized solar cells. Organic photovoltaics avoid the cost of using silicon, and have the advantage of being flexible and even paintable, for a diversity of forms and installations.[118] (Flexible materials additionally enable printing and roll-to-roll manufacturing, for major cost reductions.) Another form of nanocomposite solar cells using quantum dots or inorganic semiconductor nanorods, are an advanced technology with promise for the future. These technologies enable tunable bandgaps, meaning that the wavelengths of light that they are able to convert into electricity can be customized, and therefore maximized to use as much of the available light as possible. This all adds up to the potential for efficiencies up to 66%.[119]

Game-Changing Impacts on the Architecture

Advances in solar cell technologies could increase the amount of available power for the lunar architecture with a given mass, and it may also change the way the solar power elements are designed. More efficient cells, either by area or by mass, would directly increase the ability to generate electricity from the Sun. This would influence operations (more power available for all applications, reduced need for power-saving activities) and scalability (enabling growth of the outpost). It may also make solar power more competitive with nuclear power concepts, purely by virtue of delivering higher amounts of power for a given unit.

Since energy is essential for everything done on the lunar surface, energy generation enhances elements across the architecture. A higher baseline of energy generation increases capabilities, and reduces the cost of developing low power alternatives across NASA's technology development portfolio.

Beyond better efficiencies, new solar cell technologies could change the form and method of deployment, creating further impacts on architecture mass, packaging for launch, or changing architecture element concepts all together. Lighter cells require less structural material, lowering the cost of the overall system, assuming a deployed structure. Future technologies, however, may be capable of operation in something besides a deployed system. Photovoltaics could be integrated into structures, or painted on surface elements, for instance. System and outpost design would adapt and likely be able to take advantage of this greater flexibility.

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)		Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Benefits to the Architecture

Decreases Cost	+
Decreases Mass	+
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	
Improved Performance	+
Increases System Power	+

Technology Trajectory

The general technology is mature, but different manifestations of the technology are at varying stages of development. The photovoltaic effect was first discovered in the 1800s, and Bell Labs sold the first production silicon cell in 1954.[120] NASA and space systems were the early markets for solar power cells. Today, large and growing terrestrial markets are greater drivers of novel technologies and approaches. Early nanostructured solar cells, organic photovoltaics, dyes, and concentrator systems are beginning to enter the market, but can be expected to evolve very quickly in the coming decades.

Crystalline and thin film silicon cells are commercially available, though thin film cells have not yet found applications in space. Nanocomposites are only beginning to be used commercially, after key development by venture-funded private sector companies.[121] Quantum dot solar cells remain at a low TRL, and are being researched in a number of DoD programs, and developed commercially as well.[122]

Integration

Integrating photovoltaics designed for terrestrial applications poses a number of small challenges. The solar spectrum in space is slightly different from what filters through the Earth's atmosphere, so the bandgap of terrestrial cells will not be optimal for space applications. This is typically adjusted when adapted for space applications. Some photovoltaic materials degrade over time, an important consideration for long-term outposts.

The transformational aspects of solar power technologies require fundamental system redesign to capture the potential benefits and efficiencies of integrated photovoltaics. Thin film, organics, and photovoltaic dyes open these possibilities for photovoltaics integrated with or acting as structural materials. As mentioned above, the method of deployment of these cells would vary depending on the relative size and mass of the cells, and whether they benefit from directly facing the sun.

Advanced Cryogenic Technologies

Transformational

Advanced cryogenic technologies will be critical for crewed and robotic missions beyond low Earth orbit (LEO). These technologies have applications in ISRU, ECLSS, and power systems for the lunar surface. Advanced cryogenic technologies enable low-temperature storage, management, and transfer of cryogenic fuels. Cryogenic fuels can have higher ISPs than traditional storable propellants. Consequently, cryogenic rockets require less fuel for a mission, increasing the spacecraft mass that can be devoted to payload. These technologies could enable on-orbit refueling, such as the use of propellant depots, which could allow for architectures that greatly increase the amount of mass landed on the Moon or larger structures in orbit. Advanced cryogenic storage and cryocooler technologies also enable the use of cryogenic propellants on long-duration interplanetary missions. The greater efficiency of cryogenic propellants allows a higher amount of spacecraft mass and volume devoted to payloads, which could significantly impact the sustainability of the lunar architecture. This may also be critical for missions like a Mars sample return.

Technology Name	Description
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 childown sequence, and multiple restarts.
In-orbit Cryogenic Fuel Transfer	Enables the transfer of cryogenic propellant from one spacecraft to another while in orbit.
High Energy Density Matter Cryogenic Solids	Freeze a propellant that is normally a gas or liquid at room temperature, into a solid propellant grain.
Low-Temperature Cryocooler	Uses mechanical energy, or gas sorption, to compress and expand a contained gas through one or more thermodynamic cooling cycles; operates at less than 100K.

Cryogenic propulsion systems, propellants, and on-orbit fuel transfer are space-specific technologies. Government, military, and space programs are the primary investors in these technologies. Cryogenic propellants can be used by launch vehicles and interplanetary spacecraft, but are not well suited for missiles that must be fueled and ready for launch at any time. On-orbit fuel transfer would allow for refueling of spacecraft, such as satellites and in-space transportation vehicles. While propellants and depots are used only for space applications, cryocoolers, which are used to maintain cryogenic temperatures, have applications across the economy. Cryocoolers are used to cool infrared sensors used in military, security, environmental, and energy applications; semiconductors and superconductors in commercial applications; magnets for magnetic resonance imagers (MRIs); and cryogenic catheters for cryosurgery.[123] Investments in refining and advancing cryocooler technology come from civil and military government funding.

The increased efficiency of cryogenic propellants, liquid oxygen/liquid hydrogen (LOX/LH2) and liquid oxygen/hydrocarbon (LOX/HC) combinations, offers tremendous payload gains for most robotic missions. However, robotic planetary missions tend to use storable propellants, such as hydrazine monopropellants.[124] Current disadvantages with cryogenic systems that limit their utility for long-duration robotic missions include increased complexity of cryogenic propulsion, active refrigeration to eliminate boil-off, and increased structural loads due to the high thrust of current cryogenic engines.[125] Recent developments in thermal insulation, low power active refrigeration systems, and low thrust engines can enable simplified cryogenic engines for interplanetary missions.[126]

New technologies based on a low cost cryogenic propulsion (LCCP) concept are compatible with interplanetary missions. These technologies rely on self-pressurizing tanks; compact, low thrust engines; and zero boil-off thermal management systems.[127] LCCP technologies simplify cryogenic propulsion, eliminate chilldown sequences, and enable multiple restarts. Apogee boost motors (ABM) based on the LCCP concept can provide acceleration levels as low as 0.1 m/s^2, reducing structural loads on deployed solar panels and antennas.[128] The increased specific impulse (ISP) of these cryogenic propulsion systems reduces the fuel needed for a mission, increasing interplanetary payloads. Zero boil-off thermal management can enable cryogenic propulsion on spacecraft that have lengthy periods between use, such as the Altair Lander.

Cryogenic solid propulsion systems freeze propellants to improve performance. Solid propellants tend to be denser than their liquid counterparts, and consequently require less volume. They can include energetic additives, also known as high energy density matter (HEDM), that significantly increase specific impulse.[129] For example, lithium boride mixed with solid hydrogen or ozone mixed with solid oxygen can increase specific impulse by 107 and 25 seconds respectively.[130] Motors that use cryogenic solid propellants tend to be less complex than liquid engines, reducing technical risk.[131] Cryogenic fuels and oxidizers include water, hydrogen peroxide, polymeric materials (such as polyethylene), aluminum, hydrocarbons, solid oxygen, and solid hydrogen.[132] This technology is in an early stage of development and with potential applications in space launch, interplanetary orbit injections, or planetary return missions.

In-orbit cryogenic fuel transfer involves the transfer of cryogenic propellant from one spacecraft to another while in space. This capability enables propellant depot concepts, where cryogenic propellants are to be stored in space, for transfer to and used in other spacecraft. Major design challenges include leak-free lines and seals to prevent or minimize boil-off, mobile fluid and gas systems, and transfer and gauging techniques in the zero-g environment.[133] An in-orbit fuel transfer depot would allow systems to launch with less propellant mass, thereby increasing the amount of mass landed on the Moon or enabling larger structures in orbit.

Cryocoolers use mechanical energy, or gas sorption, to compress and expand a contained gas through one or more thermodynamic cooling cycles. Cryocooler specifications, such as minimum temperature, power consumption, and thermal or vibrational noise, vary depending on the thermodynamic cycle and system design. Cryocoolers are a mature technology with new, incremental advancements driven by materials innovation for heat exchangers and regenerators, as well as for new seals and drive units.[134] New materials are reducing the minimum cooling temperature and increasing the lifetime of the technology. Cryocoolers can operate over a wide temperature range (150K to 10K). Low-temperature cryocoolers have operating temperatures less than 100K, and ultra low-temperature cryocoolers operate at less than 30K.[135]

Game-Changing Impact on the Architecture

The potential for game-changing benefits from advanced cryogenic technologies comes when these technologies allow cryogenics to be used in new applications where they were previously impossible. For the purposes of the lunar architecture, the technology to support propellant depots would be a new and transformational application. Depots allow spacecraft to launch without having to carry all propellant needed for the mission, and then refuel once it is on orbit. This means the "dry" mass of the spacecraft can either be heavier, increasing its payload; or the spacecraft can be launched on a smaller, less expensive launch vehicle. The flexibility to use these elements could have dramatic effects on the architecture.

Apart from the transformational effects, advanced cryogenic technologies support evolutionary advances in architecture elements that already use cryogenic propellants. This includes the lander in the lunar architecture, as well as potentially any systems (lunar electric rover) that will use hydrogen fuel cells to generate electricity. It may also apply to oxygen generated by ISRU plants, should NASA chose to store this oxygen cryogenically.

These technologies could also support the use of solid fuels in some launch applications. Cryogenic solid fuels, particularly those with HEDM additives such as ozone or atomic metals, would provide increased performance over current solid propellants. Cryogenic solids also offer increased safety from catastrophic failure over liquid and solid rockets.[136] The lower volume and increased efficiency of cryogenic propellants allow more spacecraft mass and volume for payloads.

Relevant Exploration and Constellation Architecture Elements

Orion	X
Altair	X
Extra-Vehicular Activity (EVA)	X
ARES and EDS	X
Ground Systems	
Mission Systems	
ISRU	
Robotic Systems	
Lunar Science	
Lunar Power	X
Surface Mobility	
Habitat	X
Launch and Entry Suits	
Surface EVA Suits	
NASA Comm Architecture	
Crew Health	
RDT&E / Manufacturing	

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improved Health and Safety	
Lower Power to Operate	-
Increases Reliability	
Improved Performance	+
Increases System Power	

Technology Trajectory

Cryogenic fluid management is mature, but requires further evolution before it can enable new applications like propellant depots. The U.S. Air Force designed and recently deployed ultra-low temperature cryocoolers.[137] However, additional research would be necessary for safe, long-term storage of cryogenic propellants.

Cryogenic propulsion technologies are continuing to advance. A design for a low-thrust, simplified cryogenic propulsion system, the LCCP concept, has been developed. Orbital Technologies Corporation has patented a hybrid solid-liquid cryogenic engine that could use a variety of propellants.[138] SNPE Matériaux Energétiques, a French company, has tested cryogenic solid propellants consisting of mixed hydrogen peroxide, water, and aluminum.[139] Unlike solid hydrogen and oxygen, these propellants freeze near 0C, reducing power requirements, thermal insulation mass, and technical complexity usually needed in cryogenic propulsion systems. Currently, cryogenic solid propellants are not in use and engineering challenges remain.

On-orbit refueling has been demonstrated on a small scale, but currently no plans for permanent depots are underway. DARPA successfully tested Orbital Express in March of 2007.[140] In this program, two test spacecraft, ASTRO and NextSat, successfully mated and transferred propellant.[141] United Launch Alliance (ULA) has developed a propellant depot concept that uses a launch vehicle's upper stage as the depot. According to ULA, an upper stage-derived depot could be launched on an evolved expendable launch vehicle (EELV) and carry 25mT of propellant to LEO. This is about the same amount of propellant required by the Altair lander.[142] ULA is designing the depot based on their Advanced Common Evolved Stage (ACES), also called the Wide Body Centaur.[143] NASA has also studied the technical and safety challenges of operating propellant depots.[144]

Integration

Advanced cryogenic technologies are transformational to the lunar architecture, requiring system-level technology trades. Changing propellants would require a redesign of the architecture vehicles. Launch vehicles, the Earth departure stage (EDS), and the Altair lunar lander could potentially benefit from the increased performance of advanced cryogenic engines. Cryogenic solids could enable high efficiency boosters or simplified, long-duration cryogenic ascent motors for the Altair ascent stage. These types of changes would need to be made in the near term and may not be possible for Ares I.

The use of propellant depots, which could be used to refuel the EDS, would require a substantial development and testing of new technologies and operations.

Printing Manufacturing

Transformational

Printing manufacturing encompasses technologies originally based on inkjet computer printers developed to manufacture three-dimensional objects, or to print electronic circuits. Current 3D printing machines are often used for rapid prototyping; a user can upload a CAD file to the machine and print out the design in three dimensions. The technology deposits successive layers of a plastic or ceramic material that will bond to itself to create a unified, three dimensional part. High degrees of accuracy and complexity are achieved in state-of-the-art systems. Printed electronics use similar principles, but print semiconductor materials, such as silicon. In addition to enabling printed integrated circuits on flexible or common materials like fabrics, paper, or cardboard, printed electronics enables reel-to-reel manufacturing (where cells are printed similarly to newspaper printing), which stands to greatly reduce the cost of some electronics and semiconductors, including solar cells.

Technology Name	Description
Three Dimensional (3D) Printing	Fabrication of three dimensional objects by depositing successive layers of material.
Printed Electronics	A set of printing methods used to deposit semiconductors and circuits on a variety of substrates.
RepRap	A machine in development for domestic applications with 3D printing capabilities, including the ability to reproduce copies of itself, and to manufacture very wide range of products.
FAB@Home	A machine designed for home use that uses multiple materials to print working systems

Currently, investments in printed manufacturing come largely from industry, primarily serving markets for rapid prototyping. Architectural firms use 3D printing for scale models of buildings, while professional or academic product development teams will do the same with medical devices, jewelry, or car components.[145] Market growth is moderate to slow, but additional applications are emerging as the technology drops in price.[146] Inputs from medical imaging can create models of human features; these can be used as a guide for reconstructive surgery, for prosthetic development, and, in the future, for printing working artificial organs.[147] They may also be used to generate a custom model upon which a surgeon can practice immediately before an actual procedure.[148]

Printed electronics also receive most of their investment through industry, though there is some military funding for the technology, through DARPA.[149] The industry is in its early stages, but growing rapidly, and projected to continue to do so.[150] Application areas include displays, lighting, electronic display cards, radio frequency identification (RFID) tags, large area electronics, power storage, thermoelectric and photovoltaic power generation, transparent displays, and supercapacitors. This technology touches a number of important markets, and will change the way many existing products are designed and manufactured, enabling new applications.

Two integrated printing technologies speak to the direction of the area in the future. The RepRap and FAB@Home projects seek to build machines based on printing technologies that can manufacture any almost any product. These machines would be kept at home or in the office, and change the paradigm of how everyday products are delivered to the consumer—they would be delivered via file and printed on-site. The vision requires higher capability printers, major drops in the cost of the equipment, and the ability to print with multiple materials. RepRap's distinguishing feature is self-replicability.

Overall, printed manufacturing sometimes includes similar microfabrication technologies that use alternative methods to conduct layer-by-layer construction, including photopolymerization, selective laser sintering, and electron beam melting. Two photon photopolymerization, or laser photopolymerization, builds 3D micro-scale objects by solidifying resin with focused lasers.[151] Selective laser sintering (SLS) also uses lasers to build 3D objects. SLS systems fuse thin layers of thermoplastic powder or metals with laser heating to build a prototype or component.[152] Electron beam melting is identical to the SLS process, but a beam of electrons is used to heat and melt the power feedstock.[153] Each of these technologies is commercially available for free-form manufacturing.

Game-Changing Impacts on the Architecture

Printing technologies capable of producing custom parts could support free-form manufacturing on the Moon, which has the potential to have transformational impacts on the architecture in terms of maintenance and repair capabilities, and, in the longer term, on outpost buildup.

In contingency situations, the ability to print a custom replacement part or patch obviates the need for bringing spares, and increases the reliability of the outpost. During the Apollo 13 mission, astronauts and ground control were forced to improvise a scrubbing device using materials available in the capsule—a printed manufacturing capability could conceivably allow designs on Earth to be uploaded and printed into three-dimensional parts on the fly, as needed.

Printed electronics could also support in-situ manufacturing and enable new or lower mass devices for the architecture. The ability to manufacture novel, custom, or replacement devices in a lunar habitat could increase the outpost's science, exploration, or maintenance capabilities. Conceivably, design innovations on Earth could then be instantly duplicated on the lunar surface. Waste packaging material or textiles could be used as source material or printed upon. In general, however, these applications would face challenges due to few terrestrial analogs, and the hostile radiation environment in space.

A longer term transformational application of 3D printing would be the combination of free-form manufacturing with an ISRU module that would refine regolith into its component elements, and manufacture a part. In this way, large, complex machinery could be manufactured autonomously or semi-autonomously on the lunar surface, eventually eliminating launch costs for certain equipment.

Relevant Exploration and Constellation Architecture Elements

Orion	X
Altair	X
Extra-Vehicular Activity (EVA)	X
ARES and EDS	X
Ground Systems	X
Mission Systems	X
ISRU	X
Robotic Systems	X
Lunar Science	X
Lunar Power	
Surface Mobility	X
Habitat	X
Launch and Entry Suits	X
Surface EVA Suits	X
NASA Comm Architecture	X
Crew Health	X
RDT&E / Manufacturing	X

Benefits to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	

Technology Trajectory

Both forms of printing technologies are mature in a technical sense, but are developing in terms of commercialization and future applications. Machines for 3D printing have been around since the mid-1980s, but are only recently falling in price to the point of sparking innovation. Since 3D printing has primarily been used to make prototypes, and not production parts, developments in the materials used will be critical. Printed electronics is growing very rapidly, and the relative simplicity of the technology compared to 3D printing makes it a nearer term player. Innovations in printed electronics manufactured on Earth may have applications to the lunar missions, whereas 3D printing modules—outside of its potential as a terrestrial design tool—would need to be able to operate in space to reach their full NASA potential.

Integration

Printed manufacturing can expect to have radiation hardening and mass considerations. It is also possible that the reduced gravity would have an effect on the parts, or that the materials used in printing require particular atmospheric conditions to harden.

A primary concern for integrating these technologies is the materials that can be used to print parts. For 3D printing especially, the value of the parts that can be created depend largely on their composition. A machine that prints plastic parts with the quality of toys will have less application than one with more capable or functional materials.

Advanced Coatings, Adhesives, and Self-Healing Materials

Revolutionary

Advanced coatings, adhesives, and self-healing materials can augment lunar elements, adding dust mitigation properties, maintenance capacity, ruggedness, and reliability. Among the technologies profiled, advanced adhesives include those that are inspired by biological organisms with natural adhesive abilities, such as geckos or mussels. These are able to be used repeatedly without 'sticky' residues and have properties in excess of the current state of the art. Advanced coating technologies include nanostructures and amorphous boron coatings. Amorphous boron coatings are lightweight, inert chemical coatings that provide increased hardness and temperature resistance. Smart surfaces and self-cleaning coatings use nanostructures to reduce surface contamination and remove dirt and dust. With this technology, the contaminated surface structure is refreshed through a regeneration process that changes the structure of the surface, which facilitates the removal of the surface contaminants. Self-repairing and self-healing materials are a class of materials that are able to repair themselves, regain their strength, and/or regain their structural properties after being damaged.

Technology Name	Description
Amorphous Boron Coatings	Lightweight, inert chemical coatings that provide increased hardness and temperature resistance. Boron sub-oxide, a compound of mostly boron with a few percent of oxygen impurities, is harder than the ceramic boron carbide coating. These coatings are designed to be deposited in an impact-resistant amorphous form, rather than a crystalline form, using cathodic arc applications.
Anti-fouling Smart Surfaces	A coating designed to reduce fouling or surface contamination by foreign entities. The contaminated surface structure is refreshed through a regeneration process that changes the structure of the surface, which facilitates the removal of the surface contaminants. A conductive, polymer-based nanocomposite that can alter its surface electrical property is the basis of the technology.
Biomimetic Adhesives	Adhesives that use methods inspired by those in nature, such as geckos or mussels.
Photocatalytic, Self-cleaning Coating for Building Exteriors	Decomposes organic substances such as microbes, when exposed to an ultraviolet light source, such as the Sun. The hydrophilic nature of the coating causes water that comes into contact with it to form an even layer, thereby allowing the dust and dirt that have accumulated on the surface to be washed away. These two properties of the coating create the "self-cleaning" effect.
NanoTuf	A transparent coating designed to protect polycarbonate surfaces from scratches and abrasions. It is created from a solution of nanometer-sized particles suspended in an epoxy matrix.
Self-cleaning and Non-adhering Coatings	Mimic the self-cleaning properties of the Lotus plant. The plant's ability to repel water and dirt results from an unusual combination of a superhydrophobic (water-repelling) surface, a combination of micron-scale hills and valleys, and nanometer-scale waxy bumps, which create rough surfaces that do not let water or dirt adhere. These coatings attempt to duplicate the two-tier lotus surface using a variety of materials.
Self-healing Materials	A class of materials that are able to repair themselves upon scratching or breaking. While there are a variety of paradigms, the dominant are polymers with catalysts and healing agents embedded in the structure of the polymer itself. When the material cracks, or is

	breached, the catalysts and healing agents enter the crack through capillary action, and re-form the material.
Soft Surface Antibacterial Polymer	Creates a softer surface on solid object, decreasing the ability of bacterial organisms to establish themselves and create biofilms. (Biofilms are adhesive, antibiotic-resistant films created by bacterial colonies. Once established, it is difficult for antibiotics to remove or penetrate the film and kill the underlying bacteria.) These coatings are composed of 50-nanometer thick polyelectrolyte (a charged polymer), with alternating layers of different acidity levels. When hydrated with a near-neutral liquid, like water, these polymers soften the stiffness of the material.
Very Hard Ceramic Coatings	Can greatly reduce erosion and wear from high-speed impacts of abrasive particles. These coatings can be applied to complex shapes using physical vapor deposition.

These technologies receive funding internationally across the government and industry. Self-cleaning materials is a large field of study with work being conducted in the UK, United States, EU, China, Singapore, Australia, and New Zealand. The National Science Foundation is sponsoring work at the Rochester Institute of Technology and San Francisco State University, while the European Union is sponsoring the Advanced Nanostructural Surfaces for the Control of Biofouling (AMBIO) program. The AMBIO program is a collaboration of 31 organizations including universities, commercial companies and research institutes.[154] Self-healing materials have a similar broad base. The Beckman Institute at the University of Illinois is a leader in the field in the United States, with funding from Air Force Office of Scientific Research and the National Science Foundation.[155] Work is being conducted in many countries including the United States, UK, Germany, Australia, the Netherlands, Switzerland, and China.

Self-cleaning, non-adhering, and anti-fouling coatings are a class of coatings designed to keep a material or surface clean from dirt, organisms, water, corrosion, and other deposits that could impact user health or system performance. Self-cleaning and non-adhering coatings clean surfaces through active and passive mechanisms, respectively. Self-cleaning coatings actively destroy microbes through oxidization, or actively change the surface morphology to dislodge dust and other deposits.[156] Non-adhering coatings prevent particles from sticking to the surface and improve natural cleaning mechanisms, such as rainwater.[157] Anti-fouling coatings are a specific class of self-cleaning and non-adhering coatings that focus on preventing or removing fouling, a buildup of material (inorganic or biological) that impedes function.[158] Advanced antifouling coatings use nanostructures that can alter their structures to reduce adhesion. Self-cleaning and non-adhering coatings can have anti-microbial, absorbing or repelling, and regenerative properties.[159]

Very hard, abrasion-resistant coatings like amorphous boron, ceramic coatings, and NanoTuf increase surface hardness and decrease damage caused by dust, sand, and other abrasive materials. Many of these coatings are commercially available, and the military has tested some of the coatings on aircraft exposed to sandy environments.[160] Performance of abrasion resistant coatings can change depending on the environment and the base material. These materials should be selected for specific applications.

Biomimetic adhesives are being developed to mimic the adhesive properties of geckos and mussels. One adhesive, called "geckel glue," combines the adhesive properties of both to create an adhesive that works like a sticky note on both wet and dry surfaces.[161] Researchers at the Northwestern University have demonstrated proof of principle on a small area just a few millimeters long.[162]

Self-healing materials have the ability to automatically repair damage. Approaches to self-healing include liquid-based healing agents,[163] solid-state healing agents,[164] and biomimetic designs.[165] In general, self-healing materials take advantage of changes in the material's properties when damaged, to activate healing mechanisms such as a released epoxy or resistance heating.[166] The self-sealing garment, a technology profiled in the Advanced Pressure Garment section, is an example of these types of materials.

Game-Changing Impact on the Architecture

Adhesives, coatings, and self-healing surfaces are materials that can affect all surface areas in the architecture. These materials potentially mitigate dust abrasion or buildup, repair micrometeorite impacts, and improve crew health and safety. These technologies could also lower overall maintenance concerns in the lunar architecture.

Dust mitigation has been cited as a vital capability need to the architecture. Coatings and materials that are self-cleaning can be used to coat surfaces of systems and components so that lunar dust cannot stick to the surface. Very hard surface coatings can be used to reduce dust abrasion from landing plumes or on gears, wheels, actuators and other moving components. Elements that could benefit include habitats, science and power modules, EVA suits, robots, and rovers. Additionally, self-cleaning and anti-fouling surfaces can impact terrestrial systems, such as impeding corrosion on launch complexes due to weather conditions at Kennedy Space Center.

Another important aspect of the lunar architecture is sustainability. Long-duration stays on the lunar surface are greatly enhanced by systems that are self-sustaining. Systems created from self-healing materials can reseal or repair cracks caused by micrometeorite impacts and strain. Structures and systems that can repel dust and repair cracks alleviate some requirements for maintenance and repair, creating improved, self-sustaining systems. Additionally, self-cleaning or non-adhering coatings with antibiotic properties can aid in maintaining crew health by reducing the risk of infection. Decreasing maintenance and repair requirements can increase astronaut time for science and exploration, and decrease costs and mass required for spare parts, materials, and other maintenance equipment.

Relevant Exploration and Constellation Architecture Elements

Orion	X
Altair	X
Extra-Vehicular Activity (EVA)	X
ARES and EDS	
Ground Systems	X
Mission Systems	
ISRU	X
Robotic Systems	X
Lunar Science	X
Lunar Power	X
Surface Mobility	X
Habitat	X
Launch and Entry Suits	X
Surface EVA Suits	X
NASA Comm Architecture	X
Crew Health	X
RDT&E / Manufacturing	

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	
Improved Performance	+
Increases System Power	

Technology Trajectory

Photocatalytic-coatings for buildings have been developed by the Singapore Institute of Manufacturing Technology (SIMTech).[167] These coatings are currently in use in several buildings. The other advanced coatings, adhesives, and self-healing materials discussed are at TRL 4 to 5.

All of these technologies have been proven in a laboratory setting. The U.S. government, the European Union, and many universities, including the Rochester Institute of Technology, Georgia Tech, and MIT, are developing these technologies. One exception is Autonomic Materials Inc., which has commercialized a self-healing technology that repairs damage to coatings.[168]

Integration

Advanced coatings and self-healing materials are revolutionary technologies that should be integrated into the lunar architecture at the design stage. Self-healing materials could require a change to a system's structure to add self-healing elements; however, self-healing components like electronics or windows could be easier to incorporate. Advanced coatings can be more easily integrated. Though they must be accounted for during design, they should not require a change in structural material; however not all coatings are compatible with any material.

Advanced Electric Propulsion

Rapidly Evolving

Electric spacecraft propulsion creates thrust by accelerating ions or by heating propellant with electricity. Ion thrusters accelerate ionized propellant using either electrostatic or electromagnetic forces, while electrothermal thrusters accelerate propellant through heating. Although electric propulsion thrust is much smaller than traditional chemical rockets, it brings a very high specific impulse, or propellant efficiency. Electric propulsion thrusters require a lot of power and perform best in a vacuum. Currently, the thrusters listed below are only used for in-space propulsion.

Technology Name	Description
Electrostatic Ion Thruster	A form of electric propulsion used for spacecraft propulsion that creates thrust by accelerating ions with static electric fields (Coulomb Force).
Electromagnetic Ion Thruster	A form of electric propulsion used for spacecraft propulsion that creates thrust by accelerating ions with magnetic fields (Lorentz Force).
Electromagnetic (EM) Drive	A theoretical propulsion system that uses amplified resonance of electromagnetic waves to produce thrust on a wave guide without propellant.
Hybrid Combustion/Electrothermal Water Rocket	An electric rocket that uses electrolysis of water to create combustion products for high thrust maneuvers and electrothermal propulsion for high specific impulse (ISP) maneuvers.
Liquid-based Ion Propulsion	Uses ionic liquids, which are highly conductive and yield pure ion extraction.
Variable Specific Impulse Magnetoplasma Rocket (VASIMR)	An electro-magnetic thruster that uses radio waves and magnetic fields to ionize a propellant and to accelerate the resulting plasma to generate thrust.

Electric thrusters are used primarily in space technologies, though a few advanced concepts power transatmospheric vehicles. The best applications for electric propulsion include orbit transfers and attitude adjustments, although they can also be used for interplanetary and deep space missions. NASA, the military and international space agencies fund research and development of these technologies.

Electrostatic ion thrusters use the Coulomb Force (force between two or more charged bodies) to accelerate the ions in the direction of the electric field formed between two voltage potentials. Electromagnetic ion thrusters use the Lorentz Force (Coulomb Force plus the force of magnetic fields on a moving charge) to accelerate the ions perpendicular to a magnetic field.[169] Ion thrusters on spacecraft require a secondary system to eliminate electrons in order to keep the spacecraft charge neutral.[170] Electrostatic ion thrusters include hall-effect thrusters, gridded electrostatic ion thrusters, and field emission electric propulsion, while electromagnetic thrusters include pulse inductive thrusters and magnetoplasmadynamic thrusters (MPD).

Electromagnetic (EM) drives are a theoretical propulsion system currently being tested by Satellite Propulsion Research Ltd, and funded in part by the UK government.[171] The EM drive channels microwaves into a resonating wave guide with differently sized reflective plates. The chamber is designed to create a difference between the radiation pressure on each of the plates, resulting in a net thrust without propellant.[172] This thruster would have an infinite ISP and could greatly reduce the mass of the propulsion system. However, this technology has received considerable criticism; many scientists say its theory may violate the fundamental principle of conservation of momentum.[173]

The hybrid combustion/electrothermal water rocket operates in two modes depending on the thrust required. A high thrust mode works as a conventional hydrogen/oxygen engine with the fuel and oxidizer generated from a common water source through electrolysis.[174] In the low thrust mode, water is vaporized and heated with microwaves, achieving an ISP of ~800 seconds, almost twice as efficient as cryogenic rockets (LOX/LH2).[175] Currently, Orbital Technology Corporation is developing a hybrid rocket using this technology, however, it requires two separate propulsion systems for the different modes.[176] If these modes can be combined into a single engine, it could significantly decrease the mass of the propulsion system.

Liquid-based ion propulsion provides advantages over current ion engine designs. Classical plasma ion engines have manufacturing challenges: ion engines are not modular and are difficult to miniaturize.[177] Advances in ionic liquids, which are highly conductive and yield pure ion extraction, enable a simple thruster, which provides solutions to these challenges.[178] Liquid-based ion thrusters consist of an array of capillaries and an extractor electrode that accelerate ions or liquid droplets from the tip of the capillary. The simplicity of the design enables microfabricated, highly-modular thrusters.[179] These thrusters are efficient and flexible, and can be combined to increase system thrust. Ionic liquids are more compact than gas propellant for ion thrusters (such as xenon), are thermally stable, and environmentally benign. Pure ion emitter arrays using ionic liquids are currently being tested.[180]

VASIMR, or Variable Specific Impulse Magnetoplasma Rocket, is an electro-magnetic thruster that generates and heats plasma with strong electric fields and a radiofrequency booster, while superconducting magnets direct the plasma out of the rocket.[181] The thrust and specific impulse can be tailored for a variety of maneuvers. The engine can be used for station keeping for space stations, lunar cargo transport, in-space resource recovery, and ultra high-speed transportation for deep space missions.[182] It is expected to carry out these functions at a lower cost than chemical technologies.

Game-Changing Impact on the Architecture

Advanced electric propulsion could provide significant advances in transportation from Earth orbit to the lunar surface. The technology is not suitable to launch payloads from the surface of the Earth due to its low thrust to weight ratio and its need of a vacuum to operate. Current versions of electric propulsion provide very low thrust and are typically only used for station keeping. Advances in electric propulsion could provide a higher thrust, allowing these technologies to be used in lunar cargo transport, while drastically reducing the fuel requirements for in-space transportation. Currently, the Earth departure stage (EDS) is used to transfer payloads from Earth to Lunar orbit, and could benefit from advances in electric propulsion.

Advanced electric thrusters could also be critical to a Mars architecture, providing high-speed in-space transportation.[183] Over long distances, the increased specific impulse of advanced electric propulsion engines results in greater velocity with less propellant, reducing the propulsion system's weight.[184] Increased velocities due to these propulsion systems significantly reduce the time associated with interplanetary trips. The VASIMR engine, for example, could enable missions to Mars in less than four months.[185]

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	
Extra-Vehicular Activity (EVA)		Habitat	
ARES and EDS	X	Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems		NASA Comm Architecture	X
ISRU		Crew Health	
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	
Improved Performance	+
Increases System Power	

Technology Trajectory

Although electric propulsion technologies are currently in use for satellites, research and development focused on improving and advancing electric thrusters is occurring at space agencies and space companies both in the United States and internationally. NASA's Jet Propulsion Laboratory (JPL) and Busek Inc. are developing a colloid thruster using ionic liquids for the LISA Pathfinder mission (LPF) planned for launch in 2010.[186] A VASIMR engine, being developed by Ad Astra Rocket Company in partnership with NASA, has undergone numerous tests, and tests have begun on a newer demonstration engine with fully integrated superconducting magnets. If these tests are successful, Ad Astra plans to develop a flight version to be tested on the International Space Station by 2012.[187, 188] China's Northwestern Polytechnic University says they have proven the theory behind the EM drive and have received funding to build the engine. Satellite Propulsion Research Ltd continues to test the EM drive thruster.[189]

Integration

Advanced electric propulsion technologies are rapidly-evolving and require simple trades in systems that use electric thrusters such as communications satellites. However, electric propulsion is not currently designed into the lunar architecture. The best use of these technologies in the architecture is for in-space cargo transportation. In the current lunar architecture, the EDS, which uses cryogenic propellants, handles in-space transportation. The transportation system for the lunar architecture would require a complete redesign to use advanced electric propulsion systems. Another possibility for infusing electric propulsion into the architecture would be to integrate advanced electric propulsion systems in the later stages of the lunar architecture to support the ongoing logistics functions. Advanced electric propulsion is considered extremely promising for Mars missions, because it could provide decreased travel time, lower mass, and lower mission cost.

Heat Transfer Materials

Revolutionary

Advanced heat transfer materials have a high thermal conductivity, and can be used in heat pipes or radiators to cool electronic or mechanical systems. Space systems commonly use ammonia (in aluminum pipes) as a heat transfer material, while terrestrial systems often use water in copper.[190] In most industrial applications, ethylene glycol and propylene glycol heat fluids that are used for their economy, low viscosity, and high heat transfer efficiency, with the latter having the advantage of being non-toxic. New materials and fluids offer the potential for increased capability, reduced mass, and efficacy in low gravity environments.

Technology Name	Description
Nanoparticle Fluids for Heat Transfer	Heat transfer fluids doped with nanoparticles to increase the thermal conductive properties.
Inorganic Heat Transfer Technology (Supertubes)	Tubes for heat transfer, developed and patented in China, with a proprietary blend of chemicals that yield unprecedented thermal transfer properties.
Phase Change Fluids for Heat Transfer	Fluids that transfer heat through phase changes, such as boiling and condensing.
Binary Fluids for Heat Transfer	A mixture of two fluids capable of spontaneous separation when mixed.
Ferrofluids (Magnetic Fluids)	Liquid mixtures doped with nanoparticles, such that the fluid becomes magnetic in the presence of an externally applied electromagnetic field. This allows these fields to control the movement of the fluid, for heat transfer purposes.

While heat transfer has application across the economy, space technologies have unique and extreme requirements and temperature regimes. Space technologies have traditionally been important for the development of thermal management technologies. NASA was an early market and source of development for heat pipes in the 1960s, when the technology was relatively new.[191] Research furthering this area is still funded through NASA and the military, and also industry. An exception among these technologies is supertubes, which were developed internationally (China).

Heat transfer materials may be used in heat pipes and radiators. There are four main areas of innovation in heat transfer fluids: phase change fluids, binary fluids, ferrofluids, and fluids doped with nanoparticles. Additionally, supertubes, a technology developed and used in China, has been tested in the United States and found efficacious, despite a poor understanding of the underlying mechanism.

In general, heat transfer materials must absorb and release heat quickly, or reduce the thermal resistance of a container. Other heat transfer mechanisms include phase changes, i.e., transporting latent heat necessary for a phase change from a liquid to a gas.

Emerging heat transfer fluids work in a number of different ways. Ferrofluids (discovered by NASA in the 1960s) are fluids with embedded nanoscale magnetic particles whose magnetism varies with heat. A similarly variable magnetic field over the length of a heat pipe thus creates the ideal transfer of the fluids.[192] Phase change fluids transfer heat by evaporating a liquid at the hot end, and condensing the gas at the cold end. The fluid must be selected according to the appropriate boiling point in the system where it is working. Nanoparticle fluids contain small bits of various metals (nanoparticles) that alter the properties of the solution. The properties of the metals, and their very large surface area in the suspended fluid, can greatly increase thermal conductivity and heat capacity. The particular metal chosen will customize the properties of the overall system.[193] Binary fluids contain more than one kind of fluid that normally mixes heterogeneously, which increases surface-tension-based flows (Marongini flows).[194]

Supertubes have been the source of investigation by the DoD, NASA, and SRI International. Supertubes use a thin layer of powder coated on the inside of a heat pipe. This powder is a complex mixture of chemicals, the apparent cause of heat transfer effects, and source of unexplained results. (Dr. Yuzhi Qu, the developer, was purported to be working on a book about the basic physics of the supertubes).[195] The tube itself can be made from a number of metals or alloys. The tubes are very low cost, safe, work between 30 C and 1770 C, and outperform existing known technologies.[196] NASA selected this technology for use in the (now cancelled) Modular, Reconfigurable, High Energy Technology Demonstrator project.[197]

Game-Changing Impact on the Architecture

Improved heat pipe technology increases the effectiveness of thermal control, reducing the mass of the thermal control systems and ensuring high performance. Sources of heat that have to be controlled in the lunar architecture include high temperature electronics, friction, human metabolism and solar radiation. Improvements to these technologies will not significantly change the associated system, but could hold the promise of reducing the mass necessary for the thermal subsystem.

Nanoparticle fluids and supertubes have the promise of greater performance and lower mass, with nanoparticle fluids demonstrating 50% greater thermal transfer than existing materials, and supertubes producing results that are “difficult to explain by any standard means of heat transfer.”[198] Leaps in heat transfer performance affect the design of systems, allowing for smaller thermal management systems, which leave more mass available for other system components. Alternatively, these systems could be used to recycle heat in applications where heat is used for work, such as in future ISRU systems.

Relevant Exploration and Constellation Architecture Elements

Orion	X
Altair	X
Extra-Vehicular Activity (EVA)	X
ARES and EDS	X
Ground Systems	
Mission Systems	
ISRU	X
Robotic Systems	X
Lunar Science	X
Lunar Power	X
Surface Mobility	X
Habitat	X
Launch and Entry Suits	X
Surface EVA Suits	X
NASA Comm Architecture	X
Crew Health	
RDT&E / Manufacturing	

Benefits to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	+
Lower Power to Operate	+
Increases Reliability	
Improved Performance	
Increases System Power	

Technology Trajectory

Modern heat pipes originated in the 1940s, with early applications in the space program and the Alaska pipeline.[199] In general, thermal control is a mature technology, which has been driven largely by investments in civil and military space. These fields will continue to drive investment resources to advance heat transfer materials. Progress will come from materials research, with continuing innovations in the fluids used in heat pipes. Although supertubes can be reliably produced, the underlying physical mechanisms are unknown. If the physics behind supertubes is as novel as claimed, they could open a new vein of innovation in this field.

Integration

Advanced heat transfer materials promise revolutionary improvements in thermal management. The temperature regimes and gravity environments are important for selecting heat transfer materials. The temperature characteristics of the lunar base would be an important input into fluid design or section. Gravity often influences behavior as well. Ferrofluids have the advantage of working well in the absence of gravity. Supertube performance depends strongly on gravity, as the device loses its extraordinary performance characteristics at certain orientations.[200] While heat pipes for the microgravity of orbital space are well understood, designs for the 1/6th gravity on the Moon may have specialized requirements. Replacing the heat pipes currently planned in the lunar architecture with a significantly better performing technology will require the replacement of that subsystem, which will require planning for a future technology infusion. The inclusion of a more advanced heat transfer material would likely reduce mass of the thermal management subsystems, leaving more mass available for other systems.

Autonomous Systems and Vehicle Control

Revolutionary

Enhanced Autonomous Systems technologies model human behavior and decision-making processes in order to reduce or remove the need for human controllers. These technologies imitate human reasoning, represent human variability in simulations, create systems of automatic data validation, and can generate goal-seeking behavior. Autonomous vehicle controls enable enhanced robotic exploration. Autonomous or semi-autonomous vehicles require sensors, advanced control algorithms, data validation, and communications links for transferring data and receiving instructions. These technologies have a broad range of applicability and present many benefits to the lunar architecture.

Technology Name	Description
Autonomous Data Validation System	A programming and development aid for image recognition systems used in unmanned aerial vehicles (UAVs).
Behavioral Modeling	Computational models of human behavior designed to reflect human strategies.
Autonomous Systems that are Self-Aware	Model-based embedded programming languages that avoid mistakes by reasoning from hardware and software models.
Autonomous and Semi-autonomous Vehicles	Vehicles enhanced with sensors and algorithms to enable driving with minimal to no human intervention.

In recent years a number of organizations have invested in research and development in the field of autonomous systems. Universities and NASA lead the effort to create long-lived autonomous systems. The military has a high level of interest in developing synthetic agents to model human variability in combat simulations. There is also a great amount of military and commercial interest in the development of autonomous vehicles.

An automated data validation system is a process technology for testing synthetic data that will act as an input into an autonomous image recognition system, such as those used in unmanned aerial vehicles (UAVs). Image recognition systems compress images into synthetic data to simplify data storage and retrieval of captured images. The data validation system compares collected data with synthetic images, so the image recognition system can match video feeds with compressed images. This technology enables the transition of raw images into a useful, searchable, and productive image library. This technology could maximize the efficacy of lunar robotics' data collection.

Human behavior models (HBMs) are computational models of human behavior, designed to reflect human strategies. Unlike simulation technologies currently in use, HBM includes modeling of human reasoning and decision making to correctly represent human variability in simulations.[201] This technology could improve the fidelity of existing simulations of human behavior, and could present opportunities to develop new types of simulations.[202]

Autonomous systems that are self-aware is a family of model-based embedded programming languages, called Reactive Model-based Programming Languages (RMPLs). RMPLs represent an innovative approach to designing embedded software systems. They are object-oriented languages that combine the key features of synchronous programming languages and advanced robotics execution languages. Although previous autonomous systems have employed different programming and modeling languages for each major component of the system, an RMPL allows for the creation of one homogeneous representation of the spacecraft, vehicle, or habitat in which it is embedded. This reduces the complexities of software interfaces, and simplifies software processing by eliminating duplication of effort.[203, 204]

This model-based autonomy enables the creation of long-lived autonomous systems that are able to explore, command, and diagnose and repair themselves using fast, common sense reasoning.[205] Current research of model-based autonomy focuses on model-based programming and cooperative robotics. Model-based programming is embedding reasoning within robotic explorers and everyday devices by incorporating model-based deductive capabilities within traditional embedded programming languages.[206] Cooperative robotics extends model-based autonomy to robotic networks of cooperating space, air, and land vehicles, on Earth or exploring the solar system.[207] This technology can be applied to deep space explorers, distributed satellites, and lunar vehicles.[208]

Autonomous and semi-autonomous vehicles are enhanced with sensors and algorithms to enable driving with minimal to no human intervention. An example algorithm, 4D/RCS (Four Dimensional Real-time Control System), is designed to imitate human cognitive elements such as sensory processing, world modeling, value judgment, and behavior generation.[209] As these elements interact with each other, they enable perception, cognition, imagination, and reasoning.[210] At the lower levels, these elements enable goal-seeking reactive behavior, but at higher levels, they can enable goal-defining, deliberative behavior.[211] This technology could enable lunar vehicles, such as the rover, to operate without human assistance and thereby save crew time, reduce crew exposure to radiation, and expand the science capabilities of the mission.

Game-Changing Impact on the Architecture

These autonomous system technologies have the potential to transform control of space systems, providing simplicity of operations. These systems use algorithms that are extremely efficient (quickly resulting in an action selection), which yields energy savings, increased reliability, and improvements to overall performance. These systems may also introduce autonomy in new areas, such as sophisticated data collection and validation, and realistic simulations. Because these technologies reduce dependence on human controllers while providing high-quality decision making, they could impact several elements of the lunar architecture, including surface mobility, robotic systems, and extra vehicular activity (EVA).

The autonomous data validation system can impact surface mobility by improving the efficacy of image-based navigation programs.

Autonomous systems that are self-aware are more reliable than existing models, and can monitor equipment, detect flaws, and repair themselves, improving crew health and safety.

The use of high-quality, full-function HBMs could benefit NASA simulations in several ways. First, the accurate modeling of human behavior increases the realism of simulations, making simulation results more accurate and useful. Second, it reduces dependence on human controllers, thereby reducing run-time costs of simulations. Third, it would allow NASA to study human behavior in situations that normally would be difficult to observe in real life, for instance, if the situation is rare, not observable, or hypothetical.[212] These benefits could allow NASA to improve the quality of existing simulations, and to develop new simulations to support other areas of research, training, and testing.

Autonomous vehicles would allow astronauts to accomplish tasks without the risks and resources required of EVA activities. They could enable greater science and exploration range.

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	
Mission Systems	X	NASA Comm Architecture	
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	

Technology Trajectory

These technologies are at TRL 2-7. Maturity ranges from the invention stage to use in an operational environment. Technologies at high maturity levels are currently undergoing new advancements, which aim to increase quality and affordability.

Research and development of more advanced autonomous systems using RMPLs is currently underway at the Model-based Embedded and Robotic Systems (MERS) group, within the Computer Science and Artificial Intelligence Laboratory (CSAIL) at the Massachusetts Institute of Technology (MIT).[213] Mars Science Laboratory (MSL), which is planned for launch in 2011, will test a technology "proof-of-concept" demonstration of RMPL and model-based execution.[214]

Research and development of autonomously controlled vehicles is underway for a variety of commercial and government applications. One project currently underway is the MIT AgeLab's AwareCar project. The AwareCar is designed with sensors that monitor the driver's capabilities, such as the driver's eyelid movements and heart rate. Although the project's researchers do not expect that all of these sensors will be applicable to commercial vehicles within the next twenty-five years, they hope to use some of the technology to make modern cars safer.[215] There are a number of other labs doing autonomous vehicle research, including California Institute of Technology, Carnegie Mellon, Cornell, Stanford University, Lockheed Martin Advanced Technology Laboratories (ATL), Honeywell Aerospace Advanced Technology, Oshkosh Truck Corporation, and Raytheon. In 2004, 2005, and 2007, DARPA sponsored a series of prize events to promote industry development of autonomous vehicles. The 2007 DARPA Urban challenge demonstrated autonomous navigation in a complex environment.[216]

The military has been a major funder of research to make HBMs more accurate, reliable, and affordable as well as exploring new methods for validating HBMs.[217, 218] Currently the military is using HBM technology in simulations that support development, analysis, acquisition, and training functions.

Integration

These technologies are primarily revolutionary, affecting architecture subsystems, and may be integrated into the existing lunar architecture by upgrading the software of existing systems. This would allow NASA to use new software controls while leveraging existing sensor systems and robots to include these autonomous technologies. However, some autonomous solutions may require the infusion of new systems to benefit from the technological advances offered by these technologies.

Long-Distance Power Transmission

Transformational

Long-distance power transmission technologies include wired and wireless solutions for transmitting electricity over long distances. Wired solutions are innovative technologies designed for use across the terrestrial power grid. Wireless transmission technologies have been demonstrated but not yet deployed, and are the critical technology to enable space solar power concepts.

Power is a major driver of the lunar architecture. The current architecture options include solar power units or nuclear reactors for power generation, and primarily batteries and fuel cells for energy storage. Wired solutions would work with the current architecture to transmit power, while wireless solutions could supplant the current architecture designs.

Technology Name	Description
High-Voltage Direct Current (DC) Power	The unidirectional flow of electric charge, instead of alternating current for long distance transmissions.
Superconducting Power	Materials that have no resistance to electricity. High temperature superconductors can be used without cooling to extremely low temperatures and have much wider applicability.
Wireless Power Beaming	Converts electricity to microwaves at the source, and converts back to electricity at the destination.
Space Solar Power	A wireless power beaming technology where solar panels in space collect power and convert it to microwaves or lasers for beaming to its destination.

Wireless power transmission is a future technology, while direct current (DC) transmission and superconductors are being pressed into operation today. The aging electrical grid and the greater use of renewable energy accounts for drivers of DC power and superconductor investments. In the case of superconductors, new technology is a factor as well. High temperature superconductors, which require far less cooling than the first generation of superconductors, were discovered and developed in the 1980s through federal research. Though expensive, they provide enhanced performance when used in electric grids. DC power transmission is not new but is finding new markets in transmission grids. Renewable energy is driving demand for longer distance transmissions of electricity. For example, wind power may be strong in Spain and weak in Germany on any given day.[219] Wireless power transmission, or power beaming, can be used for many space applications including collecting solar power in space to provide electricity on the ground or to in-space vehicles, powering planetary rovers, and powering space elevators.

The high-voltage, direct current (HVDC) electric power transmission system uses direct current for the bulk transmission of electrical power, in contrast with the more common alternating current systems. This minimizes transmission losses and the energy required for AC conversion, from direct current sources, such as solar cells. For long-distance distribution, HVDC systems are less expensive and suffer lower electrical losses.

Superconducting power is a next generation energy transmission technology. These superconductors are oxide or ceramic-like materials that suffer negligible transmission losses and transmit several times as much electricity as copper or aluminum metals of the same size.[220] Superconductors can supply energy quickly, efficiently, and unobtrusively. They conduct 150 times the electricity of similarly sized copper wires, creating mass efficiencies, but they have potential radiation vulnerabilities.[221]

Wireless power beaming is technology for long distance electricity transmission. Beaming technologies normally convert electric current to microwaves or lasers, which is then wirelessly transmitted and converted back to a current at the receiver. Wireless electricity could offer operational advantages in habitable volumes, or enable a number of different transmission concepts in a lunar outpost scenario, including powering rovers in lunar craters.

Space solar power is a clean, renewable energy source first studied in the 1970s.[222] In a space solar power system, large satellites in space collect solar energy and convert it to microwaves or lasers. The energy is then transmitted to rectennas or photovoltaics, respectively, on the ground that convert the energy to electricity. Many space solar power studies have been done looking at providing power to the Earth from space or powering electric propulsion vehicles in-space.

Game-Changing Impact on the Architecture

Power beaming could transform the use of power on the lunar outpost. Power beaming and space solar power would enable constant power on the surface of the Moon at major power levels even during eclipse periods. Power beaming, either from the lunar surface (using lunar-based power generation) or as part of a space solar power system, could beam power for habitats, science experiments, ISRU operations, and rovers, obviating the need for most batteries. Studies for providing space solar power to the Earth have looked at developing satellites that could generate up to 1.2 GW of power.[223] Beaming power from space requires large satellites be assembled in-orbit, so using this technology would increase system mass. However, power beaming around the lunar architecture would decrease system mass as it could eliminate the need for energy storage devices and cabling on the lunar surface.

Superconducting power could reduce transmission losses from power sources at a slightly lower mass than conventional wires. DC power transmission could support long distance energy transmission for operations far from the outpost. This capability could be beneficial for transmitting power from a lunar power station located away from the main outpost site, or for transmitting power from or to ISRU locations. Overall, these technologies could increase reliability, improve performance, and increase system power.

Relevant Exploration and Constellation Architecture Elements

Orion	
Altair	
Extra-Vehicular Activity (EVA)	
ARES and EDS	
Ground Systems	
Mission Systems	
ISRU	X
Robotic Systems	X
Lunar Science	X
Lunar Power	X
Surface Mobility	X
Habitat	X
Launch and Entry Suits	
Surface EVA Suits	
NASA Comm Architecture	
Crew Health	
RDT&E / Manufacturing	

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	-
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	+

Technology Trajectory

Wired long-distance power systems are mature technologies. DC power systems are well established, and superconducting systems are currently beginning operations. High temperature superconducting systems were discovered in the 80s, and are being installed to address deficiencies in the power grid. The first superconducting cable used to power industrial plants was installed in 2001 in Carrollton, Georgia.[224]

DC power transmission is not a new technology. Alternating current (AC) was established as the standard transmission mode in the late 1800s, and that has remained unchanged. DC power systems are being built to bridge large distances, such as between countries, and to connect renewable energy farms to the greater grid. The proliferation of renewables, and concurrent markets from set locations with variable output, will drive long distance DC connections.

Long distance power beaming, for space solar power, is of great interest because of energy concerns throughout the world. In May of 2008, a joint U.S. and Japanese research team demonstrated power beaming over 148 km between two Hawaiian islands. However, only 1/1000th of a percent of the beamed power reached the receiving antenna. Although the basic necessary technology required for a space solar power system already exists, efficiency issues in both solar cells and in transmission technologies provide a major hurdle in developing a viable system. Launch costs are another significant challenge for realizing space solar power. However, commercial entrants into the launch market, such as Space-X and personal spaceflight vehicles, could bring that cost down, bringing space solar power systems within reach.[225]

In October of 2007, the U.S. National Space Security Office (NSSO) conducted an architecture feasibility study of space-based solar power.[226] This study looked at space solar power as

"Equitable access to sufficient quantities of clean, reliable, and affordable energy," and as such it could help decrease the likelihood of conflicts over the world's declining national resources.[227] Japan has been one of the leaders in space solar power research and development. The Japanese space agency, JAXA, continues to invest in space solar power development and has plans for a working system in orbit by 2030.

In addition to government interests, two commercial companies have plans to beam power from space. The California utility, Pacific Gas & Electric, has said that it will seek approval from regulators to purchase 200 megawatts worth of solar energy delivered from space solar power company Solaren over fifteen years. The goal of the project is to provide electricity to PG&E by 2016. Another company, called Space Energy, Inc, has also been formed to tap solar energy from space using a similar technique as Solaren.[228] Space Energy Inc hopes to be transmitting electricity within a decade.[229]

Power beaming is also an essential technology for space elevators. NASA and the Spaceward Organization have sponsored a power beaming challenge as part of its Centennial Challenge program since 2006. The 2009 challenge will take place at NASA Dryden Space Flight Center in August 2009. There are currently six teams competing for the $2.0M prize.[230]

Integration

Long distance power transmission technologies are primarily transformational to the lunar architecture. Power beaming technologies would require a dramatic shift in the way power is being designed into the architecture. Power units would have to be redesigned to convert solar power to microwaves or lasers for power beaming, and receivers would have to be installed on any systems that would require the beamed power. Wired long-distance power transmission technologies could be more easily integrated into the architecture for transmitting power between power units and habitats, ISRU sites, or science modules.

Advanced Chemical Propulsion

Revolutionary

Advanced chemical propulsion technologies increase the performance, storage capabilities, or environmental friendliness of rocket engines. Technologies include fuels and oxidizers, additives, nanostructured versions of existing fuels, and novel chemical rockets like the air-augmented rocket and the pulse detonated wave rocket. Two of the technologies, metastable intermolecular composites and functionalized carbon nanotubes, fall under a category of novel propellant technologies called “nanoenergetics”. Metastable intermolecular composites (MICs) are a class of energetic compounds with nanostructured fuels and oxidizers. By adjusting the size and composition of these particles, the surface area and therefore performance of the fuel can be adjusted for higher or greater customization in performance. Functionalized carbon nanotubes have high electron density and high conductance along the wall of the nanotube, which may improve ignition systems. These nanotubes may also enable higher powered, easier to store propellants. Among the more traditional chemical propellants, Ammonium Dinitramide (ADN) is a solid, organic oxidizer that, by not containing chloride or metals, leaves a reduced signature and less environmental damage. CL-20 is cited as the most explosive non-nuclear material known, consisting of a ring of nitrogen and oxygen atoms. Overall, greater energetic performance from fuels increases the amount of mass NASA is able to launch throughout the architecture.

Technology Name	Description
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.[231]
Ammonium Dinitramide (ADN)	An organic oxidizer that performs equal to or better than existing operational oxidizers.
CL-20 (Hexanitrohexaazaisowurtzitane (HNIW))	A high-energy propellant with a minimum exhaust signature.
Electrically Controlled Solid Propellant (ESP)	A solid propellant for thruster and ignition systems that is throttlable, re-startable, and environmentally sound.
Nanoenergetics: Functionalized Carbon Nanotubes	All research done in incorporating carbon nanotube structures for energetic applications.
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.

The technologies in this area have applications primarily in rocket propulsion for weapon and space systems. As such, government, military, and space programs are the primary investors. NASA and the military are studying air-augmented rockets for Earth to orbit transportation. These rockets include single-stage-to-orbit (SSTO) concepts, which would reduce ground support operations, however, significant challenges must still be overcome. NASA developed pulse detonation wave (PDW) rockets as a lightweight, low-cost alternative for upper stages for satellite orbit transfer.

The remaining technologies include existing and advanced energetic materials. Energetic materials are a major component of weapons systems. Their primary uses include explosives, gun, and missile propulsion, as well as spacecraft propulsion. ADN and electrically-controlled solid propellant (ESP) are "green" solid propellants. ADN, an oxidizer for solid propellants, has been used in Russian Soyuz vehicles since the 1990s and is currently being researched by Sweden's Defense Research with funding from NASA GRC for use in the ARES vehicle. ESPs are a controllable solid propellant funded by the Naval Sea Systems Command (NAVSEA) for applications in smart weapons, tactical rocket motors, and spacecraft propulsion. The DoD and ATK Thiokol developed CL-20 to production for use in weapons systems. Nanoenergetics is a relatively new field but is rapidly growing as all branches of the military and the DOE are conducting research.

Air-augmented rocket engines are a hybrid class of rocket/ramjet engine, which combines an ejector with a rocket engine. The ejector is designed to increase the specific impulse, enabling larger payloads to orbit.[232] For an air-augmented rocket, the ejector and rocket are integrated into airframe and designed to operate in several hybrid modes depending on rocket velocity. At low speeds, the ejector merely increases the working mass of the rocket engine by adding air to the hot rocket exhaust. At Mach 3-10, the rocket engine cuts off, and the ejector can operate in a ram or scramjet mode. At higher speeds, or outside the atmosphere, the ejector closes, and the rocket operates in a conventional mode.[233] This hybrid approach tailors the efficiency of the rocket throughout its flight regime.

PDW rockets were originally researched as boosters for launching satellites, but they could also be used for landers and other vehicles that require controlled landing. In PDWs the fuel is injected into a cylinder at low pressure. Once filled, the fuel is detonated, producing a "shock wave" that pushes exhaust out the single open end of the cylinder, producing thrust. In PDWs, detonations can be pulsed, activated multiple times. The number of pulses can be controlled to create different levels of thrust.[234]

ADN, unlike existing oxidizers, does not produce hydrogen chloride (HCl), a toxin, in the exhaust. This also reduces the signature of the projectile, as the nucleation of HCl normally creates a secondary smoke problem. ADN works with propellants with high specific impulse, and is environmentally degradable and benign.[235] ADN could potentially be used to replace ammonium perchlorate in solid propellants. This would have performance and health advantages; the Center for Disease Control (CDC) has linked perchlorate with thyroid problems, and the Environmental Protection Agency (EPA) has looked into setting perchlorate limits.[236]

Electronically-controlled solid propellants have been developed for attitude control systems. In ESPs, propellant is controlled through the use of electrodes. When the required voltage is applied to the propellant, it ignites; when the voltage is removed it stops. With this method, ignition can be started and restarted as required. These propellants will not ignite by sparks or flames, improving the overall safety of the propellant.[237]

CL-20 is a cyclic nitramine, composed entirely of nitrogen and oxygen, most often used in explosives. It appears to outperform incumbent high performance solid fuels, HMX and RDX.[238]

Nanoenergetics can store higher amounts of energy than conventional energetic materials and can be used in unprecedented ways to tailor the release of energy for customized performance characteristics. Two examples of nanoenergetics are functional and metastable nanoenergetics. Functional nanoenergetics concepts include incorporating or binding carbon nanotube (CNT) material into propellant matrices, and using the optical and electrical properties of the CNTs to generate improved propellants. The high electron density that characterizes the nanotube structure and the high conductance along the tube wall may lead to more robust and reliable ignition behavior.[239] Carbon nanotubes could be used to encapsulate nanoscale energetic ingredients, perhaps even the nitro-organic energetic compounds themselves (e.g. HMX, RDX), to yield a propellant that not only has the same, or better, performance for energy release, but also has improved performance for handling and long-term storage.[240]

Metastable nanoenergetics are nanoscale powders that have a much higher surface area than traditional powders. This increases the efficiency and power of the reaction. MIC formulations are based on intimate mixing of the reactants on the nanometer length scale, with typical particle sizes in the tens of nanometers range (e.g. 30 nm). One important characteristic of MICs is that the rate of energy release can be tailored by varying the size of the components. Three specific MIC formulations have received considerable attention to date: Al/MoO3, Al/Teflon, and Al/CuO.[241]

Game-Changing Impact on the Architecture

Advanced rocket engines and propellants can provide increased performance that, in turn, increases payload mass. Additional payload mass can increase the capabilities of the lunar architecture, reduce risk by providing additional reserves, and extend the time between resupply flights.

Functionalized carbon nanotube energetic materials could significantly improve performance in the areas of ignition, overall propellant performance, safety, and in mechanical properties. MIC characteristics could potentially increase energy output, tune the reactive power, tune reaction front velocities, and achieve reaction zone temperatures exceeding 3000 K.[242]

New “green” oxidizers, such as ADN, reduce environmental damage on Earth. Specifically, ADN could replace ammonium perchlorate.

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	
Extra-Vehicular Activity (EVA)	X	Habitat	
ARES and EDS	X	Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems		NASA Comm Architecture	X
ISRU		Crew Health	
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improves Health and Safety	
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	

Technology Trajectory

Advanced chemical propulsion technologies are at a range of technology readiness levels from TRL 3 through 9. Nanoenergetics is in the earliest stages of development, while CL-20 and ADN are currently used in military applications. In May 2009, NASA's Glenn Research Center awarded a contract to Sweden's Defense Research Agency (FOI) to conduct an evaluation of ADN as an oxidizer in solid propellants for large space launcher boosters.[243] The FOI is currently the leading research facility for ADN oxidizer development.[244] Recent research into nanostructured composites of CL-20 was conducted at the University of Delaware.[245] Space Propulsion Systems Inc, uses CL-20 in one of its microcellular propellants. The company has contracted with E'Prime Aerospace to incorporate their fuels into E'Prime's Eagle series of launch vehicles.[246]

Nanoenergetic MICs and functionalized carbon nanotube research is in the early stages of development but is already undergoing rapid growth. Currently, all of the military services, some DOE, and some academic laboratories have active development programs to use the unique properties of nanomaterials that have potential to be used in energetic formulations for advanced explosives and propellant applications.

Air-augmented rockets are an old concept, however, technical difficulties have kept this technology at a low TRL. Both the military and NASA are working on air-augmented rocket technologies or ram-/scramjet precursors, including the NASA's X-series of experimental aircraft.[247] The most notable scramjet test was NASA's X-43 aircraft, which was successfully tested in March and November of 2004, reaching speeds of Mach 10. Challenges to this design include the integrated airframe, design optimization, and lack of flight-testing.[248]

NASA MSFC along with United Technology Research Corp. and Adroit Systems built small-scale pulse detonation rocket engines for ground testing. During testing they were able to pulse (detonate) the engine more than 100 times per second, and were able to prove that a pulse detonation rocket engine can provide thrust in space.[249]

Integration

Advanced rocket engines and propellants would be a revolutionary advance for launch systems, requiring design changes to the engines of launch vehicles. Launch vehicles using air-augmented and PDW engines would have to be designed around these new engines, requiring a complete redesign for ARES and ALTAIR vehicles.

Changes in solid propellants, from ammonium perchlorate to ammonium dinitramide, would require extensive testing and development, particularly since these rockets are carrying humans. The solid stages used on the Ares rockets have heritage in the shuttle system, and have very well known performance characteristics and safety variables. Large changes to these systems would present a significant risk, real or perceived.

Massive Online Collaborative Environments

Rapidly Evolving

These technologies organize, present, and connect data to create an immersive collaborative environment. The purpose of this technology is to maximize available data online in a format that is intuitive, and easy to navigate and analyze. This technology can be implemented with various types of interfaces; from conventional hardware, such as a desktop monitor, to more advanced hardware, like an immersive, three-dimensional laboratory.

Technology Name	Description
Mirror Worlds	A dynamic, four-dimensional, virtual world, whose data sources may have a physical counterpart in the real world.
Digital Swarming	A model for distributing collective data on a network, designed to facilitate collaboration and decision-making in a corporate environment.
AlloSphere	A room-sized spherical screen that displays scientific data in high-resolution 3D video and audio streams, in real-time.

Massive online collaborative environments are rapidly evolving technologies that are cropping up in various forms in a number of fields. This technology area combines sophisticated networking and organization of data to provide cohesive, collaborative environments for users to interact with data and with one another. This technology area is particularly useful with data sets that are so large or complex that traditional data displays would overwhelm users, making the data difficult to understand or fully appreciate. This technology has been applied in many fields, including science, entertainment, business, and military applications. For example, several mirror world environments, such as Second Life™, have emerged in the field of computer gaming. Digital swarming has been employed to facilitate decision-making processes in business environments and in city transit systems. Researchers use the AlloSphere in California to study data in diverse fields including nanotechnology, theoretical physics, molecular biology, cosmology, and neurophysiology.[250]

The most popular example of a massive online collaborative environment is a "mirror world." A mirror world is "a proposed interface and structure for a global information network."[251] David Gelernter introduced this concept in his book, *Mirror Worlds*.[252] A mirror world is a four-dimensional, virtual world, accessible through a computer.[253] The structures in a Mirror World represent data sources that may or may not have a physical counterpart in the real world.[254] Windows and graphical representations can provide real time and static data on request.[255] In a mirror world, a user can browse the data or can navigate directly to specific locations.[256] The Internet itself is the biggest self-organizing and self-managing project, building the largest mirror world imaginable.[257] However, the World Wide Web is innately static, whereas a mirror world is dynamic.[258] While virtual worlds, like Second Life™, are useful within the context of cyber infrastructure, a mirror world can describe a much more substantial environment, foreseeing the existence of advanced optical networks that allow people to share real spaces and real data.[259]

Digital swarming is a concept in which input, collected from machines, people, sensors, and more, is digitized and placed onto a network.[260] This input is incorporated into a common fabric "that connects people, processes, and knowledge to enable faster, better decision making."[261] Unlike most information systems, which are application-centric, digital swarming is a distributed process, allowing information and decision making to occur throughout the network.[262] Collectively, users may rapidly filter out bad information, and thereby reduce the risk of misinformation.[263] With this technology, "companies can increase profit and productivity, because digital swarming improves collaboration, distributes intelligence, and aggregates collective experiences."[264]

The AlloSphere is a large-scale computing laboratory that integrates visual, sonic, sensory, and interactive components. The presentation space of the AlloSphere is a thirty-foot diameter spherical screen, built inside a three-story near-anechoic (echo free) cube.[265] The screen consists of two fifteen-foot diameter hemispheres.[266] Twenty to thirty people can stand on a suspended walkway that runs in between the hemispheres.[267] Two visual projectors and a system of real-time sound synthesis clusters deliver "rich, coherent, interactive, high-resolution 3D video and audio streams from voluminous amounts of scientific data, all in real-time."[268] This environment allows people to understand data that would be too complex to grasp in conventional computing environments. The AlloSphere could be useful to the lunar architecture because "it is an instrument for gaining insight and developing bodily intuition about environments into which the body cannot venture."[269] Like other massive collaborative environments, the AlloSphere could help people on the ground comprehend the environment of the Moon, and thereby assist the relatively few astronauts on the lunar surface.

Game-Changing Impacts on the Architecture

Massive online collaborative environments could improve performance by enhancing collaboration between people on the ground and people in space. These environments could increase reliability by integrating environmental data for accurate mission simulations, and providing real-time ground control inputs.

These environments would have particular effect on NASA's communication architecture. With this type of technology, the lunar architecture could develop a system where sensors all over the Moon feed data into an online collaborative environment, which would allow ground control to have a real-time integrated experience of conditions on the Moon. It would also allow ground control and astronauts to interact in a simulated environment, with raw data presented graphically.

This technology is important to research scientists at NASA who work with large data sets and complex systems. These environments facilitate distribution of data and collaboration, which can result in better and more efficient decision-making and analysis.

Since these environments are created with real data from lunar or in-space operations, they could also be a source and method of outreach and communications with the public. For example, the public could access a massive online collaborative environment to virtually explore the lunar environment and learn about NASA's operations. These massive online environments are well aligned with the communication methods of younger generations, as evidenced by the popularity of massively multi-player online games such as Second Life™ and World of Warcraft™, in which players can interact in real-time with a virtual world.

Relevant Exploration and Constellation Architecture Elements

Orion		Lunar Power	
Altair		Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	
Mission Systems	X	NASA Comm Architecture	X
ISRU		Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Benefits to the Architecture

Decreases Cost	
Decreases Mass	
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	

Technology Trajectory

Currently, NASA is partnering with Cisco Systems to create a massive online collaborative global monitoring platform called the "Planetary Skin" to capture, collect, analyze, and report data on environmental conditions around the world, while also providing researchers social web services for collaboration.[270] The project's first layer, "Rainforest Skin," will be prototyped during 2010.[271] Researchers have several plans for using the globally collected information, including targeting tropical deforestation and monitoring changes in carbon dioxide in rainforests.[272]

A current example of digital swarming is a web-based service called the personal travel assistant (PTA).[273] Cisco Systems, MIT, and select cities began this project, which makes a real-time representation of the city's transit system available to users via smartphones, personal digital assistants (PDAs), vehicles, transit stations, and websites.[274] The PTA maintains this real-time transit environment by pulling together various types of data, including traffic conditions, roadway construction, bus and train routes and schedules, and available parking. Users can interact with the data in order to travel the city more efficiently (reducing cost, travel time, and carbon footprint).[275]

A fully constructed AlloSphere is in Santa Barbara, California.[276] The laboratory itself is completed, and researchers are now primarily engaged in building the computing platform and interactive display parts of the instrument.[277]

These technologies enabling online collaborative environments are already commercially available and tested, but as the number of projects using these technologies increases, the technology will continue to be refined and improved.

Integration

Online collaborative environments are a rapidly-evolving technology. At its most basic level, this technology involves using and interacting with data differently, and therefore does not inherently require that the lunar architecture change. The amount of involvement needed to integrate this technology would be determined by the way in which NASA chose to implement the technology.

One factor that would impact the integration is the type of display used to interact with the online environment, which ranges from desktop monitors, to the highly advanced audio and video systems that are used in the AlloSphere. The latter could potentially involve a significant effort to integrate, particularly if such advanced display systems are used in space.

The type and amount of data that would be used in the online environment also affects integration. NASA could choose to use only data gathered by sensor networks that already exist in the lunar architecture. NASA could also choose to collect more data, or different types of data to populate the online environment, which would involve more integration effort. This increased amount of data being transferred could also necessitate higher bandwidth communications links in order to achieve a real-time experience. Scope and purpose are further considerations. Use in communications changes not only hardware and software, but also communication protocols, as these online environments require different ways of thinking and communicating.

Emerging Communication Systems

Transformational

Emerging communication systems promise increased bandwidth and throughput for data between systems, and from the lunar surface to Earth. The technologies profiled here employ different technological solutions to improving communications, and would impact different parts of the lunar architecture. In general, these technologies satisfy one or more of the following needs: lower power to operate, higher data transfer rates, and a reduction in noise and data loss.

Technology Name	Description
Optical Crosslinks, uplinks, and downlinks	Direct links between satellites, other data processing nodes, and users that use optical signals, typically lasers.
Optical Wireless Communications Onboard the Spacecraft	By replacing wired communication technology, these could decrease weight onboard spacecraft, and increase data transfer rates.
X-ray Communications	This system uses a Modulated X-ray Source (MXS) to vary the intensity of the X-rays, creating an amplitude modulation signal.

Commercial, military, and academic institutions are performing research to improve communications technology. The military is a significant driver for satellite communications demand, and pursues high-risk development projects that drive innovation in emerging satellite communications.[278] The DoD's Transformational Communications Satellite (TSAT) program developed several technologies for satellite communications that could have game-changing impacts on the lunar architecture. One example technology is laser satellite crosslinks, which enable a 10 Gbps worldwide capacity.[279] However, the TSAT program was recently terminated in favor of the more mature Advanced Extremely High Frequency (AEHF) Satellite, which uses extremely high frequency (EHF) crosslinks.[280] Commercial innovations in satellite communications architectures could also have benefits to NASA. One example of this innovation is the Iridium satellite constellation's use of microwave (Ka band) downlinks and satellite crosslinks.[281] Emerging satellite communications technologies are increasing bandwidth, improving signal strength, and decreasing power or mass requirements. The technologies highlighted below represent some of the most applicable innovations for the lunar architecture. Research into theoretical communication architectures could lead to far term technologies for Mars exploration or other future NASA missions.

X-ray communication systems use a modulated x-ray source (MXS), invented by Goddard Space Flight Center scientist Keith Gendreau, to modulate the intensity of x-rays. The source is composed of a precisely controlled ultraviolet diode, an electron emitting photo-multiplier, a voltage source, and an electron target that emits x-rays. By controlling the intensity of the diode the amplitude of the x-ray signal can be varied.[282] This technology has the potential to provide high-data rate communications over vast distances in space, using little power.[283] Diffraction-limited optics can be used to limit the spread of the x-ray beam, increasing the signal-to-noise and decreasing the power necessary to communicate in space. X-Ray communication can penetrate radio frequency interference from shielding or plasmas generated during hypersonic-reentry.[284]

Optical satellite links can increase data rates between satellites, between satellites and ground segments, and between ground elements in a local area network.[285, 286] For terrestrial communications, satellite crosslinks minimize the number of links necessary to transmit information around a planet, improving the signal, bandwidth and speed, and reducing costs. If applied to a space communications architecture, optical communications can potentially dramatically increase capacity and the capabilities of a satellite network.[287] The link usually consists of a low power laser that uses free space optics to limit diffraction and increase signal strength. New techniques using low cost, commercial silicon-based sensors for tracking the direction of the transmit laser, regardless of the transmit wavelength, could reduce the cost and complexity of optical satellite links.[288]

Optical wireless communications could decrease mass and increase data transfer rates by removing wires onboard habitable architecture elements such as Altair and the habitat. This technology is already prevalent in the commercial industry, in PDAs for example, however, the technology has not been developed for high radiation environments.[289] Ionizing radiation can cause temporary damage in optical wireless communication devices. A larger concern is displacement damage, which can be permanent. Displacement damage is caused by high-energy protons and electrons, which are common in space radiation.[290] This type of damage could be attenuated by radiation shielding for crew health.

Game-Changing Impact on the Architecture

These technologies are transformational to the architecture and have the potential to improve performance and increase reliability of NASA's communication systems. Wireless and optical communication technologies could decrease overall mass, while new technologies for a pointing laser communication link could reduce system costs. Some x-ray communication systems could provide interplanetary communications at a lower power than the current technologies. In general, emerging communications increase the data transfer rates, reduce noise, and reduce data loss in NASA's communication architecture.

The greater availability of bandwidth provided by these technologies could allow new applications, such as more sophisticated user interfaces, which would impact the ground systems and mission systems. The improved communication systems could also impact robotic systems, by improving the data transfer between robotic systems, such as the rover, and the lunar habitat. This could help enhance or increase the science and exploration conducted during the lunar mission.

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Benefits to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	+
Lower Power to Operate	+
Increases Reliability	+
Improved Performance	+
Increases System Power	+

Technology Trajectory

These technologies range from TRL 4-9. Optical satellites links have been tested but are not widely employed. X-ray communications are in development but have a low technical maturity. Optical wireless communications are commercially available for terrestrial applications but might require additional hardening for in-space applications.

Specific examples of optical satellite links include Artemis, the European Space Agency Advanced Relay and Technology Mission Satellite. This mission first used optical free space communications to relay data between satellites, and from satellites to aircraft.[291] The DoD has researched optical inter-satellite links under the TSAT program. This program was canceled due to funding, however, the program spent more than four years reducing technology risk.[292] Technology development on free space optical links is continuing.

GSFC and the DoD are developing x-ray communications. The modulated x-ray source, developed by GSFC, was tested in 2007. The inventor intends to integrate the system with x-ray optics to demonstrate 50kbps-1Mbps data rates, with an ultimate goal of transmitting gigabytes per second.[293] The DoD has contributed funding to this project, which may lead to high-speed switching and multichannel x-ray communication.[294]

Integration

These technologies could have a transformational effect on the lunar architecture. Integrating the optical wireless technology would involve removing the heavier wired technologies from the habitat, Altair lander, Orion, and LER, and installing sensors and transmitters. Although this would involve serious system changes, the impact of reduced mass for wiring and increased performance may make the trade worthwhile. Optical satellite links require advanced optics, beam pointing and tracking technology, and sensors, and would need to be integrated with other segments of the communications infrastructure. Due to advancements in the DoD and commercial sectors, it is likely that NASA could infuse commercially available optical satellite link technology, thus reducing overall system costs.

5.0 TECHNOLOGY AREA WATCH LIST

The technology area watch list contains those technologies that will be developed within NASA's lunar architecture timeframe with or without funding or collaboration with NASA. The goal of the watch list is for NASA to monitor the development of these technologies so that they may be considered for inclusion throughout the development lifespan of the lunar architecture. Further information on these technologies can be found on the quad charts used in the expert panel review in Appendix A: Technology Area Quad Charts. Some of the technologies on this list have been identified as the most game-changing and are profiled in this report.

Technology Area	Description
Anti-Radiation Drugs	Pharmaceutical drugs that counteract the toxic effects of exposure to radiation.
Emerging Therapeutics	Transformational advances in therapeutic medicine including nanomedicine and tissue engineering.
In-Situ Medicine	Medical interventions for use in space that could fit with the mass and operational concepts of the lunar architecture.
Highly-Adaptive Communications Technologies	Communications technologies that broaden their applicability through high levels of adaptability by utilizing more operating frequencies, taking advantage of more bandwidth, and dynamically allocating bandwidth.
Advanced Data Storage	Data storage technologies that dramatically increase the amount of data that can be stored.
Flexible Electronics	Thin, flexible electronics including some that are flexible enough to be rolled up like a newspaper. Technologies include stretchable silicon that can produce high-performance conformable circuits.
Nanoelectronics	Nanoscale electronic components, particularly transistors. Nanoelectronics can be roughly divided into two broad categories: molecular electronics and quantum effect devices.
Next Generation Semiconductors	Alternatives to silicon semiconductor technologies. Some of these technologies involve continuing miniaturization by using alternative semiconducting material systems such as graphene, gallium nitride or single-electron transistors (SETs), while others are moving toward completely different concepts such as spintronics.
Electric Vehicle Technologies	Technologies, standards, and lessons learned from this industry that can inform development of lunar technologies. In addition to battery and ultracapacitors developed for terrestrial use, drive train components, regenerative breaking technologies, adaptive control algorithms, and battery alignment and recharging protocols may have applications for the architecture.
Autonomous Systems and AI	Technologies that model human behavior and decision-making processes. These technologies are used to create long-lived autonomous systems that are able to explore, command, diagnose and repair themselves using fast, commonsense reasoning.
Complex Data Recognition and Acquisition	Hardware, software, algorithms, and models for complex data recognition and acquisition.
Enhanced Human-Computer Interaction	Technologies that use a broad range of new techniques to facilitate communication between humans and computers. These techniques include: sound, speech, motion and gesture recognition.
Massive Data Capturing and Processing	Hardware, algorithms, scripting languages and data structures addressing the special computational challenges of computing with very large data sets.
Massive Online	Technologies for organizing, presenting and connecting data to create an

Collaborative Environments	immersive collaborative environment.
Predictive Data Modeling	Models and algorithms for predicting future events. These technologies use advanced techniques of data mining and machine learning and take into account human cognitive processes.
Printing Manufacturing Technologies	Manufacturing process that uses technology similar to ink and laser computer printers for precision manufacturing of parts and electronics.
Advanced Nanotube-based Materials	Long, thin, atomic scale cylinders, typically created from carbon atoms, or of boron and nitrogen. These cylindrical molecules are extraordinarily strong and have a broad range of electronic, thermal and structural properties.
Artificial Muscles	Robotic muscles created from carbon nanotubes that have been developed into polymer yarns. These yarns utilize electroactive polymers that allow the yarns to act as muscles with dramatic strength that work in a wide range of temperatures.
Metamaterials	Composites that can reflect and bend light and sound waves in ways not readily observed in nature. They can be used to greatly improve the performance of devices that are limited by the way light moves through materials.
Self-Repairing and Self-Cleaning Materials	Materials that are able to repair themselves, regain their strength, and/or regain their structural properties after being damaged.
Transparent Composites	Composite materials with a transparency equivalent to window glass. These composites can be stiff or flexible and are impact resistant.
Energy Storage Technologies	New technologies and concepts for energy storage including new batteries and battery materials, and materials that are able to hold gaseous or volatile fuels in a solid state.
Next Generation Fuel Cell Technologies	Fuel cell technologies including those small enough to replace batteries in portable applications, those able to accommodate a greater diversity of fuels, the use of less expensive catalysts, and other cost and mass efficiencies.
Next Generation Solar Cells	Technologies that offer the potential for greater efficiency than existing systems, and may have simpler or different methods of deployment.
Scalable Micro-Propulsion	Miniaturized thrusters and engines that provide relativity small thrust but have high efficiency and large thrust to weight ratios. These technologies can be scaled by using multiple thrusters in arrays or clustered together.
Service Robotics	Single-application robots and related systems implemented in a wide range of civil and defense applications.
Biomimetic Sensor Technologies	Sensors that emulate biological sensory mechanisms for sensing temperature, pressure or flow. Inspirations for these sensors include both insect and human eyes.
Smart Wireless Sensor Networks	The combination of network embedded sensors with sensors in smart objects creating systems that can perceive and control many aspects in the real world as well as interact with humans.

6.0 NEXT STEPS

A review of technology development trends across the world economy provides a view of the environment and context in which NASA's missions will be operating. The integrated nature of the lunar missions will bring technological requirements from across the economy, where commercial and military innovations are also advancing technologies that were once used by few entities besides NASA.

Awareness of emerging technology areas and economic forces driving investment bring several benefits in strategic planning, including planning flexibility into the architecture, determining the best technologies to address particular requirements, and informing investment and partnering decisions. While it is unlikely that surprising breakthroughs will occur in NASA-specific areas like human life support systems, there would be a decade and millions of dollars in wasted investment were the same true of solar cells. Planning within specific technology areas should reflect the respective levels of innovation within each area, and the extent to which those innovations will affect the architecture elements relevant to the area. In addition, should the architecture be reconceived, whether due to changes in political forces, major cooperation commitments from international partners, changes in expected transportation system performance, or external economic events, the identification of dynamic game-changing technologies across the economy could be a valuable tool to inform the trade space of future assessments.

This analysis is important for NASA investment decisions. Some of the technology areas profiled in this report are developing fast enough in other industries and government agencies that advances can be anticipated, and revolutionary and transformational changes tracked. These may be technology areas that are nearly identical with NASA requirements (solar cells) and other areas that may add capability that NASA is not currently planning (massive online collaborative environments). Investment decisions based on this knowledge may enable NASA to proceed with its current strategy and continue to watch these technologies; or they may reach a point where NASA feels they are ready to be developed for space systems.

This process feeds partnership decisions, when it is appropriate for NASA to proactively advance dynamic technology developments. Commercial entities or other government agencies with similar technology goals or advanced technical knowledge can be identified as part of this process, and partnerships initiated. Partnerships could be as simple as a memorandum of understanding, or as integrated as joint technology development. The level of partnership will depend on the complexity of the technology, the similarities in requirements between agencies, the relative funding requirements, and proximity. The nature of the partnership 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.

The results of this study are the identification of nineteen dynamic, emerging technology areas with great potential to enhance the lunar architecture and a technology watch list of 28 fast-moving technologies whose advance is not contingent on NASA funding and research. As the methodology of the study sought to highlight fast-moving or emerging areas and correlate those areas with keystone segments of the lunar architecture, the nineteen resulting technologies fall upon a continuum between those two values. Some of the areas bring together disparate technologies that apply similarly to a NASA area of particular import. ISRU manufacturing is such an area, where use of indigenous resources and free-form manufacturing of those resources calls on capabilities from solar cell manufacturing to welding. On this same end of the spectrum, another technology area, advanced chemical propulsion, will contain innovations that apply to NASA, and could have major impacts on operations, but which apply to NASA so closely that developments will not blindside NASA and its ecosystem of subcontractor, working groups, and cross-agency links. On the other end of the spectrum are technologies developing rapidly outside of NASA, with little NASA help, that the agency might do well to investigate and find ways to use and augment in their own systems. Online collaborative environments, including mirror worlds, are an example of a technology that NASA does not need to fulfill its mission, but may be able to use to great effect in public outreach. Between these two extremes lie Advanced Fuel Cells and Next Generation Solar Cells, technologies that have been used by NASA even before they were first commercialized, that are now quickly being advanced by a number of commercial organizations.

Technology development is inherently unpredictable, and often subject to trade secrets and intellectual property protections. The technology watch list highlights those technologies that are candidates for ‘surprise’ capabilities. These are areas with economic and technical forces propelling development. NASA does not need to be proactive in developing these technologies, but would be well served to monitor these areas periodically, and reassess their maturity and applicability to the architecture.

Updates to this study, or further investigations following this approach, are important to maintaining contact with external technology development trajectories, with a focus on NASA architecture requirements. The watch list can be assessed annually, with areas identified as game-changing checked as well. An occasional fresh look across the economy within two years could result in several key changes among technology areas.

The results of this study should inform NASA investment decisions by putting each technology area in a context with appropriate expectations of future developments, sustained technological leadership, or potential for obsolescence. It could help NASA understand where it can save development resources by allowing existing trajectories to unfold, and it can help foster NASA’s technological leadership by showing where technology partnerships can make key symbiotic contributions.

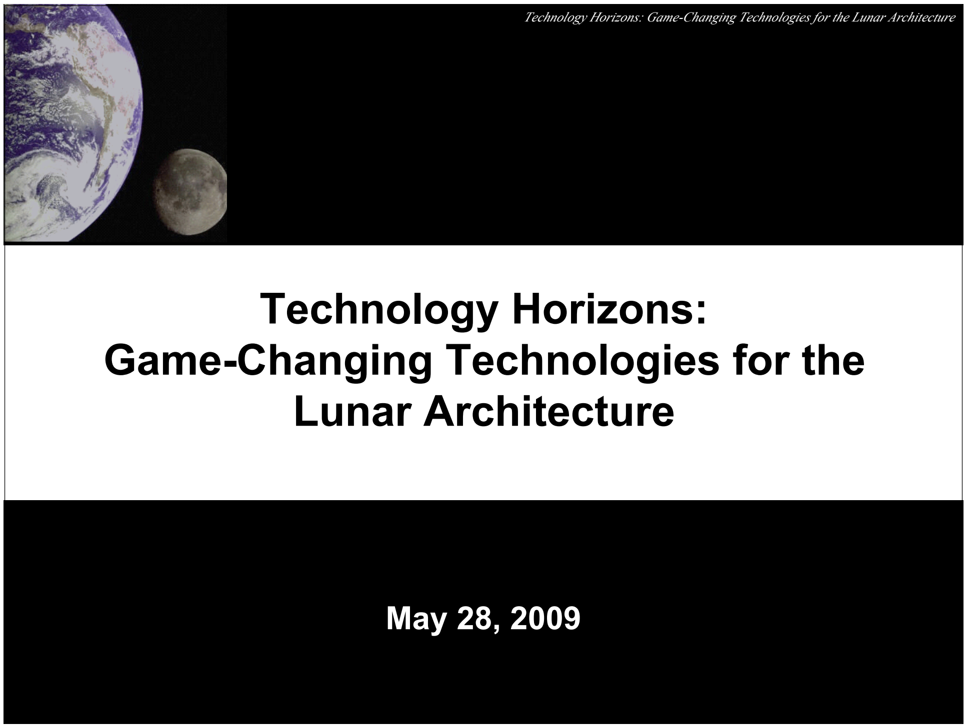
This report has been developed to provide support, throughout NASA, for assessing and communicating advanced technologies for the lunar architecture. The Advanced Concepts Group, Exploration Technology Development Program, and Human Research Program can use the findings to identify potential technology solutions for capability requirements. It can also be used as a reference document for future architecture assessment studies. In addition, this report has already helped NASA respond to questions from Congress and NASA’s Senior Management Council regarding NASA's approach to innovative technology solutions, and will continue to be a reference for addressing those types of questions.

This document represents the first in a two-part series of documents on game-changing technologies. The forthcoming companion document will address longer-term technologies, focused on those that enable conceptual transformations of space architectures; those that are "extremely" game changing. The report, due to be completed in mid 2010, will include a broader set of technologies and will use a technical approach to identify technologies appropriate to the changes in subject matter and scope. While the starting point for this report was technologies that could be infused into the near-term lunar architecture, this follow-on document will look at longer-term, emerging technologies and capability areas having the greatest potential impact on NASA. These two reports will be updated every other year in series.

APPENDICES

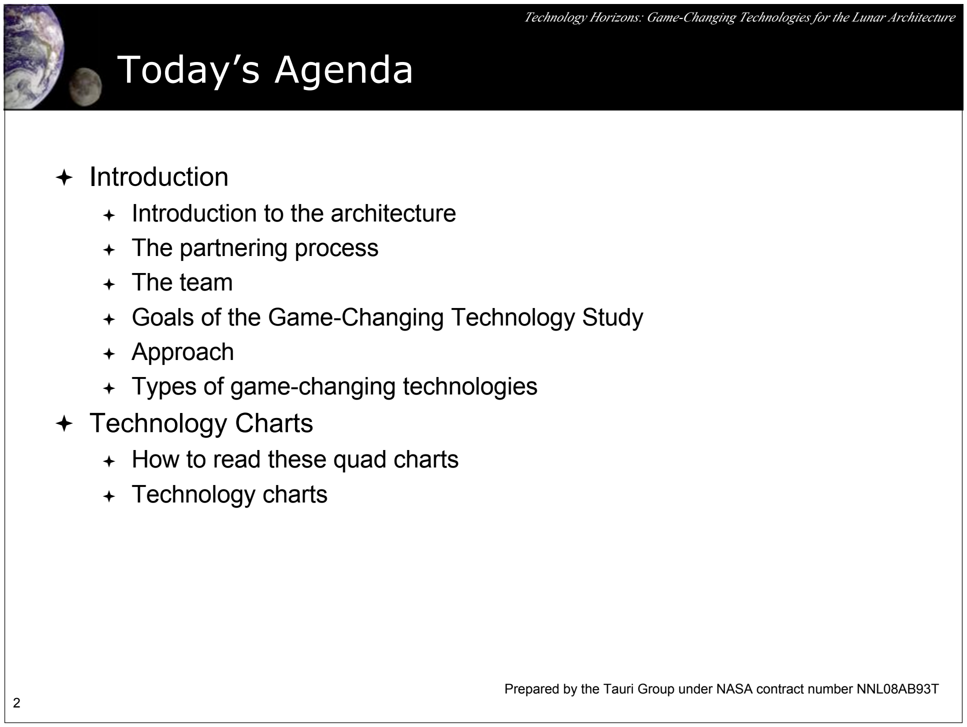
Appendix A: Technology Area Quad Charts

These quad charts were presented at the Expert Panel Review on May 28, 2009. This panel of technology experts from both inside and outside of NASA reviewed the material on these quad charts to identify the top game-changing technology areas further discussed in this report. During the course of this meeting, the panel supplied further example technologies for some of the technology areas. This version of the quad charts was updated with new technology examples supplied by the panel for those technology areas not chosen for inclusion in this report.



Technology Horizons: Game-Changing Technologies for the Lunar Architecture

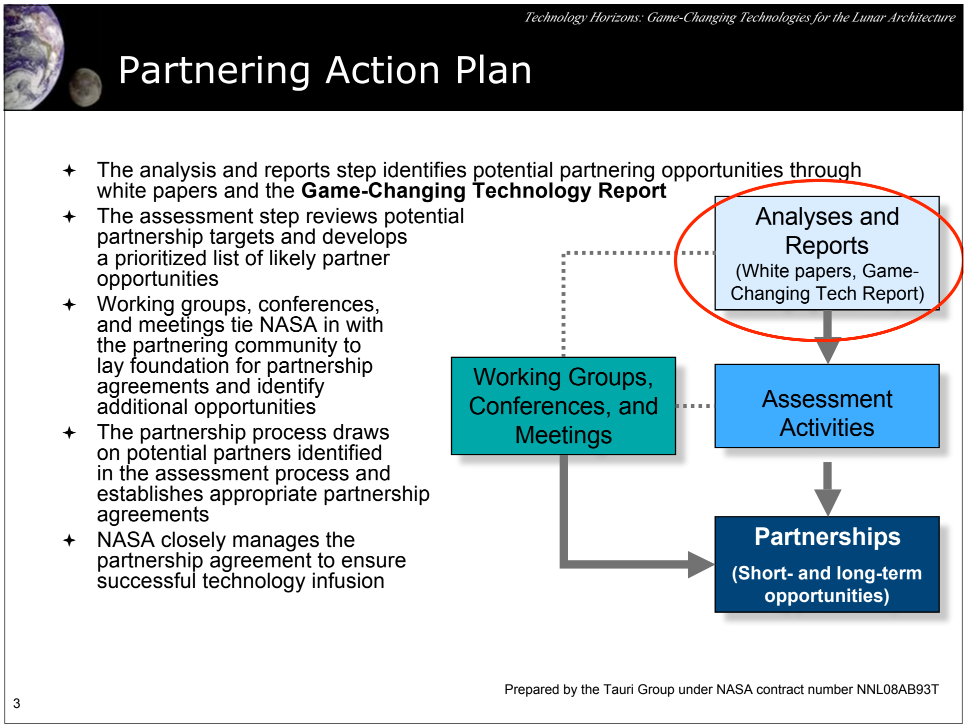
May 28, 2009



Today’s Agenda

- Introduction
  - Introduction to the architecture
  - The partnering process
  - The team
  - Goals of the Game-Changing Technology Study
  - Approach
  - Types of game-changing technologies
- Technology Charts
  - How to read these quad charts
  - Technology charts

Prepared by the Tauri Group under NASA contract number NNL08AB93T



Partnering Action Plan

- The analysis and reports step identifies potential partnering opportunities through white papers and the **Game-Changing Technology Report**
- The assessment step reviews potential partnership targets and develops a prioritized list of likely partner opportunities
- Working groups, conferences, and meetings tie NASA in with the partnering community to lay foundation for partnership agreements and identify additional opportunities
- The partnership process draws on potential partners identified in the assessment process and establishes appropriate partnership agreements
- NASA closely manages the partnership agreement to ensure successful technology infusion

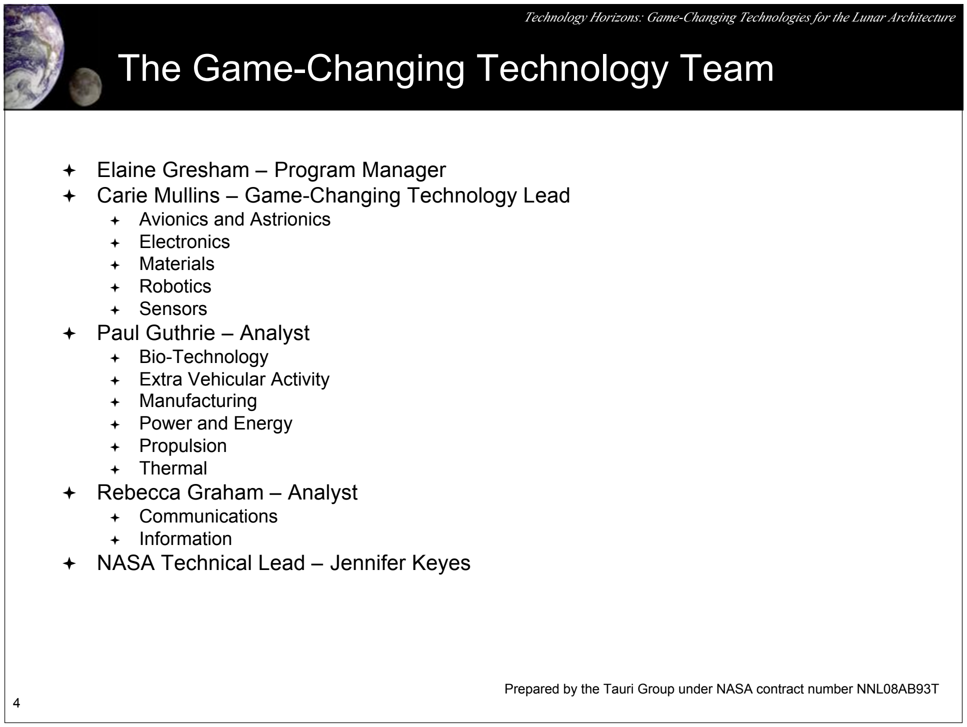
Analyses and Reports (White papers, Game-Changing Tech Report)

Working Groups, Conferences, and Meetings

Assessment Activities

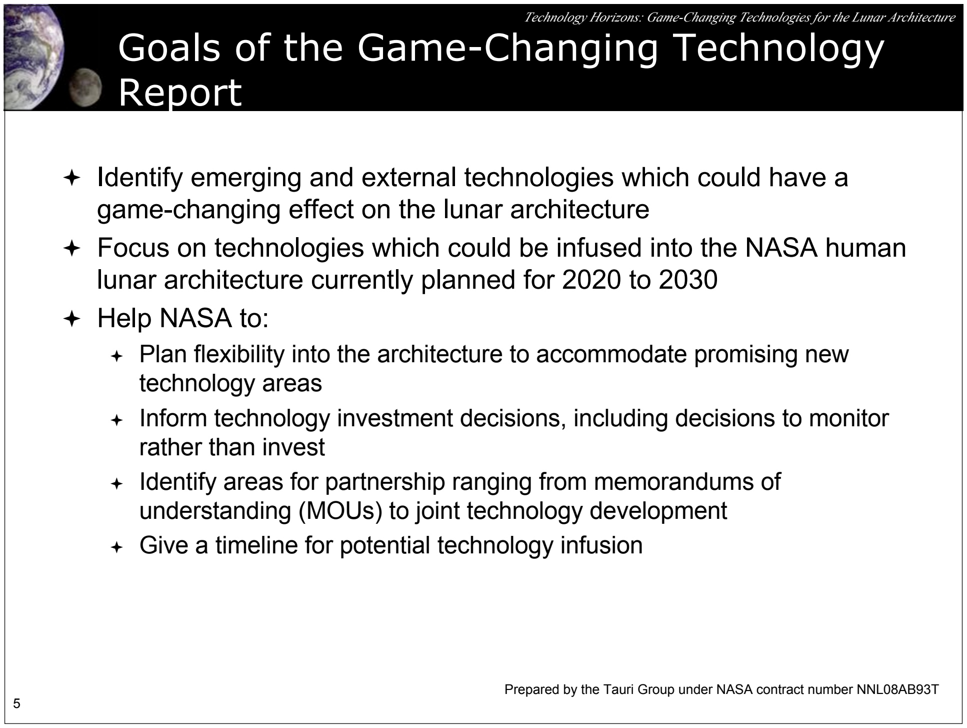
Partnerships

(Short- and long-term opportunities)



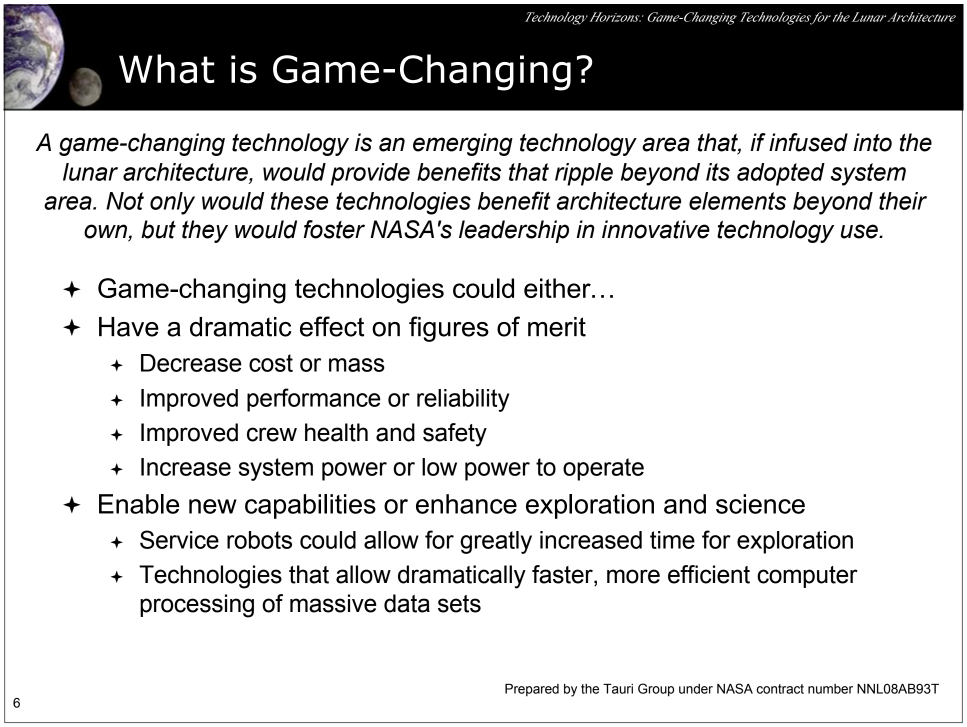
The Game-Changing Technology Team

- Elaine Gresham – Program Manager
- Carie Mullins – Game-Changing Technology Lead
  - Avionics and Astrionics
  - Electronics
  - Materials
  - Robotics
  - Sensors
- Paul Guthrie – Analyst
  - Bio-Technology
  - Extra Vehicular Activity
  - Manufacturing
  - Power and Energy
  - Propulsion
  - Thermal
- Rebecca Graham – Analyst
  - Communications
  - Information
- NASA Technical Lead – Jennifer Keyes



Goals of the Game-Changing Technology Report

- Identify emerging and external technologies which could have a game-changing effect on the lunar architecture
- Focus on technologies which could be infused into the NASA human lunar architecture currently planned for 2020 to 2030
- Help NASA to:
  - Plan flexibility into the architecture to accommodate promising new technology areas
  - Inform technology investment decisions, including decisions to monitor rather than invest
  - Identify areas for partnership ranging from memorandums of understanding (MOUs) to joint technology development
  - Give a timeline for potential technology infusion



What is Game-Changing?

A game-changing technology is an emerging technology area that, if infused into the lunar architecture, would provide benefits that ripple beyond its adopted system area. Not only would these technologies benefit architecture elements beyond their own, but they would foster NASA's leadership in innovative technology use.

- Game-changing technologies could either…
- Have a dramatic effect on figures of merit
  - Decrease cost or mass
  - Improved performance or reliability
  - Improved crew health and safety
  - Increase system power or low power to operate
- Enable new capabilities or enhance exploration and science
  - Service robots could allow for greatly increased time for exploration
  - Technologies that allow dramatically faster, more efficient computer processing of massive data sets

Approach: List of Technology Areas

- The Tauri Group has developed a list of candidate technology areas
  - Leveraged 16 related game-changing technology reports from diverse sources to develop our candidate technology list
  - Eliminated technologies with low applicability to NASA (e.g. digital money, feminization of the workforce, green buildings)
  - Grouped individual technologies into technology areas, to ensure even comparisons
  - Characterized technology areas based on measures such as TRL, level of interest, applicability and benefits to the architecture, and relevance to architecture elements
  - Used decision tools to characterize technologies as high, medium, or low impact

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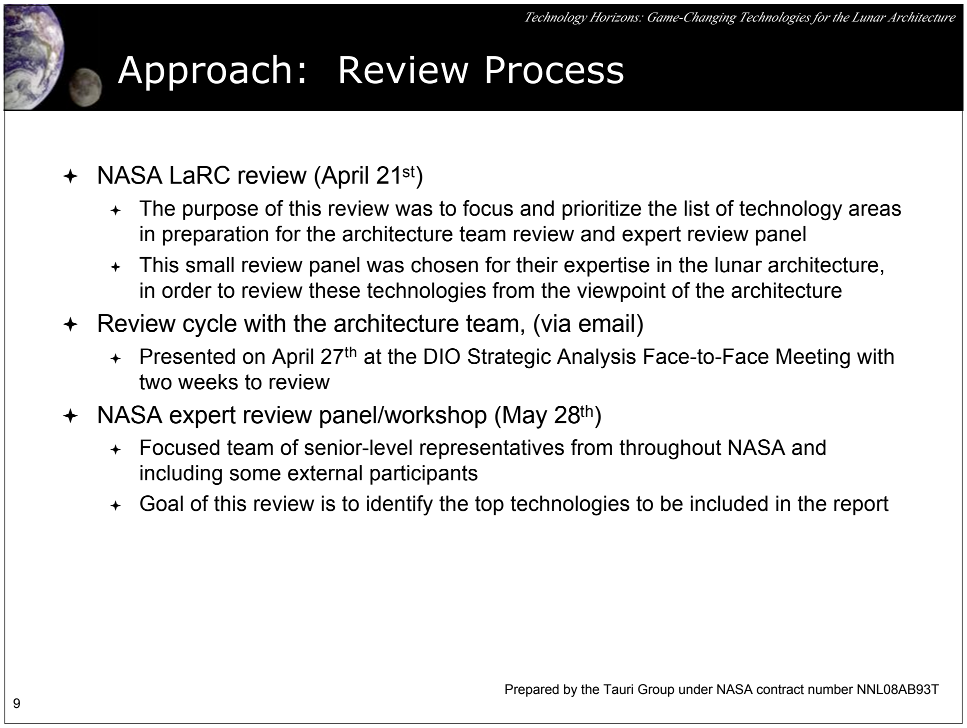
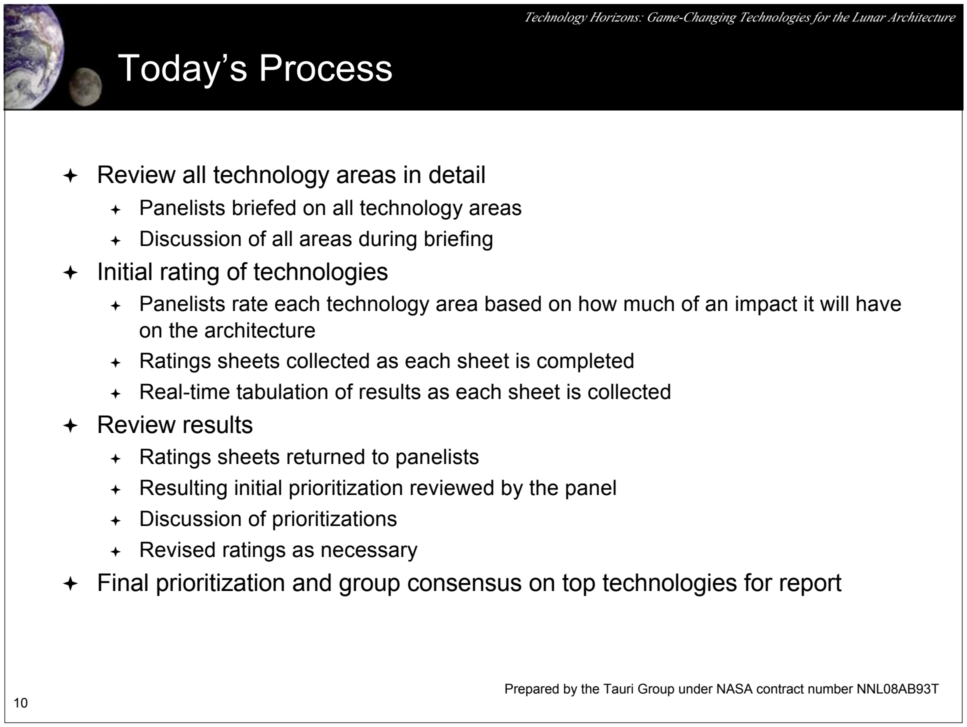
Approach: Sources

- National Intelligence Council, Disruptive Civil Technologies, Six Technologies with Potential Impacts on U.S. Interests Out to 2025, 2008
  - We have obtained full list of 124 technologies
  - Used government screening and ranking criteria
  - SRI willing to give other government employees more information
- MIT-NASA Workshop: Transformational Technologies, 2005
- SRI Consulting Business Intelligence, Technology List
- CNES, 1st Symposium on Potentially Disruptive Technologies and Their Impact in Space Programs, July 2005
- MIT Technology Review: 10 Emerging Technologies 2006 to 2009
- MITRE Emerging Technologies
  - The MITRE Corporation is a non-profit organization that manages three FFRDCs. Through the FFRDCs MITRE performs research in aviation, defense and intelligence, and enterprise modernization
- Technology Strategy Board Technology Research Areas
  - The Technology Strategy Board is a non-departmental, executive level advisory committee for the UK government. The TSB promotes innovation through collaborative research, knowledge transfer networks and partnerships, key research centers, and international programs.
- Defense Intelligence Agency, Avoiding Surprise in an Era of Global Technology Advances, 2005
- The Aerospace Corporation, Advanced Space System Concepts and Technologies: 2010-2030+, 2003
- National Research Council, Space Technology for the New Century, 1998
- Other works:
  - DTIC, 3rd Annual Disruptive Technology Conference, 2006
  - NATO Assessment of Possible Disruptive Technologies for Defense and Security
  - Terry C. Pierce, Warfighting and Disruptive Technologies: Disguising Innovation (London, England: Frank Cass Publishers, 2004)
  - Daniel Talmage, Forecasting Future Disruptive Technologies, http://www8.nationalacademies.org/cp/projectview.aspx?key=48795, in progress



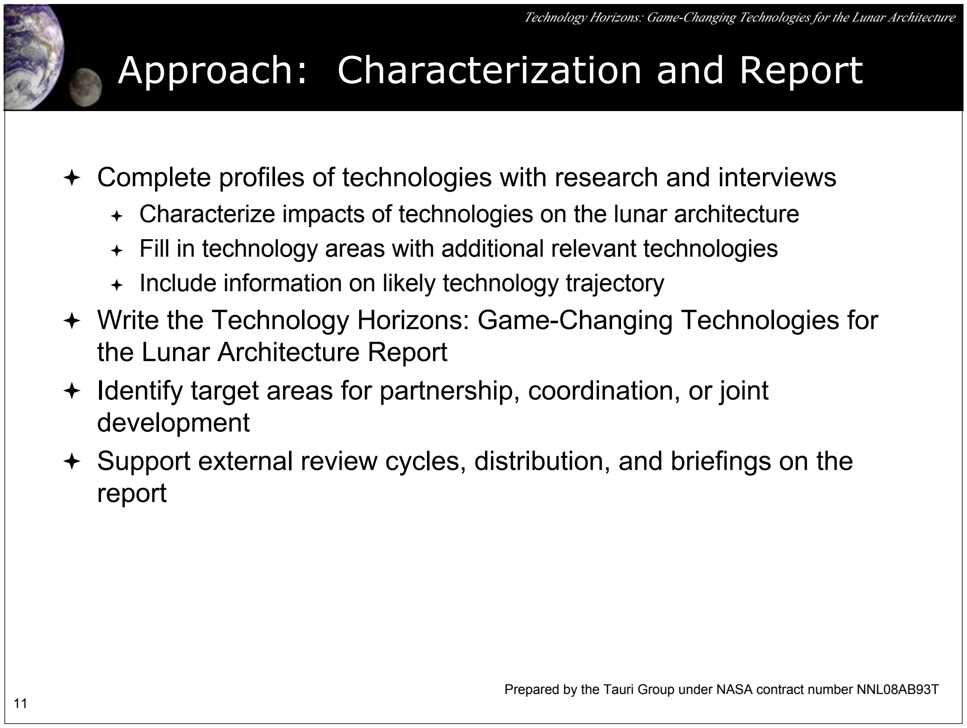
Approach: Review Process

- NASA LaRC review (April 21st)
  - The purpose of this review was to focus and prioritize the list of technology areas in preparation for the architecture team review and expert review panel
  - This small review panel was chosen for their expertise in the lunar architecture, in order to review these technologies from the viewpoint of the architecture
- Review cycle with the architecture team, (via email)
  - Presented on April 27th at the DIO Strategic Analysis Face-to-Face Meeting with two weeks to review
- NASA expert review panel/workshop (May 28th)
  - Focused team of senior-level representatives from throughout NASA and including some external participants
  - Goal of this review is to identify the top technologies to be included in the report



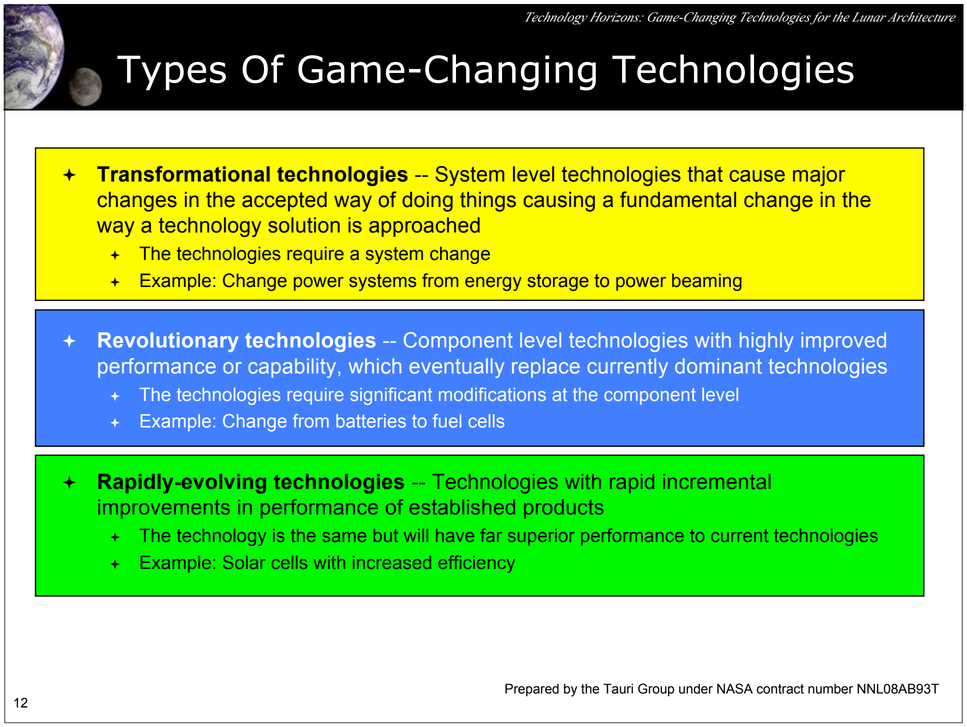
Today's Process

- Review all technology areas in detail
  - Panelists briefed on all technology areas
  - Discussion of all areas during briefing
- Initial rating of technologies
  - Panelists rate each technology area based on how much of an impact it will have on the architecture
  - Ratings sheets collected as each sheet is completed
  - Real-time tabulation of results as each sheet is collected
- Review results
  - Ratings sheets returned to panelists
  - Resulting initial prioritization reviewed by the panel
  - Discussion of prioritizations
  - Revised ratings as necessary
- Final prioritization and group consensus on top technologies for report



Approach: Characterization and Report

- Complete profiles of technologies with research and interviews
  - Characterize impacts of technologies on the lunar architecture
  - Fill in technology areas with additional relevant technologies
  - Include information on likely technology trajectory
- Write the Technology Horizons: Game-Changing Technologies for the Lunar Architecture Report
- Identify target areas for partnership, coordination, or joint development
- Support external review cycles, distribution, and briefings on the report

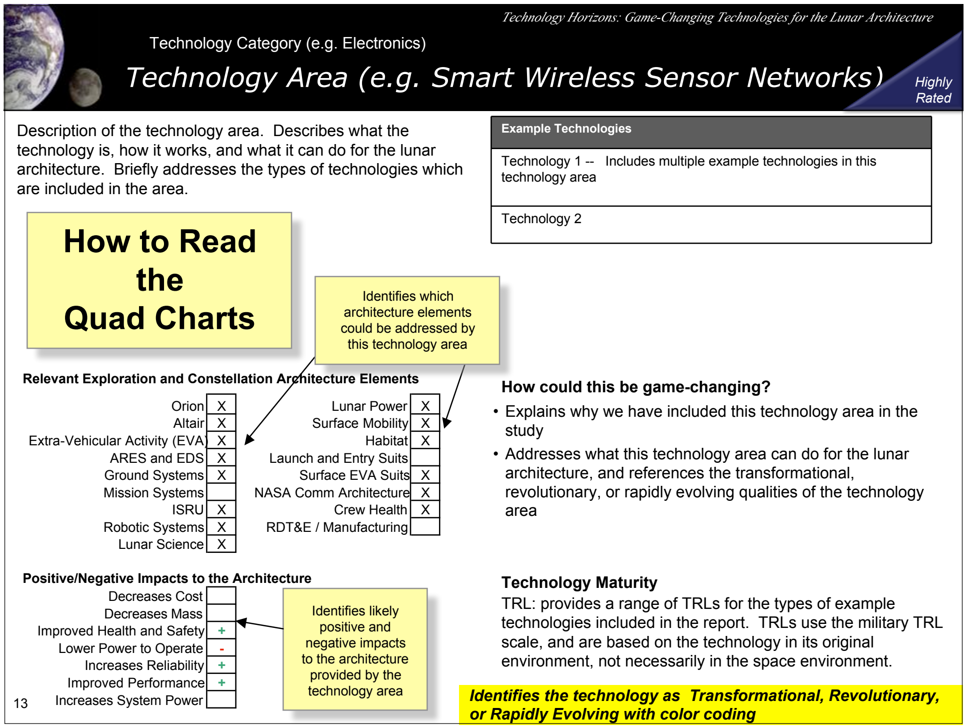


Types Of Game-Changing Technologies

- **Transformational technologies** -- System level technologies that cause major changes in the accepted way of doing things causing a fundamental change in the way a technology solution is approached
  - The technologies require a system change
  - Example: Change power systems from energy storage to power beaming

- **Revolutionary technologies** -- Component level technologies with highly improved performance or capability, which eventually replace currently dominant technologies
  - The technologies require significant modifications at the component level
  - Example: Change from batteries to fuel cells

- **Rapidly-evolving technologies** -- Technologies with rapid incremental improvements in performance of established products
  - The technology is the same but will have far superior performance to current technologies
  - Example: Solar cells with increased efficiency



Technology Category (e.g. Electronics)

Technology Area (e.g. Smart Wireless Sensor Networks)

Highly Rated

Description of the technology area. Describes what the technology is, how it works, and what it can do for the lunar architecture. Briefly addresses the types of technologies which are included in the area.

Example Technologies
Technology 1 -- Includes multiple example technologies in this technology area
Technology 2

How to Read the Quad Charts

Identifies which architecture elements could be addressed by this technology area

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	X
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

How could this be game-changing?

- Explains why we have included this technology area in the study
- Addresses what this technology area can do for the lunar architecture, and references the transformational, revolutionary, or rapidly evolving qualities of the technology area

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improved Health and Safety	+
Lower Power to Operate	-
Increases Reliability	+
Improved Performance	+
Increases System Power	

Identifies likely positive and negative impacts to the architecture provided by the technology area

Technology Maturity

TRL: provides a range of TRLs for the types of example technologies included in the report. TRLs use the military TRL scale, and are based on the technology in its original environment, not necessarily in the space environment.

Identifies the technology as Transformational, Revolutionary, or Rapidly Evolving with color coding

Technology Categories

Avionics and Astrionics
Bio-Technology
Communications
Electronics
Extra Vehicular Activity
Information
Manufacturing
Materials
Power and Energy
Propulsion
Robotics
Sensors
Thermal

Avionics and Astrionics

Autonomous Control Tools for Vehicle Teams

Autonomous Satellite Navigation

Avionics and Astrionics

Autonomous Control Tools For Vehicle Teams

Autonomous controls for vehicle teams, sometimes called swarming technologies or formation flying technologies, are those technologies that allow teams of vehicles such as ground robots or UAVs to work together to carry out a mission. Autonomous controls are enhanced with sensors and algorithms to allow these vehicles to work with little or no human intervention.

Example Technologies
Autonomous and Semi-Autonomous Vehicles
Coordination Tools for Autonomous Vehicle Teams
Modular Stability Tools for Distributed Computation and Control
Swarm Technology

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improved Health and Safety	
Lower Power to Operate	+
Increases Reliability	+
Improved Performance	
Increases System Power	

How could this be game-changing?

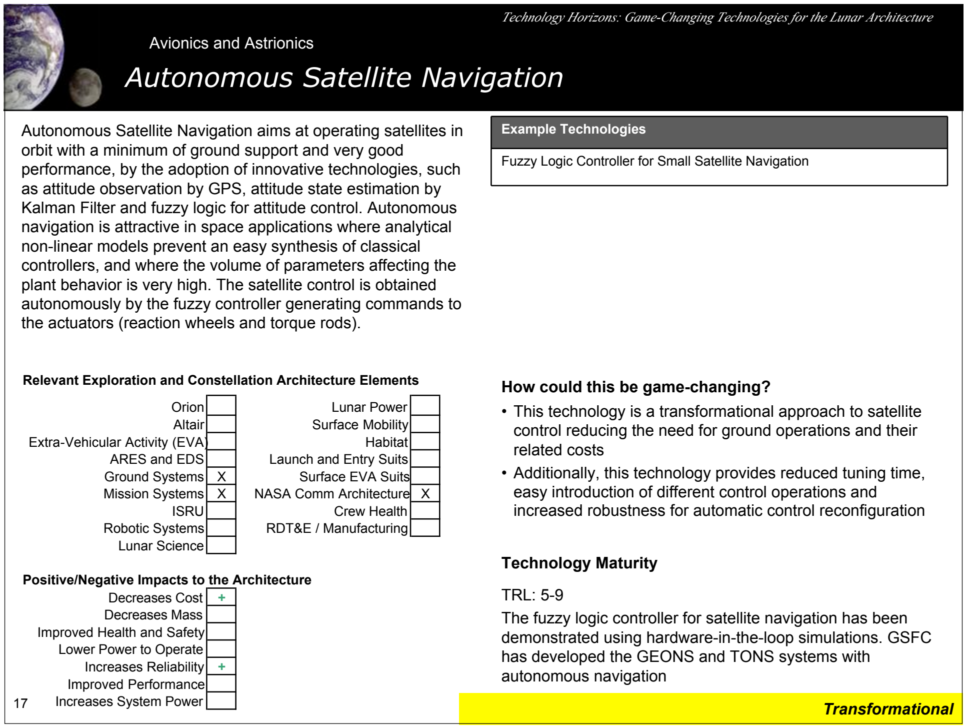
- Autonomous control algorithms transform control of space systems, providing simplicity of operations and lower mass
- These algorithms are extremely efficient in autonomous robot action selection, which yields energy savings
- Autonomous control is essential for lander offloading activities
- These technologies could also support autonomous rescue missions in a contingency scenario

Technology Maturity

TRL: 3-7

Autonomous control tools range in maturity from those already proven like autonomous vehicles to those in the early stages with laboratory demonstrations.

Transformational



Avionics and Astrionics

Autonomous Satellite Navigation

Autonomous Satellite Navigation aims at operating satellites in orbit with a minimum of ground support and very good performance, by the adoption of innovative technologies, such as attitude observation by GPS, attitude state estimation by Kalman Filter and fuzzy logic for attitude control. Autonomous navigation is attractive in space applications where analytical non-linear models prevent an easy synthesis of classical controllers, and where the volume of parameters affecting the plant behavior is very high. The satellite control is obtained autonomously by the fuzzy controller generating commands to the actuators (reaction wheels and torque rods).

Example Technologies

Fuzzy Logic Controller for Small Satellite Navigation

Relevant Exploration and Constellation Architecture Elements

Orion	☐	Lunar Power	☐
Altair	☐	Surface Mobility	☐
Extra-Vehicular Activity (EVA	☐	Habitat	☐
ARES and EDS	☐	Launch and Entry Suits	☐
Ground Systems	X	Surface EVA Suits	☐
Mission Systems	X	NASA Comm Architecture	X
ISRU	☐	Crew Health	☐
Robotic Systems	☐	RDT&E / Manufacturing	☐
Lunar Science	☐		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	☐
Improved Health and Safety	☐
Lower Power to Operate	☐
Increases Reliability	+
Improved Performance	☐
Increases System Power	☐

How could this be game-changing?

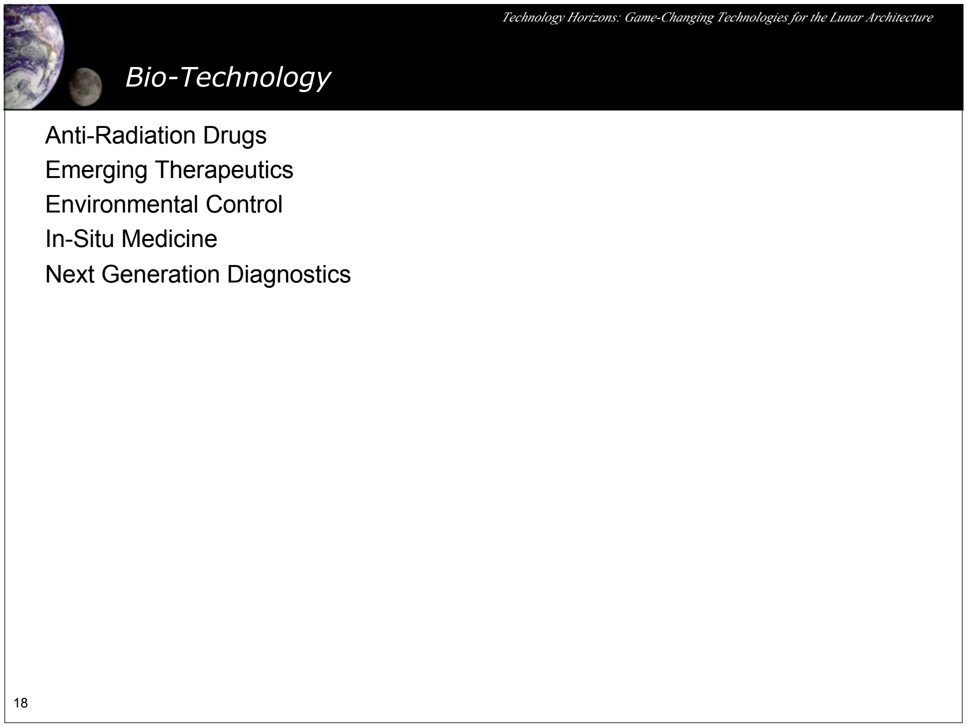
- This technology is a transformational approach to satellite control reducing the need for ground operations and their related costs
- Additionally, this technology provides reduced tuning time, easy introduction of different control operations and increased robustness for automatic control reconfiguration

Technology Maturity

TRL: 5-9

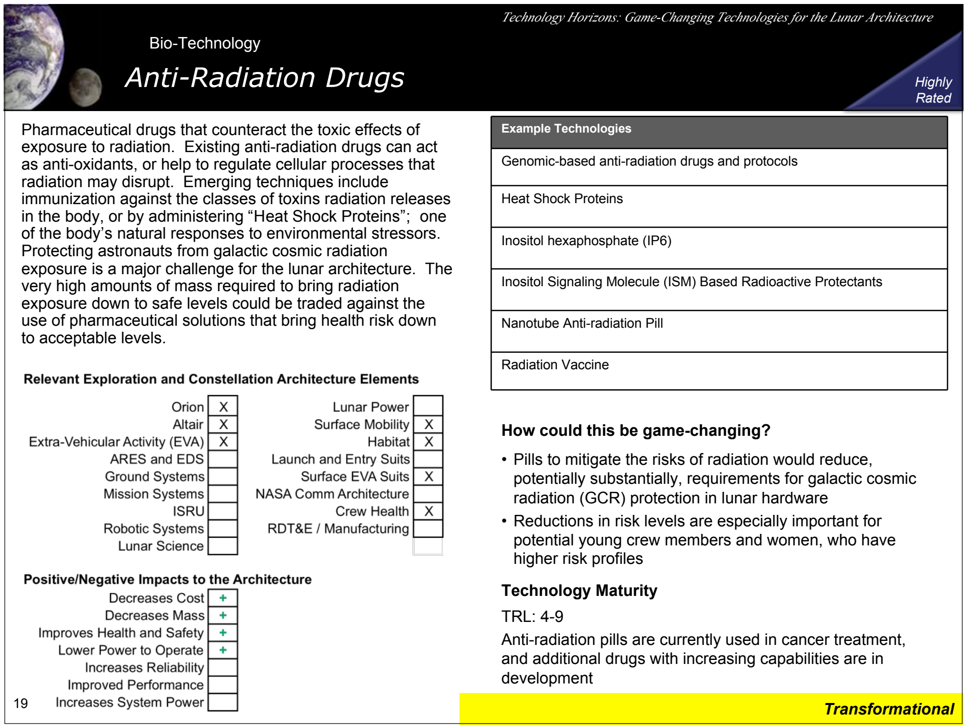
The fuzzy logic controller for satellite navigation has been demonstrated using hardware-in-the-loop simulations. GSFC has developed the GEONS and TONS systems with autonomous navigation

Transformational



Bio-Technology

Anti-Radiation Drugs
Emerging Therapeutics
Environmental Control
In-Situ Medicine
Next Generation Diagnostics



Technology Horizons: Game-Changing Technologies for the Lunar Architecture

Bio-Technology

Anti-Radiation Drugs

Highly Rated

Pharmaceutical drugs that counteract the toxic effects of exposure to radiation. Existing anti-radiation drugs can act as anti-oxidants, or help to regulate cellular processes that radiation may disrupt. Emerging techniques include immunization against the classes of toxins radiation releases in the body, or by administering “Heat Shock Proteins”; one of the body’s natural responses to environmental stressors. Protecting astronauts from galactic cosmic radiation exposure is a major challenge for the lunar architecture. The very high amounts of mass required to bring radiation exposure down to safe levels could be traded against the use of pharmaceutical solutions that bring health risk down to acceptable levels.

Relevant Exploration and Constellation Architecture Elements

- Orion ☒
- Altair ☒
- Extra-Vehicular Activity (EVA) ☒
- ARES and EDS ☐
- Ground Systems ☐
- Mission Systems ☐
- ISRU ☐
- Robotic Systems ☐
- Lunar Science ☐
- Lunar Power ☐
- Surface Mobility ☒
- Habitat ☒
- Launch and Entry Suits ☐
- Surface EVA Suits ☒
- NASA Comm Architecture ☐
- Crew Health ☒
- RDT&E / Manufacturing ☐

Positive/Negative Impacts to the Architecture

- Decreases Cost +
- Decreases Mass +
- Improves Health and Safety +
- Lower Power to Operate +
- Increases Reliability ☐
- Improved Performance ☐
- Increases System Power ☐

Example Technologies
Genomic-based anti-radiation drugs and protocols
Heat Shock Proteins
Inositol hexaphosphate (IP6)
Inositol Signaling Molecule (ISM) Based Radioactive Protectants
Nanotube Anti-radiation Pill
Radiation Vaccine

How could this be game-changing?

- Pills to mitigate the risks of radiation would reduce, potentially substantially, requirements for galactic cosmic radiation (GCR) protection in lunar hardware
- Reductions in risk levels are especially important for potential young crew members and women, who have higher risk profiles

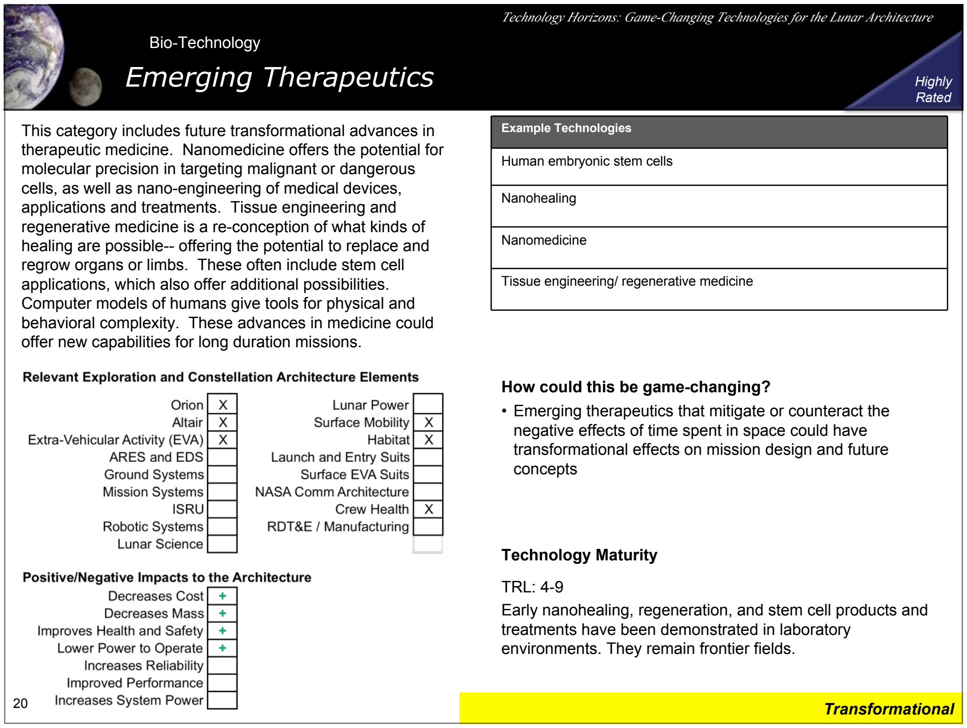
Technology Maturity

TRL: 4-9

Anti-radiation pills are currently used in cancer treatment, and additional drugs with increasing capabilities are in development

Transformational

19



Technology Horizons: Game-Changing Technologies for the Lunar Architecture

Bio-Technology

Emerging Therapeutics

Highly Rated

This category includes future transformational advances in therapeutic medicine. Nanomedicine offers the potential for molecular precision in targeting malignant or dangerous cells, as well as nano-engineering of medical devices, applications and treatments. Tissue engineering and regenerative medicine is a re-conception of what kinds of healing are possible-- offering the potential to replace and regrow organs or limbs. These often include stem cell applications, which also offer additional possibilities. Computer models of humans give tools for physical and behavioral complexity. These advances in medicine could offer new capabilities for long duration missions.

Relevant Exploration and Constellation Architecture Elements

- Orion ☒
- Altair ☒
- Extra-Vehicular Activity (EVA) ☒
- ARES and EDS ☐
- Ground Systems ☐
- Mission Systems ☐
- ISRU ☐
- Robotic Systems ☐
- Lunar Science ☐
- Lunar Power ☐
- Surface Mobility ☒
- Habitat ☒
- Launch and Entry Suits ☐
- Surface EVA Suits ☐
- NASA Comm Architecture ☐
- Crew Health ☒
- RDT&E / Manufacturing ☐

Positive/Negative Impacts to the Architecture

- Decreases Cost +
- Decreases Mass +
- Improves Health and Safety +
- Lower Power to Operate +
- Increases Reliability ☐
- Improved Performance ☐
- Increases System Power ☐

Example Technologies
Human embryonic stem cells
Nanohealing
Nanomedicine
Tissue engineering/ regenerative medicine

How could this be game-changing?

- Emerging therapeutics that mitigate or counteract the negative effects of time spent in space could have transformational effects on mission design and future concepts

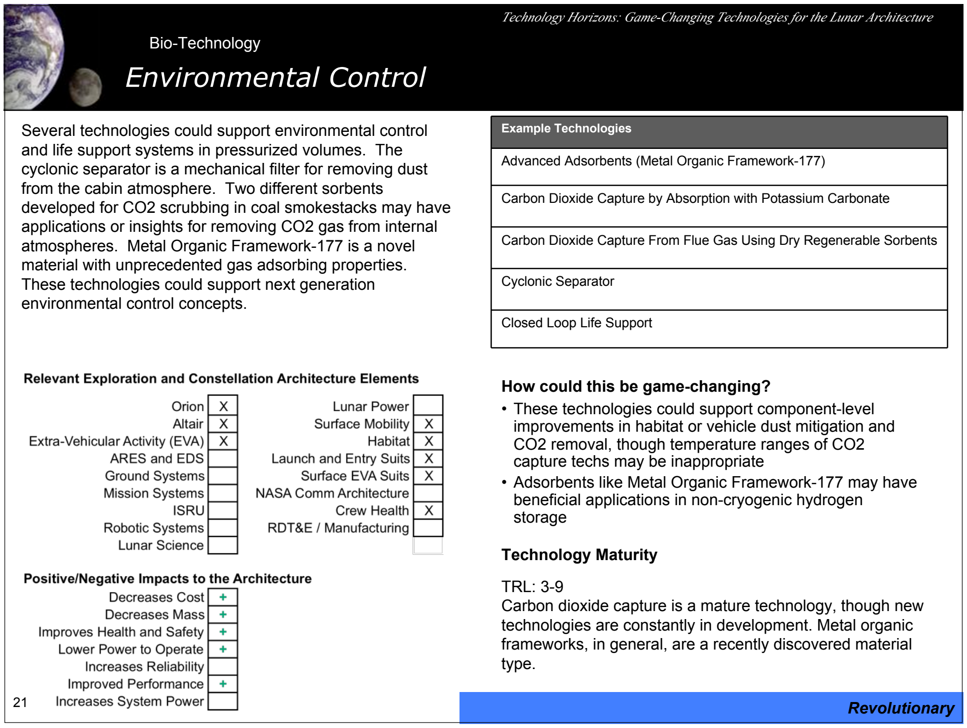
Technology Maturity

TRL: 4-9

Early nanohealing, regeneration, and stem cell products and treatments have been demonstrated in laboratory environments. They remain frontier fields.

Transformational

20



Bio-Technology

Environmental Control

Several technologies could support environmental control and life support systems in pressurized volumes. The cyclonic separator is a mechanical filter for removing dust from the cabin atmosphere. Two different sorbents developed for CO2 scrubbing in coal smokestacks may have applications or insights for removing CO2 gas from internal atmospheres. Metal Organic Framework-177 is a novel material with unprecedented gas adsorbing properties. These technologies could support next generation environmental control concepts.

Example Technologies
Advanced Adsorbents (Metal Organic Framework-177)
Carbon Dioxide Capture by Absorption with Potassium Carbonate
Carbon Dioxide Capture From Flue Gas Using Dry Regenerable Sorbents
Cyclonic Separator
Closed Loop Life Support

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	X
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU		Crew Health	X
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improves Health and Safety	+
Lower Power to Operate	+
Increases Reliability	
Improved Performance	+
Increases System Power	

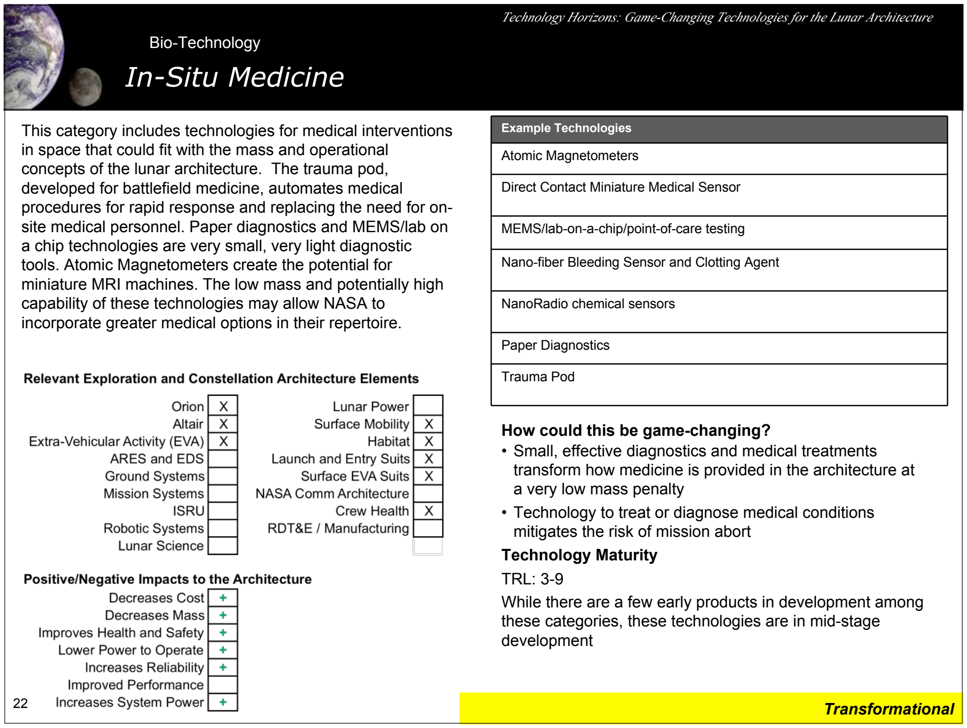
How could this be game-changing?

- These technologies could support component-level improvements in habitat or vehicle dust mitigation and CO2 removal, though temperature ranges of CO2 capture techs may be inappropriate
- Adsorbents like Metal Organic Framework-177 may have beneficial applications in non-cryogenic hydrogen storage

Technology Maturity

TRL: 3-9
Carbon dioxide capture is a mature technology, though new technologies are constantly in development. Metal organic frameworks, in general, are a recently discovered material type.

Revolutionary



Bio-Technology

In-Situ Medicine

This category includes technologies for medical interventions in space that could fit with the mass and operational concepts of the lunar architecture. The trauma pod, developed for battlefield medicine, automates medical procedures for rapid response and replacing the need for on-site medical personnel. Paper diagnostics and MEMS/lab on a chip technologies are very small, very light diagnostic tools. Atomic Magnetometers create the potential for miniature MRI machines. The low mass and potentially high capability of these technologies may allow NASA to incorporate greater medical options in their repertoire.

Example Technologies
Atomic Magnetometers
Direct Contact Miniature Medical Sensor
MEMS/lab-on-a-chip/point-of-care testing
Nano-fiber Bleeding Sensor and Clotting Agent
NanoRadio chemical sensors
Paper Diagnostics
Trauma Pod

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	X
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU		Crew Health	X
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improves Health and Safety	+
Lower Power to Operate	+
Increases Reliability	+
Improved Performance	
Increases System Power	+

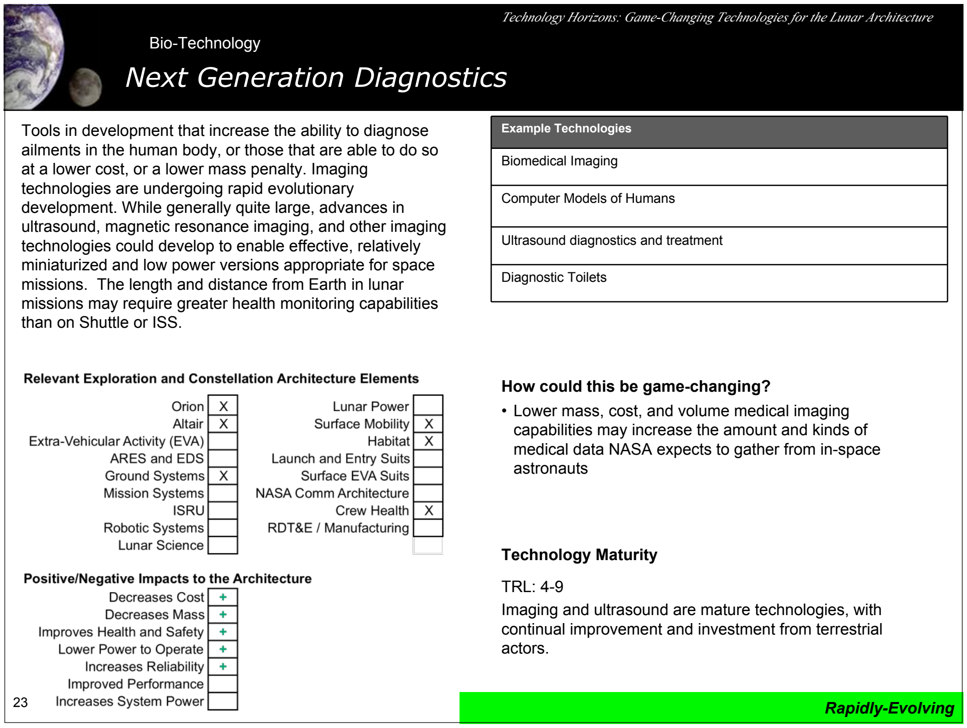
How could this be game-changing?

- Small, effective diagnostics and medical treatments transform how medicine is provided in the architecture at a very low mass penalty
- Technology to treat or diagnose medical conditions mitigates the risk of mission abort

Technology Maturity

TRL: 3-9
While there are a few early products in development among these categories, these technologies are in mid-stage development

Transformational



Bio-Technology

Next Generation Diagnostics

Tools in development that increase the ability to diagnose ailments in the human body, or those that are able to do so at a lower cost, or a lower mass penalty. Imaging technologies are undergoing rapid evolutionary development. While generally quite large, advances in ultrasound, magnetic resonance imaging, and other imaging technologies could develop to enable effective, relatively miniaturized and low power versions appropriate for space missions. The length and distance from Earth in lunar missions may require greater health monitoring capabilities than on Shuttle or ISS.

Example Technologies
Biomedical Imaging
Computer Models of Humans
Ultrasound diagnostics and treatment
Diagnostic Toilets

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)		Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	
Mission Systems		NASA Comm Architecture	
ISRU		Crew Health	X
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improves Health and Safety	+
Lower Power to Operate	+
Increases Reliability	+
Improved Performance	
Increases System Power	

How could this be game-changing?

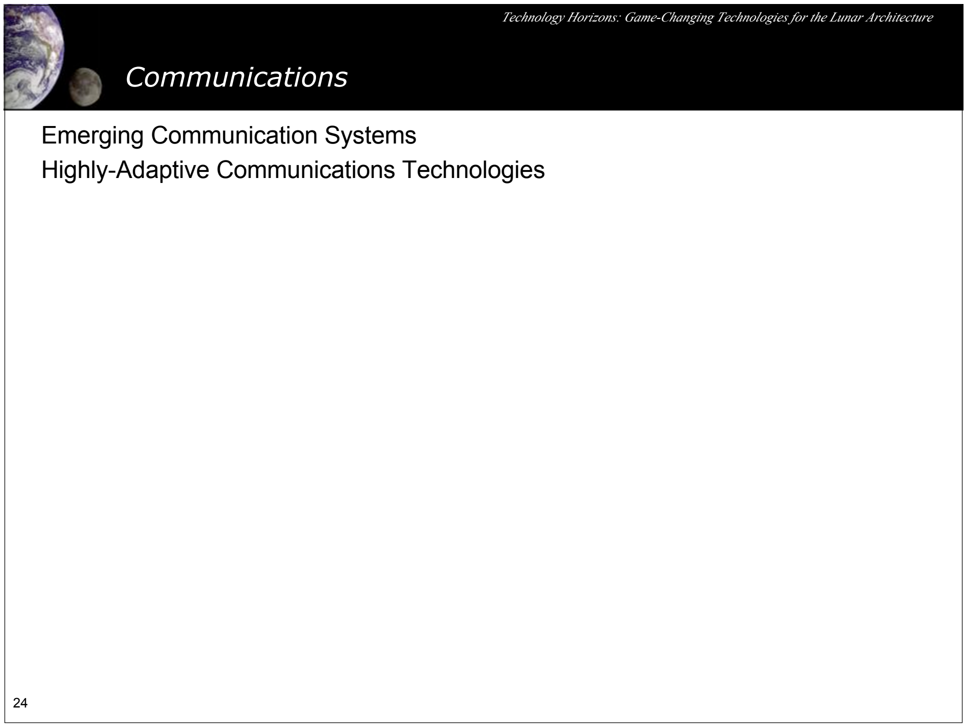
- Lower mass, cost, and volume medical imaging capabilities may increase the amount and kinds of medical data NASA expects to gather from in-space astronauts

Technology Maturity

TRL: 4-9

Imaging and ultrasound are mature technologies, with continual improvement and investment from terrestrial actors.

Rapidly-Evolving



Communications

Emerging Communication Systems

Highly-Adaptive Communications Technologies

Communications

Emerging Communication Systems

Emerging communication systems provide increased bandwidth and throughput for data between systems, and from the lunar surface to Earth. Optical crosslinks or signals can increase data rates to satellites or in a local area network. X-ray communications could provide high data rates and while penetrating radio frequency interference from shielding, or plasmas generated during reentry. Neutrino communications provide a theoretical alternative to electromagnetic signals that would not be affected by objects in the beam's path.

Example Technologies
Neutrino Communications
New Space Communications Architectures - optical crosslinks
Optical Free Space Communications Open New Borders for Future Civilian and Defense Systems
Optical Wireless Communications Onboard the Spacecraft
X-ray Communications

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improves Health and Safety	+
Lower Power to Operate	+
Increases Reliability	+
Improves Performance	+
Increases System Power	+

How could this be game-changing?

- Emerging communication systems could dramatically increase communication data rates of exploration systems
- These technologies could reduce the effects of noise or data loss
- The greater availability of bandwidth provided by these technologies allows new applications or more sophisticated user interfaces

Technology Maturity

TRL: 1-8

Advanced communications are still in the early stages of development. Optical data links between satellites have been tested but are not widely employed. X-ray communications have a very low technical maturity and neutrino communications are still conceptual.

Transformational

Communications

Highly-Adaptive Communications Technologies

This category includes technologies which broaden their applicability through high levels of adaptability. These technologies may achieve adaptability through utilizing more operating frequencies, taking advantage of more bandwidth, and dynamically allocating bandwidth. An example technology, advanced tunable antennas, involves more advanced antenna design in order to utilize different operating frequencies and beam geometries. The combination of tuning architecture and newly emerging electrically tunable materials enables the development of large-scale, flexible, steerable and frequency-agile antenna arrays for use in adaptive telecommunications.

Example Technologies
Advanced Tunable Antennas
Cognitive Radio

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)		Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems		NASA Comm Architecture	X
ISRU		Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improves Health and Safety	
Lower Power to Operate	
Increases Reliability	
Improves Performance	+
Increases System Power	

How could this be game-changing?

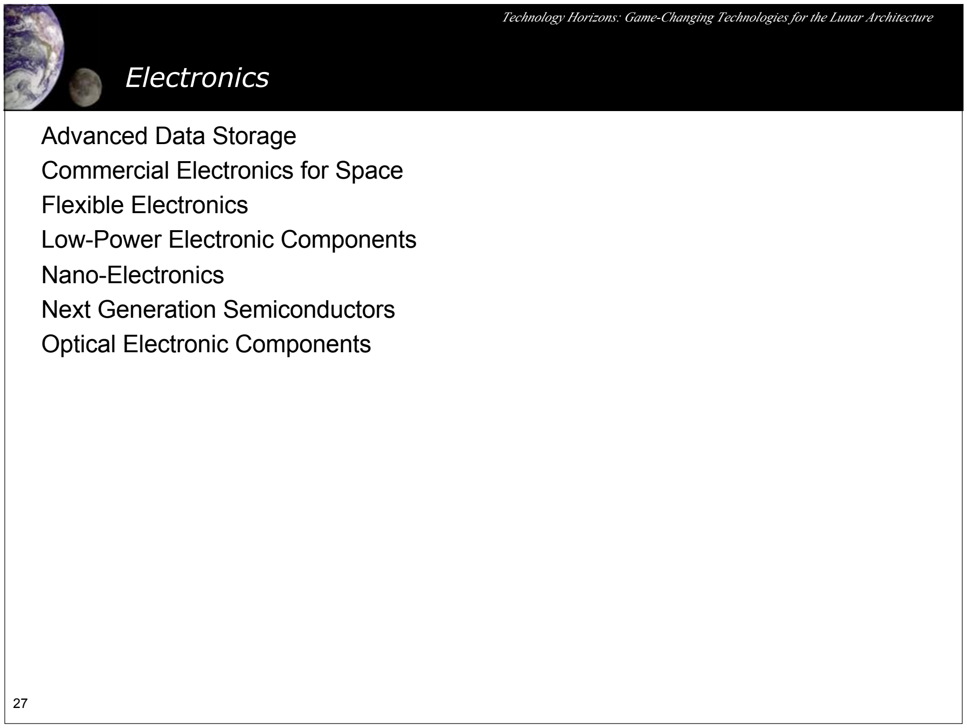
- Adaptable communication devices capable of operating at different frequencies more effectively manage available bandwidth and spectrum; creating mass, data and operational efficiencies
- Highly adaptive systems may minimize the number of communications systems required on a vehicle and be able to provide communications in unforeseen circumstances

Technology Maturity

TRL: 3-6

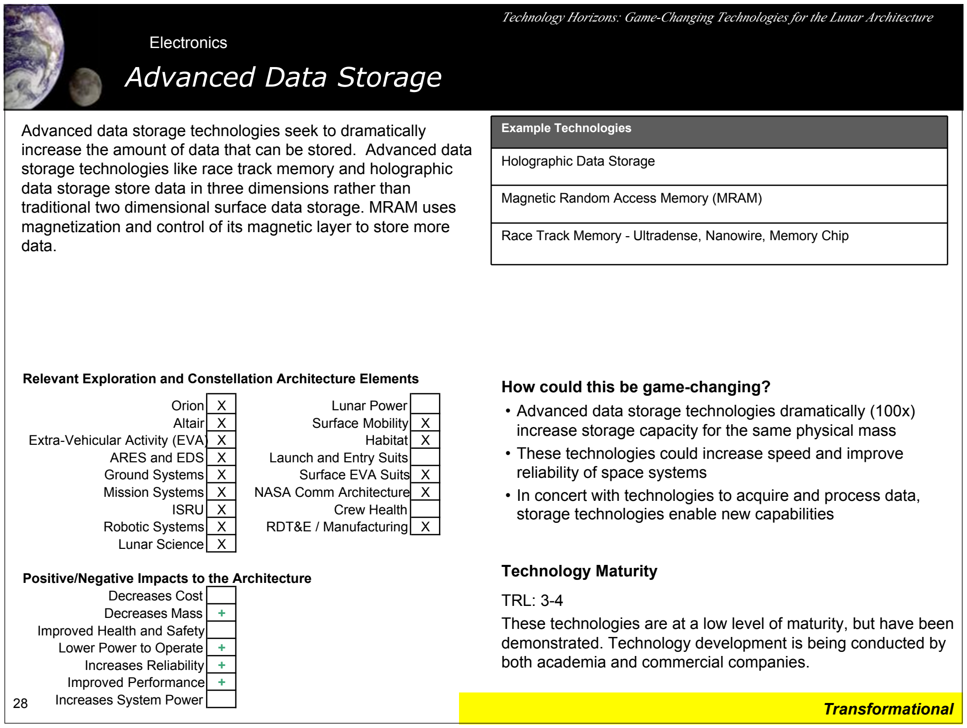
Advanced tunable antennas are currently being tested and advanced for many application areas. Cognitive Radio is currently being tested in a laboratory setting.

Revolutionary



Electronics

Advanced Data Storage
Commercial Electronics for Space
Flexible Electronics
Low-Power Electronic Components
Nano-Electronics
Next Generation Semiconductors
Optical Electronic Components



Electronics

Advanced Data Storage

Advanced data storage technologies seek to dramatically increase the amount of data that can be stored. Advanced data storage technologies like race track memory and holographic data storage store data in three dimensions rather than traditional two dimensional surface data storage. MRAM uses magnetization and control of its magnetic layer to store more data.

Example Technologies
Holographic Data Storage
Magnetic Random Access Memory (MRAM)
Race Track Memory - Ultradense, Nanowire, Memory Chip

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	
Lower Power to Operate	+
Increases Reliability	+
Improved Performance	+
Increases System Power	

How could this be game-changing?

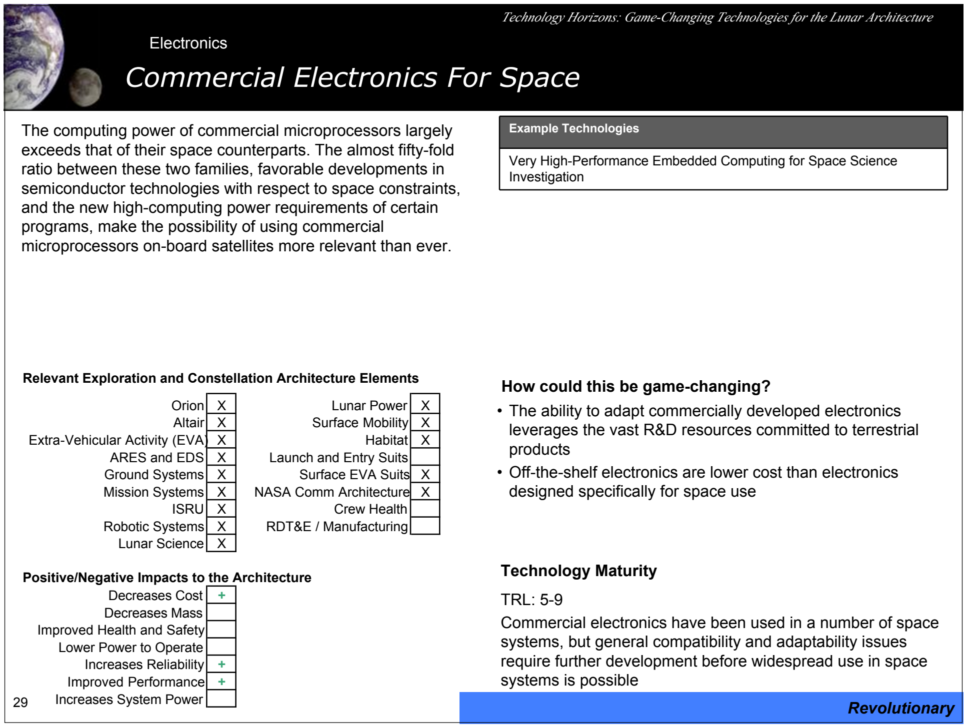
- Advanced data storage technologies dramatically (100x) increase storage capacity for the same physical mass
- These technologies could increase speed and improve reliability of space systems
- In concert with technologies to acquire and process data, storage technologies enable new capabilities

Technology Maturity

TRL: 3-4

These technologies are at a low level of maturity, but have been demonstrated. Technology development is being conducted by both academia and commercial companies.

Transformational



Electronics

Commercial Electronics For Space

The computing power of commercial microprocessors largely exceeds that of their space counterparts. The almost fifty-fold ratio between these two families, favorable developments in semiconductor technologies with respect to space constraints, and the new high-computing power requirements of certain programs, make the possibility of using commercial microprocessors on-board satellites more relevant than ever.

Example Technologies
Very High-Performance Embedded Computing for Space Science Investigation

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	

How could this be game-changing?

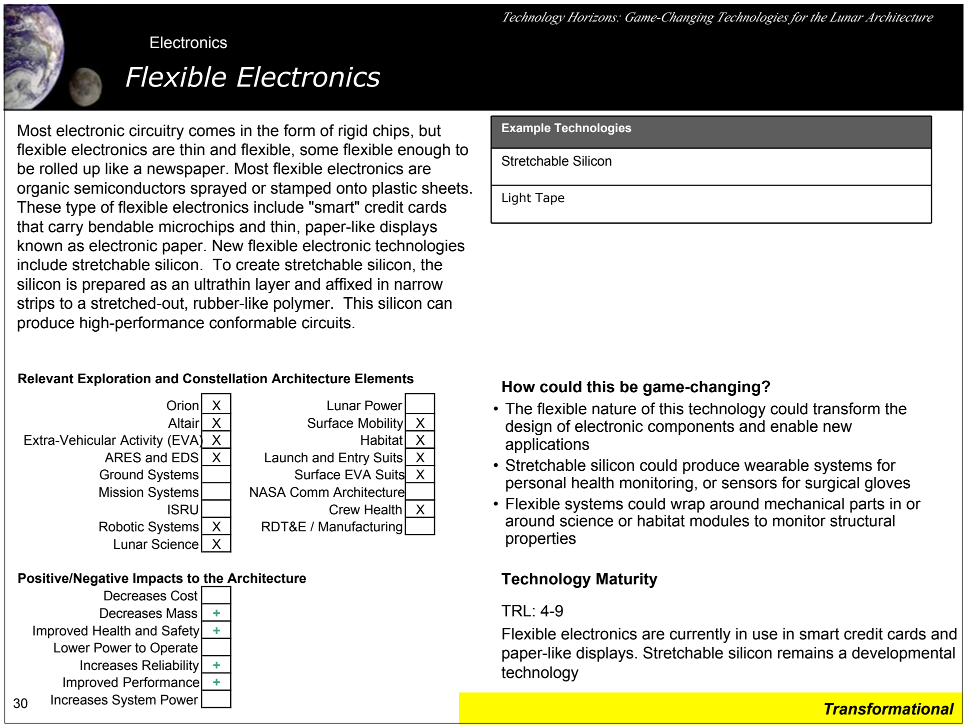
- The ability to adapt commercially developed electronics leverages the vast R&D resources committed to terrestrial products
- Off-the-shelf electronics are lower cost than electronics designed specifically for space use

Technology Maturity

TRL: 5-9

Commercial electronics have been used in a number of space systems, but general compatibility and adaptability issues require further development before widespread use in space systems is possible

Revolutionary



Electronics

Flexible Electronics

Most electronic circuitry comes in the form of rigid chips, but flexible electronics are thin and flexible, some flexible enough to be rolled up like a newspaper. Most flexible electronics are organic semiconductors sprayed or stamped onto plastic sheets. These type of flexible electronics include "smart" credit cards that carry bendable microchips and thin, paper-like displays known as electronic paper. New flexible electronic technologies include stretchable silicon. To create stretchable silicon, the silicon is prepared as an ultrathin layer and affixed in narrow strips to a stretched-out, rubber-like polymer. This silicon can produce high-performance conformable circuits.

Example Technologies
Stretchable Silicon
Light Tape

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	X
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU		Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	

How could this be game-changing?

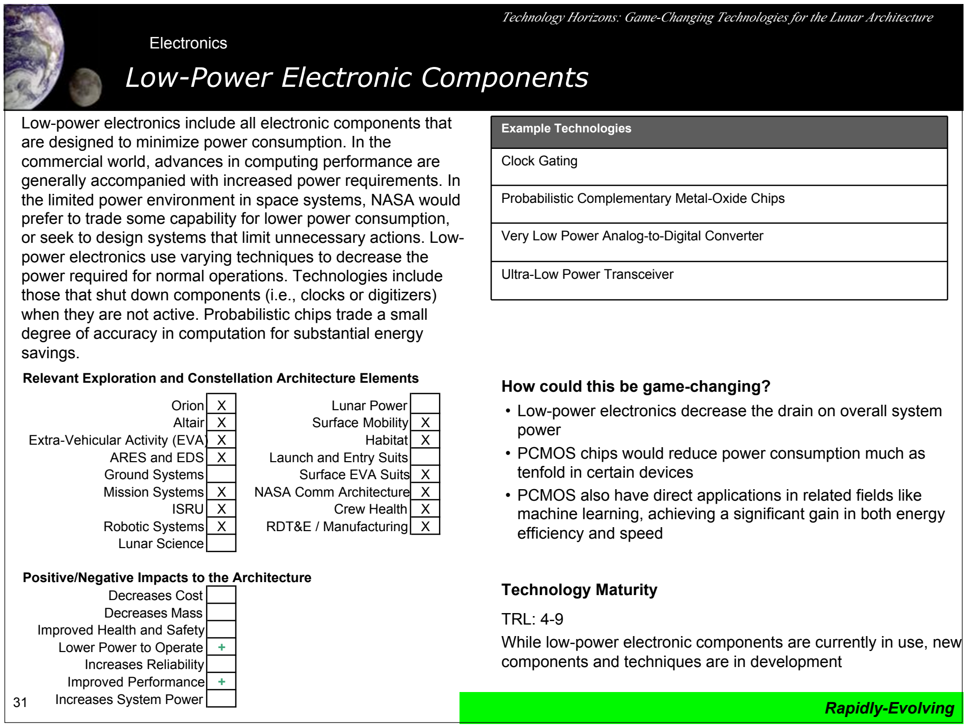
- The flexible nature of this technology could transform the design of electronic components and enable new applications
- Stretchable silicon could produce wearable systems for personal health monitoring, or sensors for surgical gloves
- Flexible systems could wrap around mechanical parts in or around science or habitat modules to monitor structural properties

Technology Maturity

TRL: 4-9

Flexible electronics are currently in use in smart credit cards and paper-like displays. Stretchable silicon remains a developmental technology

Transformational



Electronics

Low-Power Electronic Components

Low-power electronics include all electronic components that are designed to minimize power consumption. In the commercial world, advances in computing performance are generally accompanied with increased power requirements. In the limited power environment in space systems, NASA would prefer to trade some capability for lower power consumption, or seek to design systems that limit unnecessary actions. Low-power electronics use varying techniques to decrease the power required for normal operations. Technologies include those that shut down components (i.e., clocks or digitizers) when they are not active. Probabilistic chips trade a small degree of accuracy in computation for substantial energy savings.

Example Technologies
Clock Gating
Probabilistic Complementary Metal-Oxide Chips
Very Low Power Analog-to-Digital Converter
Ultra-Low Power Transceiver

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improved Health and Safety	
Lower Power to Operate	+
Increases Reliability	
Improved Performance	+
Increases System Power	

How could this be game-changing?

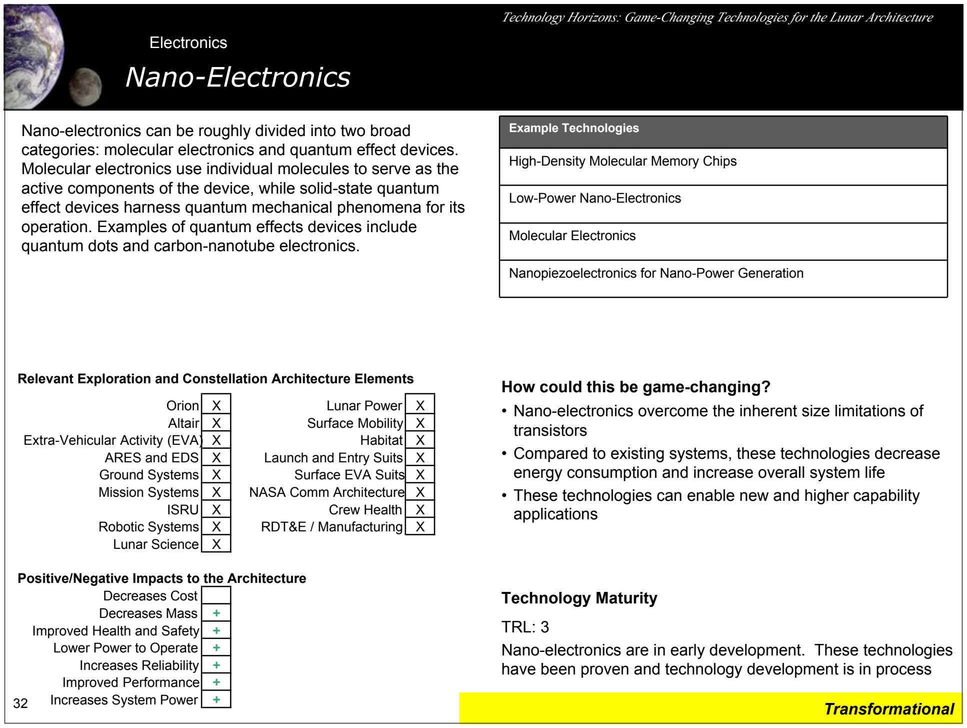
- Low-power electronics decrease the drain on overall system power
- PCMOS chips would reduce power consumption much as tenfold in certain devices
- PCMOS also have direct applications in related fields like machine learning, achieving a significant gain in both energy efficiency and speed

Technology Maturity

TRL: 4-9

While low-power electronic components are currently in use, new components and techniques are in development

Rapidly-Evolving



Electronics

Nano-Electronics

Nano-electronics can be roughly divided into two broad categories: molecular electronics and quantum effect devices. Molecular electronics use individual molecules to serve as the active components of the device, while solid-state quantum effect devices harness quantum mechanical phenomena for its operation. Examples of quantum effects devices include quantum dots and carbon-nanotube electronics.

Example Technologies
High-Density Molecular Memory Chips
Low-Power Nano-Electronics
Molecular Electronics
Nanopiezoelectronics for Nano-Power Generation

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	X
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	+
Lower Power to Operate	+
Increases Reliability	+
Improved Performance	+
Increases System Power	+

How could this be game-changing?

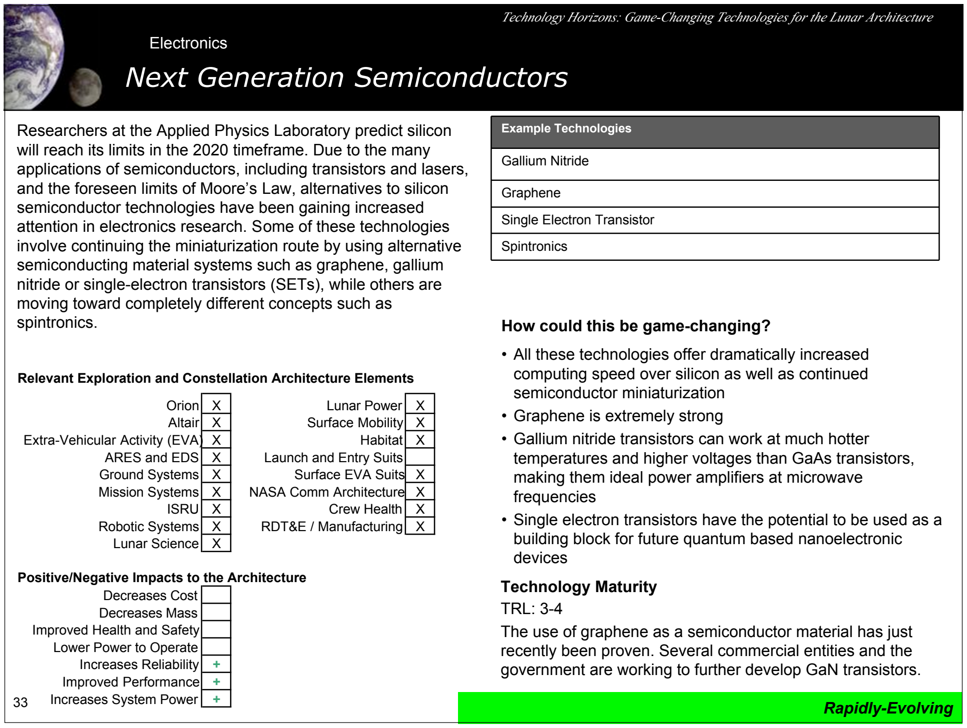
- Nano-electronics overcome the inherent size limitations of transistors
- Compared to existing systems, these technologies decrease energy consumption and increase overall system life
- These technologies can enable new and higher capability applications

Technology Maturity

TRL: 3

Nano-electronics are in early development. These technologies have been proven and technology development is in process

Transformational



Electronics

Next Generation Semiconductors

Researchers at the Applied Physics Laboratory predict silicon will reach its limits in the 2020 timeframe. Due to the many applications of semiconductors, including transistors and lasers, and the foreseen limits of Moore's Law, alternatives to silicon semiconductor technologies have been gaining increased attention in electronics research. Some of these technologies involve continuing the miniaturization route by using alternative semiconducting material systems such as graphene, gallium nitride or single-electron transistors (SETs), while others are moving toward completely different concepts such as spintronics.

Example Technologies
Gallium Nitride
Graphene
Single Electron Transistor
Spintronics

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	+

How could this be game-changing?

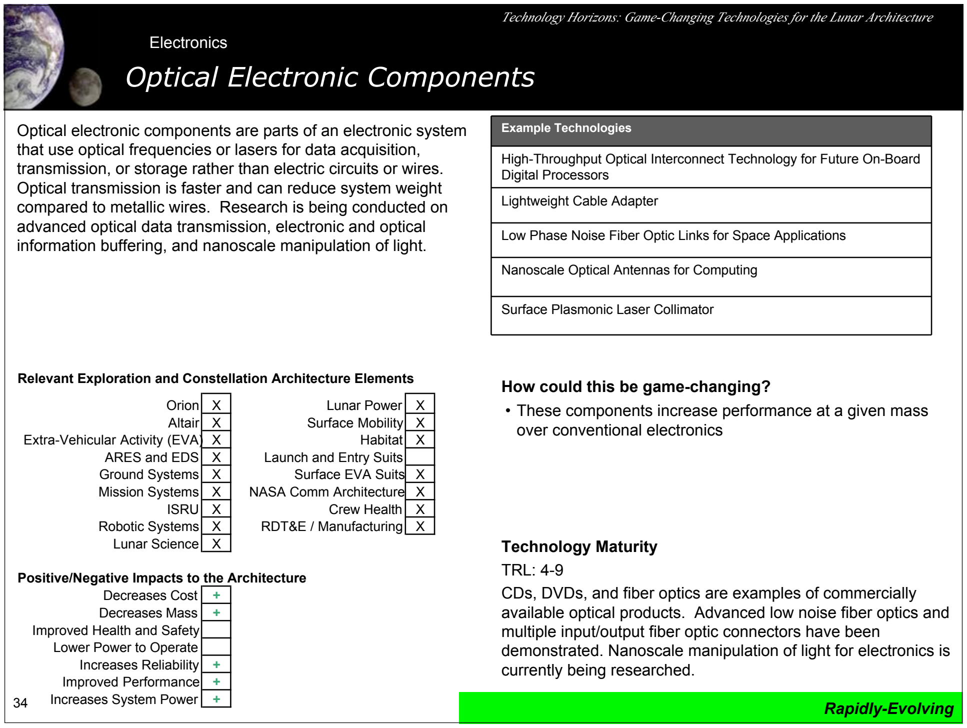
- All these technologies offer dramatically increased computing speed over silicon as well as continued semiconductor miniaturization
- Graphene is extremely strong
- Gallium nitride transistors can work at much hotter temperatures and higher voltages than GaAs transistors, making them ideal power amplifiers at microwave frequencies
- Single electron transistors have the potential to be used as a building block for future quantum based nanoelectronic devices

Technology Maturity

TRL: 3-4

The use of graphene as a semiconductor material has just recently been proven. Several commercial entities and the government are working to further develop GaN transistors.

Rapidly-Evolving



Electronics

Optical Electronic Components

Optical electronic components are parts of an electronic system that use optical frequencies or lasers for data acquisition, transmission, or storage rather than electric circuits or wires. Optical transmission is faster and can reduce system weight compared to metallic wires. Research is being conducted on advanced optical data transmission, electronic and optical information buffering, and nanoscale manipulation of light.

Example Technologies
High-Throughput Optical Interconnect Technology for Future On-Board Digital Processors
Lightweight Cable Adapter
Low Phase Noise Fiber Optic Links for Space Applications
Nanoscale Optical Antennas for Computing
Surface Plasmonic Laser Collimator

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	+

How could this be game-changing?

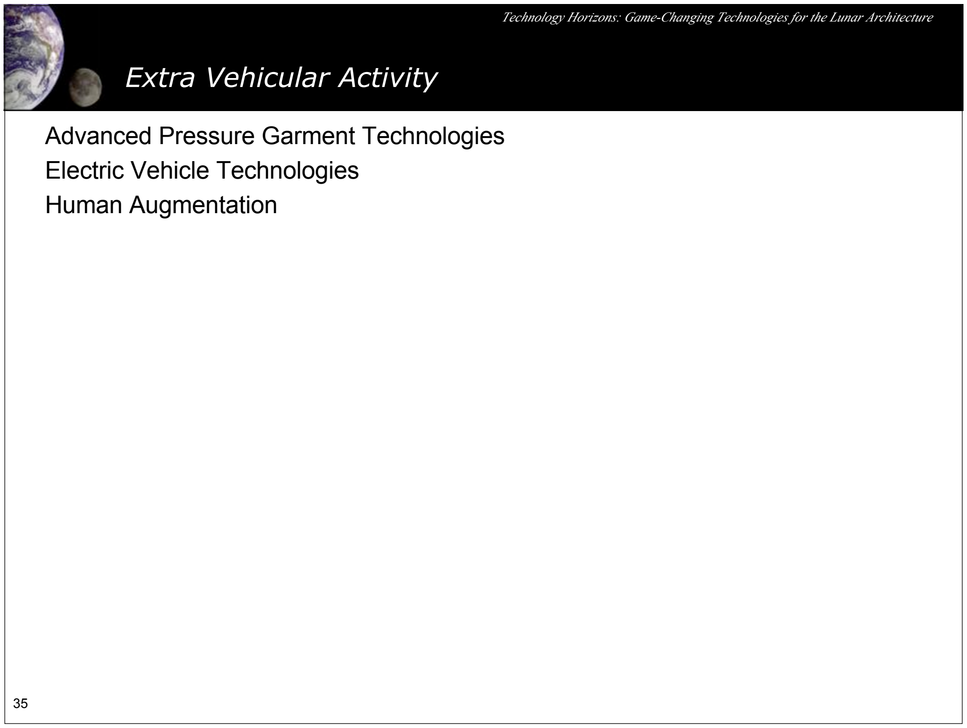
- These components increase performance at a given mass over conventional electronics

Technology Maturity

TRL: 4-9

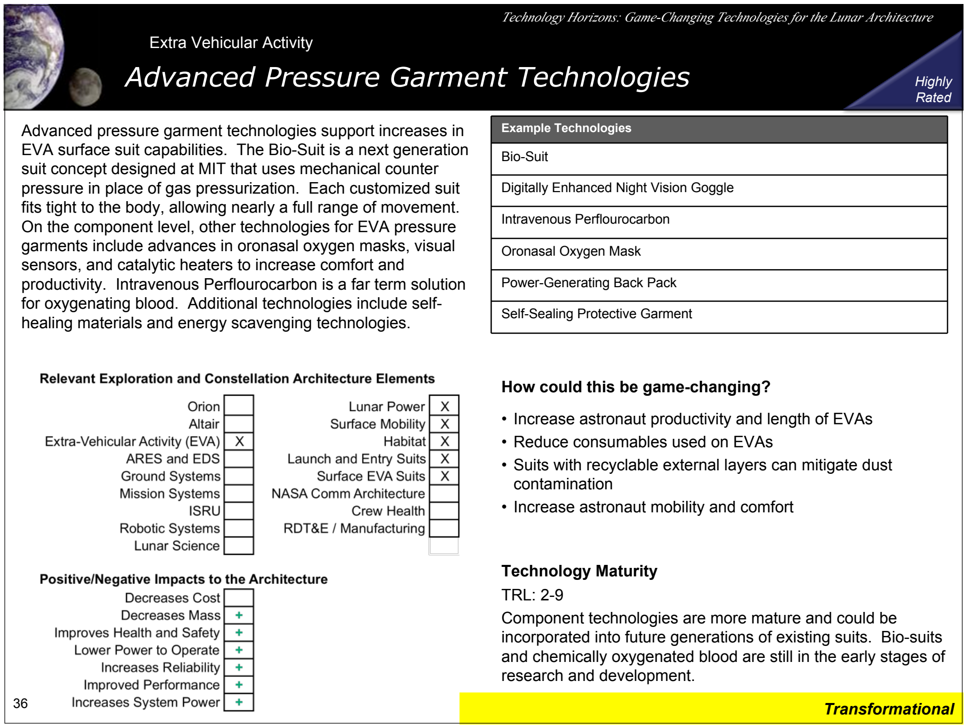
CDs, DVDs, and fiber optics are examples of commercially available optical products. Advanced low noise fiber optics and multiple input/output fiber optic connectors have been demonstrated. Nanoscale manipulation of light for electronics is currently being researched.

Rapidly-Evolving



Extra Vehicular Activity

Advanced Pressure Garment Technologies
Electric Vehicle Technologies
Human Augmentation



Extra Vehicular Activity

Advanced Pressure Garment Technologies

Highly Rated

Advanced pressure garment technologies support increases in EVA surface suit capabilities. The Bio-Suit is a next generation suit concept designed at MIT that uses mechanical counter pressure in place of gas pressurization. Each customized suit fits tight to the body, allowing nearly a full range of movement. On the component level, other technologies for EVA pressure garments include advances in oronasal oxygen masks, visual sensors, and catalytic heaters to increase comfort and productivity. Intravenous Perflourocarbon is a far term solution for oxygenating blood. Additional technologies include self-healing materials and energy scavenging technologies.

Example Technologies
Bio-Suit
Digitally Enhanced Night Vision Goggle
Intravenous Perflourocarbon
Oronasal Oxygen Mask
Power-Generating Back Pack
Self-Sealing Protective Garment

Relevant Exploration and Constellation Architecture Elements

Orion ☐
Altair ☐
Extra-Vehicular Activity (EVA) ☒
ARES and EDS ☐
Ground Systems ☐
Mission Systems ☐
ISRU ☐
Robotic Systems ☐
Lunar Science ☐

Lunar Power ☒
Surface Mobility ☒
Habitat ☒
Launch and Entry Suits ☒
Surface EVA Suits ☒
NASA Comm Architecture ☐
Crew Health ☐
RDT&E / Manufacturing ☐

Positive/Negative Impacts to the Architecture

Decreases Cost ☐
Decreases Mass +
Improves Health and Safety +
Lower Power to Operate +
Increases Reliability +
Improved Performance +
Increases System Power +

How could this be game-changing?

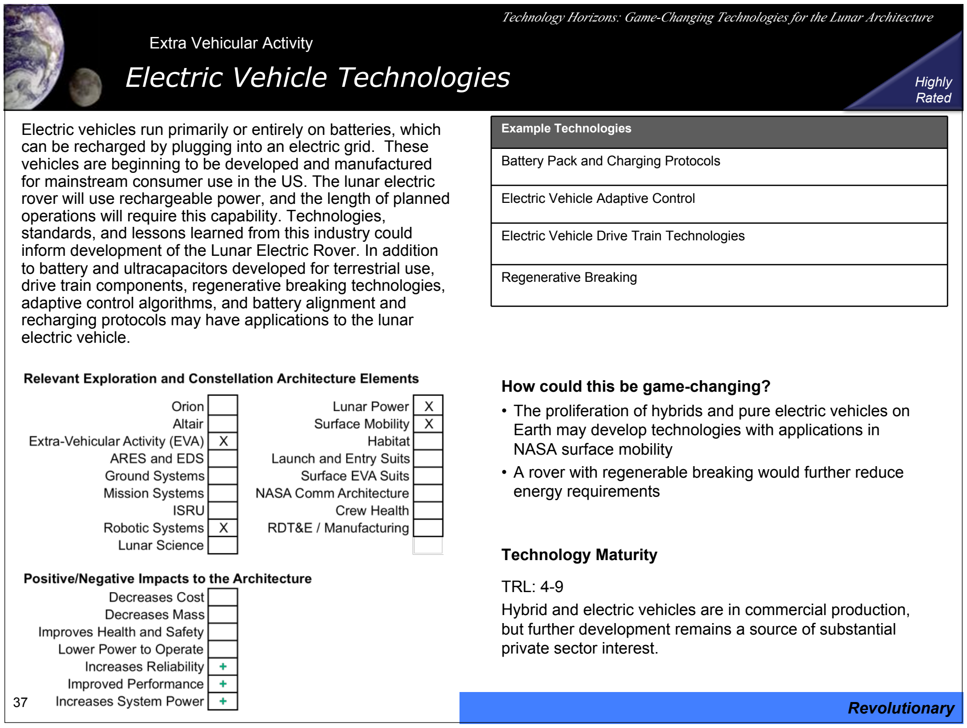
- Increase astronaut productivity and length of EVAs
- Reduce consumables used on EVAs
- Suits with recyclable external layers can mitigate dust contamination
- Increase astronaut mobility and comfort

Technology Maturity

TRL: 2-9

Component technologies are more mature and could be incorporated into future generations of existing suits. Bio-suits and chemically oxygenated blood are still in the early stages of research and development.

Transformational



Extra Vehicular Activity

Electric Vehicle Technologies

Highly Rated

Electric vehicles run primarily or entirely on batteries, which can be recharged by plugging into an electric grid. These vehicles are beginning to be developed and manufactured for mainstream consumer use in the US. The lunar electric rover will use rechargeable power, and the length of planned operations will require this capability. Technologies, standards, and lessons learned from this industry could inform development of the Lunar Electric Rover. In addition to battery and ultracapacitors developed for terrestrial use, drive train components, regenerative breaking technologies, adaptive control algorithms, and battery alignment and recharging protocols may have applications to the lunar electric vehicle.

Example Technologies
Battery Pack and Charging Protocols
Electric Vehicle Adaptive Control
Electric Vehicle Drive Train Technologies
Regenerative Breaking

Relevant Exploration and Constellation Architecture Elements

Orion	☐	Lunar Power	☒
Altair	☐	Surface Mobility	☒
Extra-Vehicular Activity (EVA)	☒	Habitat	☐
ARES and EDS	☐	Launch and Entry Suits	☐
Ground Systems	☐	Surface EVA Suits	☐
Mission Systems	☐	NASA Comm Architecture	☐
ISRU	☐	Crew Health	☐
Robotic Systems	☒	RDT&E / Manufacturing	☐
Lunar Science	☐		

Positive/Negative Impacts to the Architecture

Decreases Cost	☐
Decreases Mass	☐
Improves Health and Safety	☐
Lower Power to Operate	☐
Increases Reliability	+
Improved Performance	+
Increases System Power	+

How could this be game-changing?

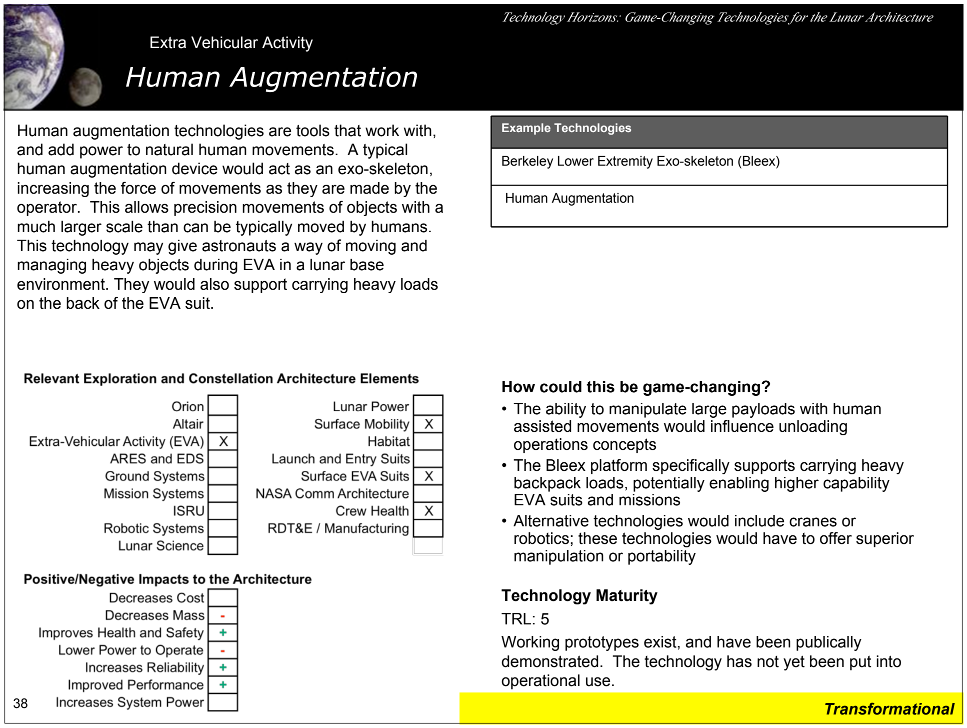
- The proliferation of hybrids and pure electric vehicles on Earth may develop technologies with applications in NASA surface mobility
- A rover with regenerable breaking would further reduce energy requirements

Technology Maturity

TRL: 4-9

Hybrid and electric vehicles are in commercial production, but further development remains a source of substantial private sector interest.

Revolutionary



Extra Vehicular Activity

Human Augmentation

Human augmentation technologies are tools that work with, and add power to natural human movements. A typical human augmentation device would act as an exo-skeleton, increasing the force of movements as they are made by the operator. This allows precision movements of objects with a much larger scale than can be typically moved by humans. This technology may give astronauts a way of moving and managing heavy objects during EVA in a lunar base environment. They would also support carrying heavy loads on the back of the EVA suit.

Example Technologies
Berkeley Lower Extremity Exo-skeleton (Bleex)
Human Augmentation

Relevant Exploration and Constellation Architecture Elements

Orion	☐	Lunar Power	☐
Altair	☐	Surface Mobility	☒
Extra-Vehicular Activity (EVA)	☒	Habitat	☐
ARES and EDS	☐	Launch and Entry Suits	☐
Ground Systems	☐	Surface EVA Suits	☒
Mission Systems	☐	NASA Comm Architecture	☐
ISRU	☐	Crew Health	☒
Robotic Systems	☐	RDT&E / Manufacturing	☐
Lunar Science	☐		

Positive/Negative Impacts to the Architecture

Decreases Cost	☐
Decreases Mass	-
Improves Health and Safety	+
Lower Power to Operate	-
Increases Reliability	+
Improved Performance	+
Increases System Power	☐

How could this be game-changing?

- The ability to manipulate large payloads with human assisted movements would influence unloading operations concepts
- The Bleex platform specifically supports carrying heavy backpack loads, potentially enabling higher capability EVA suits and missions
- Alternative technologies would include cranes or robotics; these technologies would have to offer superior manipulation or portability

Technology Maturity

TRL: 5

Working prototypes exist, and have been publically demonstrated. The technology has not yet been put into operational use.

Transformational

Information

Autonomous Systems and AI
Complex Data Recognition and Acquisition
Enhanced Human-Computer Interaction
Massive Data Capturing and Processing
Massive Online Collaborative Environments
Predictive Data Modeling
Quantum Computing

Information

Autonomous Systems and AI

Enhanced Autonomous Systems and AI describes technologies that model human behavior and decision making processes. These technologies are used to create: 1. Long-lived autonomous systems that are able to explore, command, diagnose and repair themselves using fast, commonsense reasoning (achieved through the use of embedded programming languages). 2. Synthetic agents that are designed to reflect human strategies, correctly representing human variability in simulations. 3. Systems of automatic data validation.

Example Technologies
Automated Data Validation System
Human Behavioral Modeling
Robust Autonomous Systems that are Self Aware

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	
Mission Systems	X	NASA Comm Architecture	
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improves Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improves Performance	+
Increases System Power	

How could this be game-changing?

- These technologies may increase the performance of current autonomous and AI systems, and/or introduce autonomy in new areas (for example, automated validation of images taken by robots)
- These technologies reduce dependence on human controllers
- These technologies are particularly needed on Mars, because communication delays will reduce the ability of ground crew to directly control & monitor the robots & sensors.

Technology Maturity

TRL: 2-7

Maturity ranges from the invention stage to use in an operational environment. Technologies at high maturity levels are currently undergoing new advancements which aim to increase quality and affordability.

Revolutionary

Information

Complex Data Recognition and Acquisition

This category includes hardware, software, algorithms, and models for complex data recognition and acquisition. Technologies in this category include monitoring and recording devices such as GPS trackers, recognition systems such as video recognition software, and data mining algorithms such as Personal Reality Mining, which infers information such as personal and community health.

Example Technologies
Event Recorders and GPS Tracking Devices
Reality Mining
Video Recognition

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improves Health and Safety	+
Lower Power to Operate	
Increases Reliability	
Improves Performance	
Increases System Power	

How could this be game-changing?

- These systems could provide sophisticated monitoring of lunar conditions, such as astronaut mental and physical health, science and exploration (terrain analysis), and maintenance (flaw detection)
- These technologies both collect data and recognize phenomena within the data

Technology Maturity

TRL: 5-9
GPS tracking devices are widely available commercially, as are early video recognition products. Reality mining is in a prototype stage.

Rapidly-Evolving

Information

Enhanced Human-Computer Interaction

Highly Rated

This category includes interfaces that enhance human computer interaction. These technologies use a broad range of new techniques to facilitate communication between humans and computers. These techniques include: sound, speech, motion and gesture recognition, Affective Computing (which allows computers to detect, adapt to, respond to, mimic and influence human emotion), brain-computer interfaces (BCIs) (also called called a direct neural interface), virtual reality, artificial intelligence, and telepresence tools. 3-D Navigation displays could be used in the rover. These displays would reduce the need for astronauts to see out of the windows, allowing us to reduce window size, thereby lessening the threat of radiation and micrometeorites. This example is one of many new possible applications of these technologies.

Example Technologies
3-D Navigation Displays
Affective Computing
Augmented Reality
Biometrics
Gesture Recognition
Human Brain-Machine Interfaces
Intelligent Software Assistant
Machine Dialog
Mixed Reality
Motion Displays Fusion
Telepresence
Five Sensor Virtual Reality Holographic Crew Member

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improves Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improves Performance	+
Increases System Power	

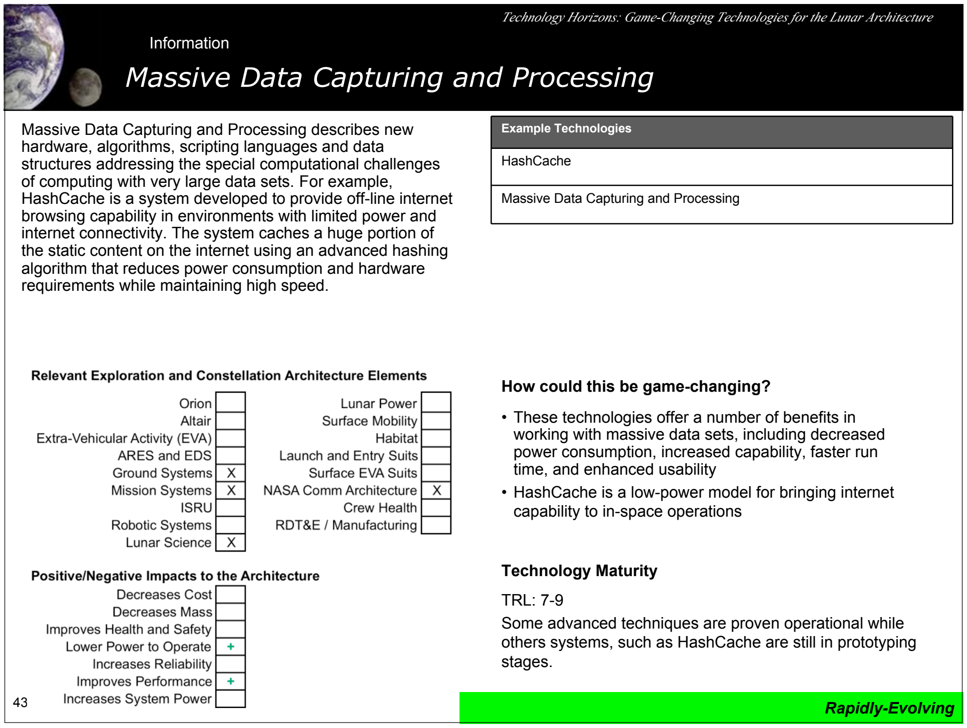
How could this be game-changing?

- Simplified and effective computer interfaces can reduce stress, increase productivity, reduce training time, and influence system development

Technology Maturity

TRL: 3-9
Early voice, speech, facial recognition, and biometrics technologies have been commercially available for some time, but this technology area is still a focused area of investment.

Rapidly-Evolving



Technology Horizons: Game-Changing Technologies for the Lunar Architecture

Information

Massive Data Capturing and Processing

Massive Data Capturing and Processing describes new hardware, algorithms, scripting languages and data structures addressing the special computational challenges of computing with very large data sets. For example, HashCache is a system developed to provide off-line internet browsing capability in environments with limited power and internet connectivity. The system caches a huge portion of the static content on the internet using an advanced hashing algorithm that reduces power consumption and hardware requirements while maintaining high speed.

Example Technologies
HashCache
Massive Data Capturing and Processing

Relevant Exploration and Constellation Architecture Elements

Orion	☐	Lunar Power	☐
Altair	☐	Surface Mobility	☐
Extra-Vehicular Activity (EVA)	☐	Habitat	☐
ARES and EDS	☐	Launch and Entry Suits	☐
Ground Systems	X	Surface EVA Suits	☐
Mission Systems	X	NASA Comm Architecture	X
ISRU	☐	Crew Health	☐
Robotic Systems	☐	RDT&E / Manufacturing	☐
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	☐
Decreases Mass	☐
Improves Health and Safety	☐
Lower Power to Operate	+
Increases Reliability	☐
Improves Performance	+
Increases System Power	☐

How could this be game-changing?

- These technologies offer a number of benefits in working with massive data sets, including decreased power consumption, increased capability, faster run time, and enhanced usability
- HashCache is a low-power model for bringing internet capability to in-space operations

Technology Maturity

TRL: 7-9

Some advanced techniques are proven operational while others systems, such as HashCache are still in prototyping stages.

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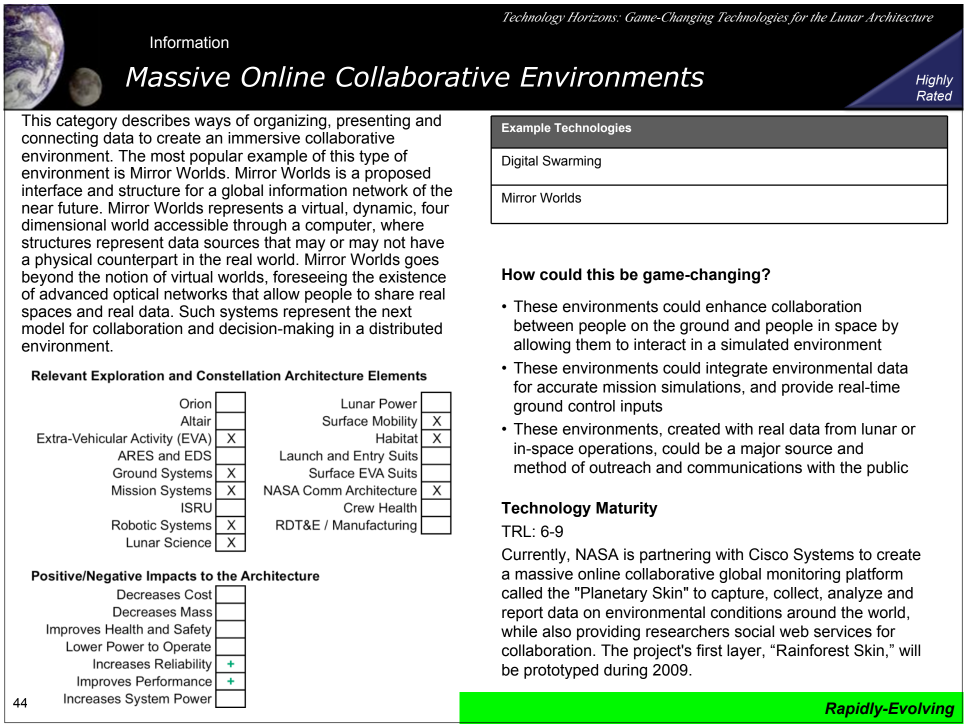
Rapidly-Evolving



Technology Horizons: Game-Changing Technologies for the Lunar Architecture

Information

Massive Online Collaborative Environments

Highly Rated

This category describes ways of organizing, presenting and connecting data to create an immersive collaborative environment. The most popular example of this type of environment is Mirror Worlds. Mirror Worlds is a proposed interface and structure for a global information network of the near future. Mirror Worlds represents a virtual, dynamic, four dimensional world accessible through a computer, where structures represent data sources that may or may not have a physical counterpart in the real world. Mirror Worlds goes beyond the notion of virtual worlds, foreseeing the existence of advanced optical networks that allow people to share real spaces and real data. Such systems represent the next model for collaboration and decision-making in a distributed environment.

Example Technologies
Digital Swarming
Mirror Worlds

Relevant Exploration and Constellation Architecture Elements

Orion	☐	Lunar Power	☐
Altair	☐	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	☐	Launch and Entry Suits	☐
Ground Systems	X	Surface EVA Suits	☐
Mission Systems	X	NASA Comm Architecture	X
ISRU	☐	Crew Health	☐
Robotic Systems	X	RDT&E / Manufacturing	☐
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	☐
Decreases Mass	☐
Improves Health and Safety	☐
Lower Power to Operate	☐
Increases Reliability	+
Improves Performance	+
Increases System Power	☐

How could this be game-changing?

- These environments could enhance collaboration between people on the ground and people in space by allowing them to interact in a simulated environment
- These environments could integrate environmental data for accurate mission simulations, and provide real-time ground control inputs
- These environments, created with real data from lunar or in-space operations, could be a major source and method of outreach and communications with the public

Technology Maturity

TRL: 6-9

Currently, NASA is partnering with Cisco Systems to create a massive online collaborative global monitoring platform called the "Planetary Skin" to capture, collect, analyze and report data on environmental conditions around the world, while also providing researchers social web services for collaboration. The project's first layer, "Rainforest Skin," will be prototyped during 2009.

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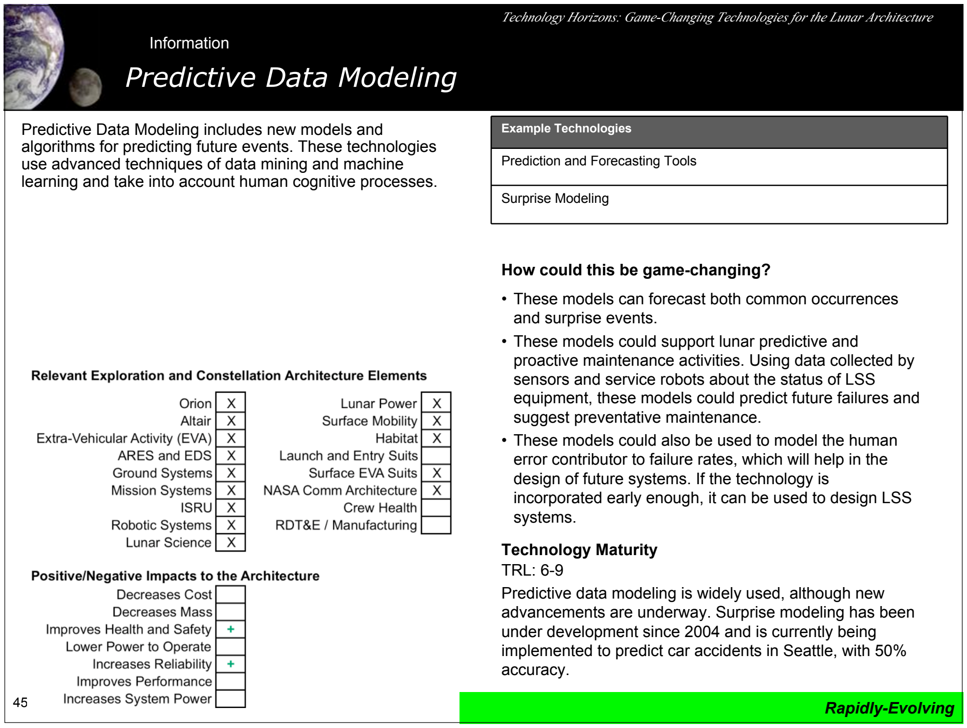
Rapidly-Evolving



Information

Predictive Data Modeling

Predictive Data Modeling includes new models and algorithms for predicting future events. These technologies use advanced techniques of data mining and machine learning and take into account human cognitive processes.

Example Technologies
Prediction and Forecasting Tools
Surprise Modeling

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improves Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improves Performance	
Increases System Power	

How could this be game-changing?

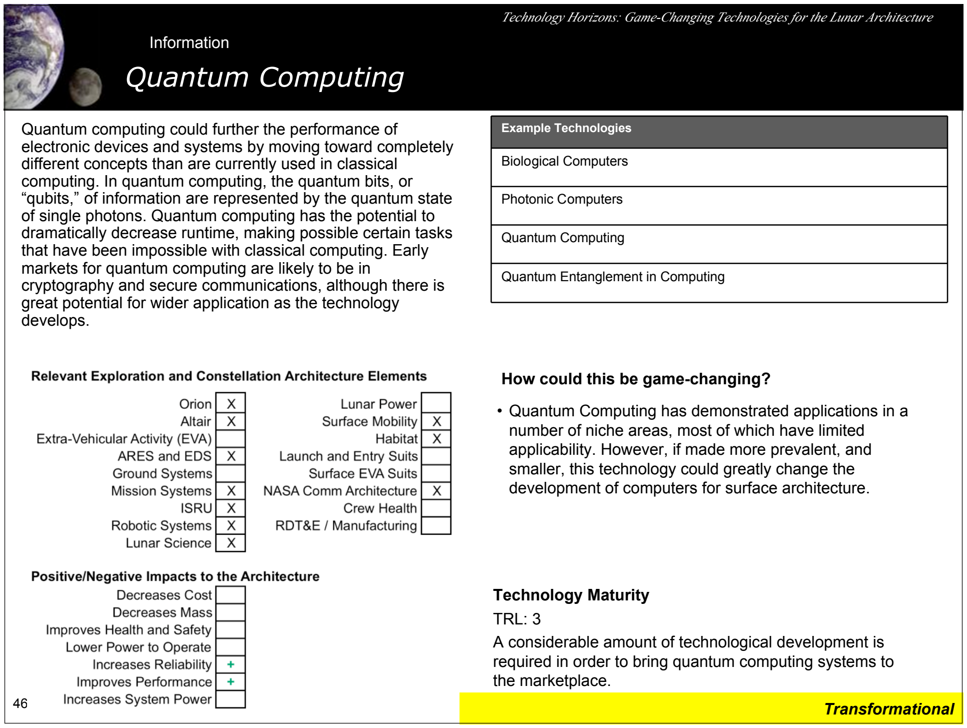
- These models can forecast both common occurrences and surprise events.
- These models could support lunar predictive and proactive maintenance activities. Using data collected by sensors and service robots about the status of LSS equipment, these models could predict future failures and suggest preventative maintenance.
- These models could also be used to model the human error contributor to failure rates, which will help in the design of future systems. If the technology is incorporated early enough, it can be used to design LSS systems.

Technology Maturity

TRL: 6-9

Predictive data modeling is widely used, although new advancements are underway. Surprise modeling has been under development since 2004 and is currently being implemented to predict car accidents in Seattle, with 50% accuracy.

Rapidly-Evolving



Information

Quantum Computing

Quantum computing could further the performance of electronic devices and systems by moving toward completely different concepts than are currently used in classical computing. In quantum computing, the quantum bits, or “qubits,” of information are represented by the quantum state of single photons. Quantum computing has the potential to dramatically decrease runtime, making possible certain tasks that have been impossible with classical computing. Early markets for quantum computing are likely to be in cryptography and secure communications, although there is great potential for wider application as the technology develops.

Example Technologies
Biological Computers
Photonic Computers
Quantum Computing
Quantum Entanglement in Computing

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)		Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improves Health and Safety	
Lower Power to Operate	
Increases Reliability	+
Improves Performance	+
Increases System Power	

How could this be game-changing?

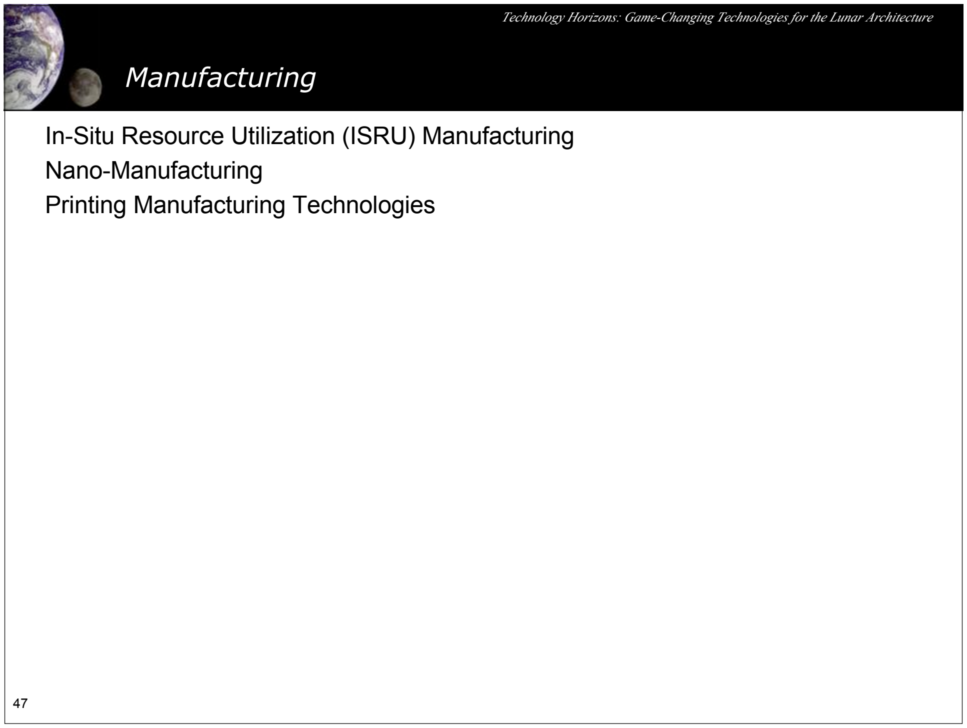
- Quantum Computing has demonstrated applications in a number of niche areas, most of which have limited applicability. However, if made more prevalent, and smaller, this technology could greatly change the development of computers for surface architecture.

Technology Maturity

TRL: 3

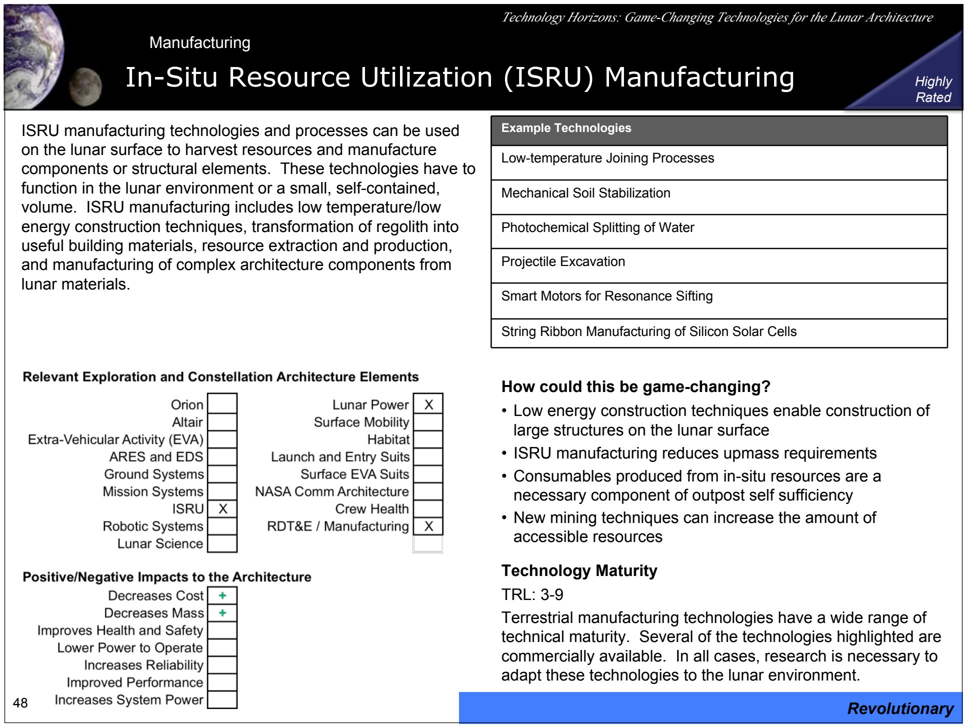
A considerable amount of technological development is required in order to bring quantum computing systems to the marketplace.

Transformational



Manufacturing

In-Situ Resource Utilization (ISRU) Manufacturing
Nano-Manufacturing
Printing Manufacturing Technologies



Manufacturing

In-Situ Resource Utilization (ISRU) Manufacturing

Highly Rated

ISRU manufacturing technologies and processes can be used on the lunar surface to harvest resources and manufacture components or structural elements. These technologies have to function in the lunar environment or a small, self-contained, volume. ISRU manufacturing includes low temperature/low energy construction techniques, transformation of regolith into useful building materials, resource extraction and production, and manufacturing of complex architecture components from lunar materials.

Example Technologies
Low-temperature Joining Processes
Mechanical Soil Stabilization
Photochemical Splitting of Water
Projectile Excavation
Smart Motors for Resonance Sifting
String Ribbon Manufacturing of Silicon Solar Cells

Relevant Exploration and Constellation Architecture Elements

Orion ☐
Altair ☐
Extra-Vehicular Activity (EVA) ☐
ARES and EDS ☐
Ground Systems ☐
Mission Systems ☐
ISRU ☒
Robotic Systems ☐
Lunar Science ☐

Lunar Power ☒
Surface Mobility ☐
Habitat ☐
Launch and Entry Suits ☐
Surface EVA Suits ☐
NASA Comm Architecture ☐
Crew Health ☐
RDT&E / Manufacturing ☒

Positive/Negative Impacts to the Architecture

Decreases Cost +
Decreases Mass +
Improves Health and Safety ☐
Lower Power to Operate ☐
Increases Reliability ☐
Improved Performance ☐
Increases System Power ☐

How could this be game-changing?

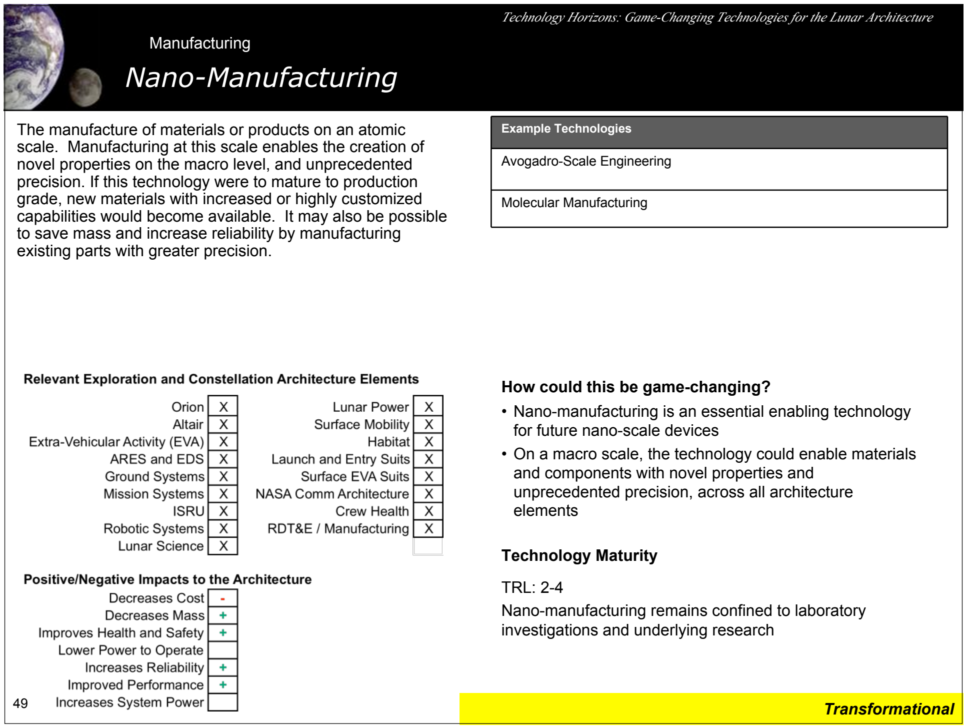
- Low energy construction techniques enable construction of large structures on the lunar surface
- ISRU manufacturing reduces upmass requirements
- Consumables produced from in-situ resources are a necessary component of outpost self sufficiency
- New mining techniques can increase the amount of accessible resources

Technology Maturity

TRL: 3-9

Terrestrial manufacturing technologies have a wide range of technical maturity. Several of the technologies highlighted are commercially available. In all cases, research is necessary to adapt these technologies to the lunar environment.

Revolutionary



Manufacturing

Nano-Manufacturing

The manufacture of materials or products on an atomic scale. Manufacturing at this scale enables the creation of novel properties on the macro level, and unprecedented precision. If this technology were to mature to production grade, new materials with increased or highly customized capabilities would become available. It may also be possible to save mass and increase reliability by manufacturing existing parts with greater precision.

Example Technologies
Avogadro-Scale Engineering
Molecular Manufacturing

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	X
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	-
Decreases Mass	+
Improves Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	

How could this be game-changing?

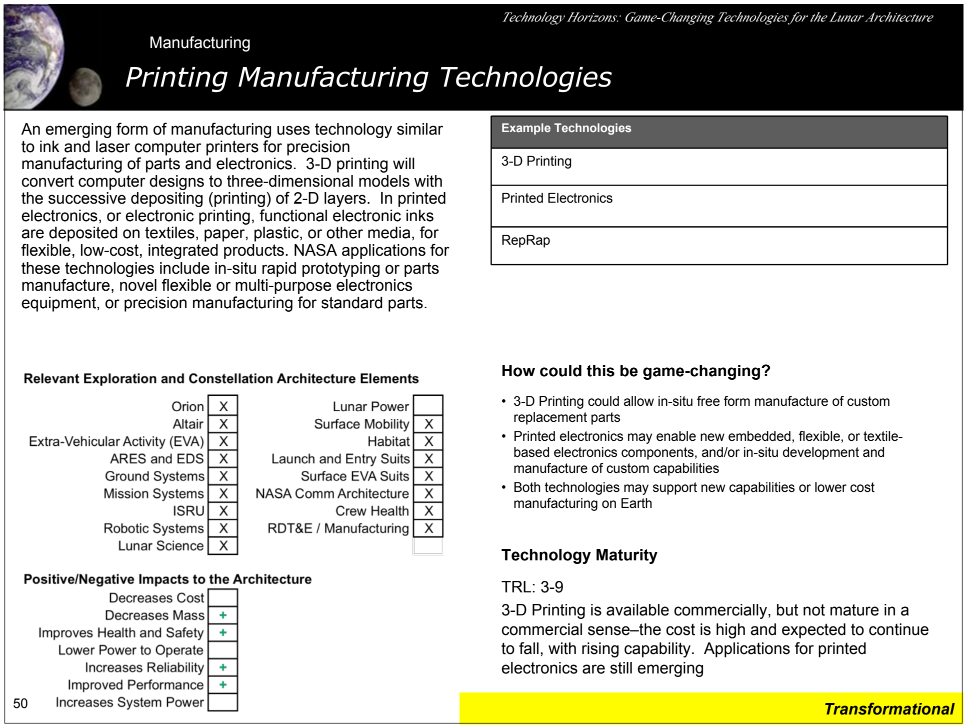
- Nano-manufacturing is an essential enabling technology for future nano-scale devices
- On a macro scale, the technology could enable materials and components with novel properties and unprecedented precision, across all architecture elements

Technology Maturity

TRL: 2-4

Nano-manufacturing remains confined to laboratory investigations and underlying research

Transformational



Manufacturing

Printing Manufacturing Technologies

An emerging form of manufacturing uses technology similar to ink and laser computer printers for precision manufacturing of parts and electronics. 3-D printing will convert computer designs to three-dimensional models with the successive depositing (printing) of 2-D layers. In printed electronics, or electronic printing, functional electronic inks are deposited on textiles, paper, plastic, or other media, for flexible, low-cost, integrated products. NASA applications for these technologies include in-situ rapid prototyping or parts manufacture, novel flexible or multi-purpose electronics equipment, or precision manufacturing for standard parts.

Example Technologies
3-D Printing
Printed Electronics
RepRap

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	X
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improves Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	

How could this be game-changing?

- 3-D Printing could allow in-situ free form manufacture of custom replacement parts
- Printed electronics may enable new embedded, flexible, or textile-based electronics components, and/or in-situ development and manufacture of custom capabilities
- Both technologies may support new capabilities or lower cost manufacturing on Earth

Technology Maturity

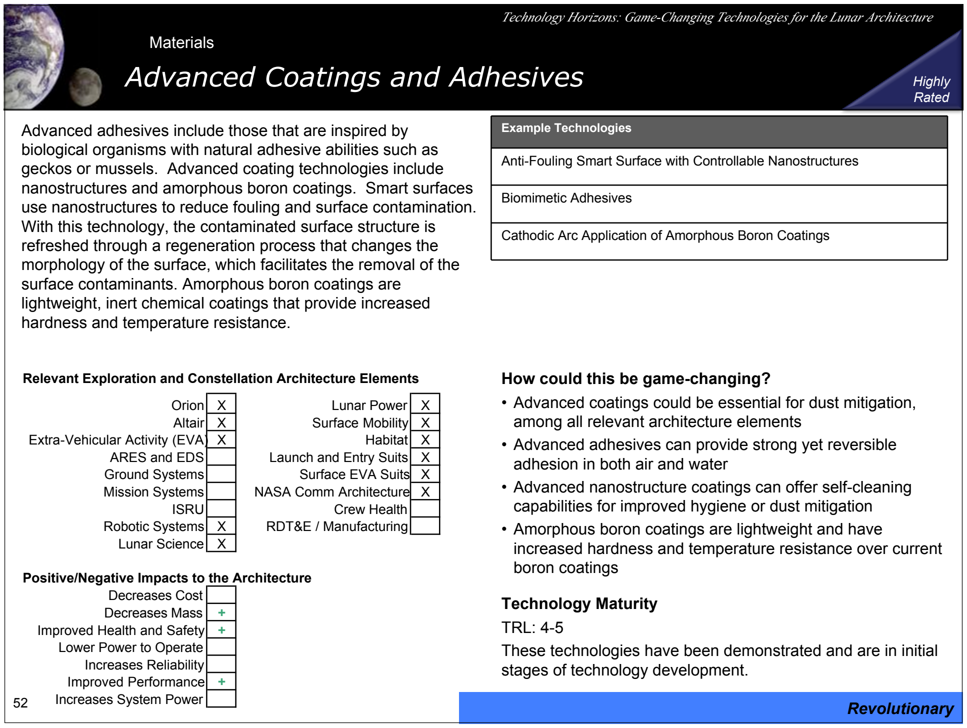
TRL: 3-9

3-D Printing is available commercially, but not mature in a commercial sense–the cost is high and expected to continue to fall, with rising capability. Applications for printed electronics are still emerging

Transformational

Materials

- Advanced Coatings and Adhesives
- Advanced Nanotube-Based Materials
- Artificial Muscles
- Improved Polymers
- Metamaterials
- Power-Generating Materials
- Radiation Shielding
- Self-Repairing and Self-Cleaning Materials
- Transparent Composites



Materials

Advanced Coatings and Adhesives

Highly Rated

Advanced adhesives include those that are inspired by biological organisms with natural adhesive abilities such as geckos or mussels. Advanced coating technologies include nanostructures and amorphous boron coatings. Smart surfaces use nanostructures to reduce fouling and surface contamination. With this technology, the contaminated surface structure is refreshed through a regeneration process that changes the morphology of the surface, which facilitates the removal of the surface contaminants. Amorphous boron coatings are lightweight, inert chemical coatings that provide increased hardness and temperature resistance.

Example Technologies
Anti-Fouling Smart Surface with Controllable Nanostructures
Biomimetic Adhesives
Cathodic Arc Application of Amorphous Boron Coatings

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	X
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	X
ISRU		Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	
Improved Performance	+
Increases System Power	

How could this be game-changing?

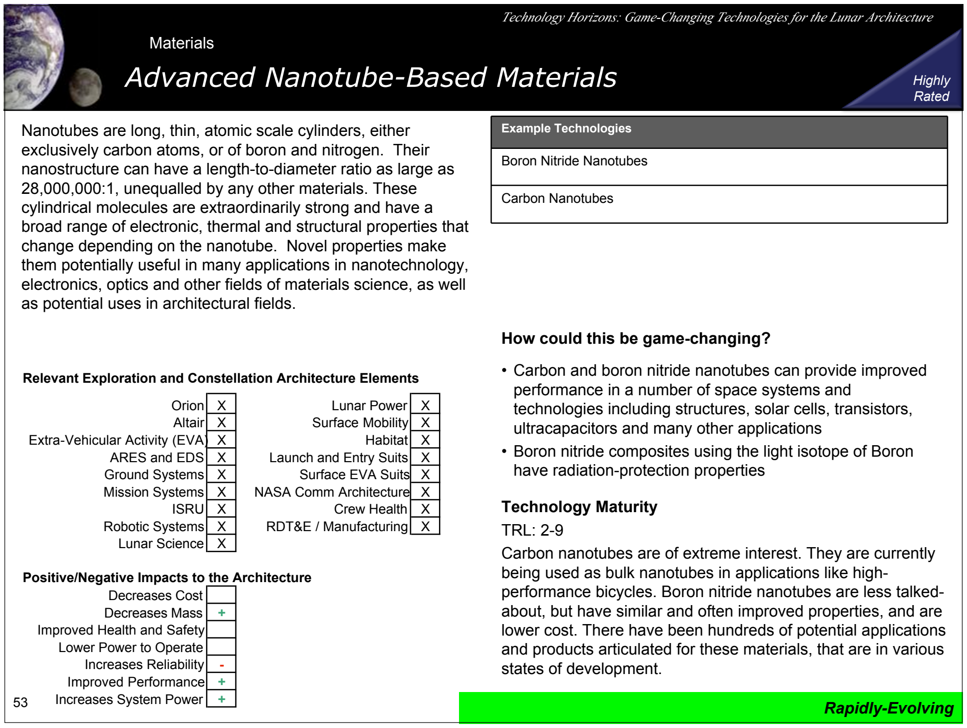
- Advanced coatings could be essential for dust mitigation, among all relevant architecture elements
- Advanced adhesives can provide strong yet reversible adhesion in both air and water
- Advanced nanostructure coatings can offer self-cleaning capabilities for improved hygiene or dust mitigation
- Amorphous boron coatings are lightweight and have increased hardness and temperature resistance over current boron coatings

Technology Maturity

TRL: 4-5

These technologies have been demonstrated and are in initial stages of technology development.

Revolutionary



Materials

Advanced Nanotube-Based Materials

Highly Rated

Nanotubes are long, thin, atomic scale cylinders, either exclusively carbon atoms, or of boron and nitrogen. Their nanostructure can have a length-to-diameter ratio as large as 28,000,000:1, unequalled by any other materials. These cylindrical molecules are extraordinarily strong and have a broad range of electronic, thermal and structural properties that change depending on the nanotube. Novel properties make them potentially useful in many applications in nanotechnology, electronics, optics and other fields of materials science, as well as potential uses in architectural fields.

Example Technologies
Boron Nitride Nanotubes
Carbon Nanotubes

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	X
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	-
Improved Performance	+
Increases System Power	+

How could this be game-changing?

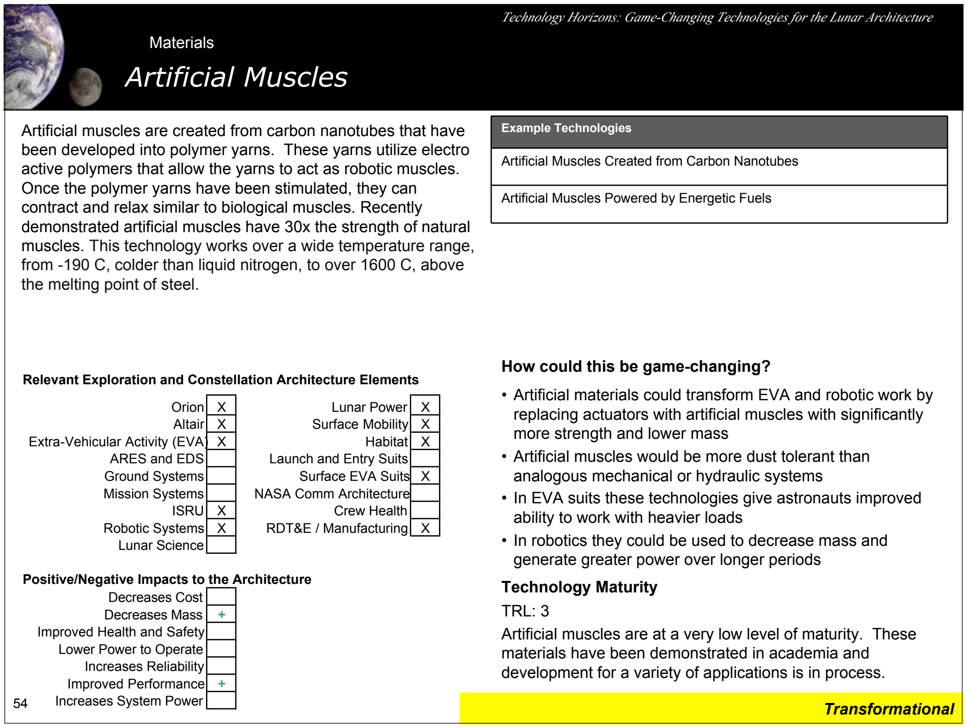
- Carbon and boron nitride nanotubes can provide improved performance in a number of space systems and technologies including structures, solar cells, transistors, ultracapacitors and many other applications
- Boron nitride composites using the light isotope of Boron have radiation-protection properties

Technology Maturity

TRL: 2-9

Carbon nanotubes are of extreme interest. They are currently being used as bulk nanotubes in applications like high-performance bicycles. Boron nitride nanotubes are less talked-about, but have similar and often improved properties, and are lower cost. There have been hundreds of potential applications and products articulated for these materials, that are in various states of development.

Rapidly-Evolving



Materials

Artificial Muscles

Artificial muscles are created from carbon nanotubes that have been developed into polymer yarns. These yarns utilize electro active polymers that allow the yarns to act as robotic muscles. Once the polymer yarns have been stimulated, they can contract and relax similar to biological muscles. Recently demonstrated artificial muscles have 30x the strength of natural muscles. This technology works over a wide temperature range, from -190 C, colder than liquid nitrogen, to over 1600 C, above the melting point of steel.

Example Technologies
Artificial Muscles Created from Carbon Nanotubes
Artificial Muscles Powered by Energetic Fuels

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	
Improved Performance	+
Increases System Power	

How could this be game-changing?

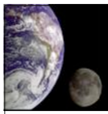
- Artificial materials could transform EVA and robotic work by replacing actuators with artificial muscles with significantly more strength and lower mass
- Artificial muscles would be more dust tolerant than analogous mechanical or hydraulic systems
- In EVA suits these technologies give astronauts improved ability to work with heavier loads
- In robotics they could be used to decrease mass and generate greater power over longer periods

Technology Maturity

TRL: 3

Artificial muscles are at a very low level of maturity. These materials have been demonstrated in academia and development for a variety of applications is in process.

Transformational



Materials

Improved Polymers

Improved polymers have enhanced physical properties. These enhancements may include withstanding extreme temperatures or reinforcements that create greater flexibility. Due to their use in everything from packaging to structures, improved polymers continue to attract development resources.

Example Technologies
Improved Elastic Polyurethane
Thermoplastic Tank Liner
Ultra-High Temperature Polymers

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA		Habitat	X
ARES and EDS	X	Launch and Entry Suits	X
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	
Improved Performance	+
Increases System Power	

How could this be game-changing?

- Improved polymer technology could affect structures, robotic systems, vehicles, and suit fabrics
- They have high physical strength, high stiffness, and flexibility and some can withstand extreme temperatures

Technology Maturity

TRL: 3-9

While most of these technologies have only been demonstrated in a laboratory, thermoplastic tank liners have already been developed to replace titanium liners.

Rapidly-Evolving

Materials

Metamaterials

Metamaterials are composites made up of precisely arranged patterns of two or more distinct materials. These structures can manipulate light and sound waves, in ways not readily observed in nature. For example, photonic crystals -- arrays of identical microscopic blocks separated by voids -- can reflect or even inhibit the propagation of certain wavelengths of light; assemblies of small wire circuits can bend light in strange ways. Because of their unique capabilities for reflecting and bending light metamaterials can be used to greatly improve the performance of devices that are limited by the way light moves through materials.

Example Technologies
Acoustic Metamaterials
Optical Metamaterials

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	
Improved Performance	+
Increases System Power	+

How could this be game-changing?

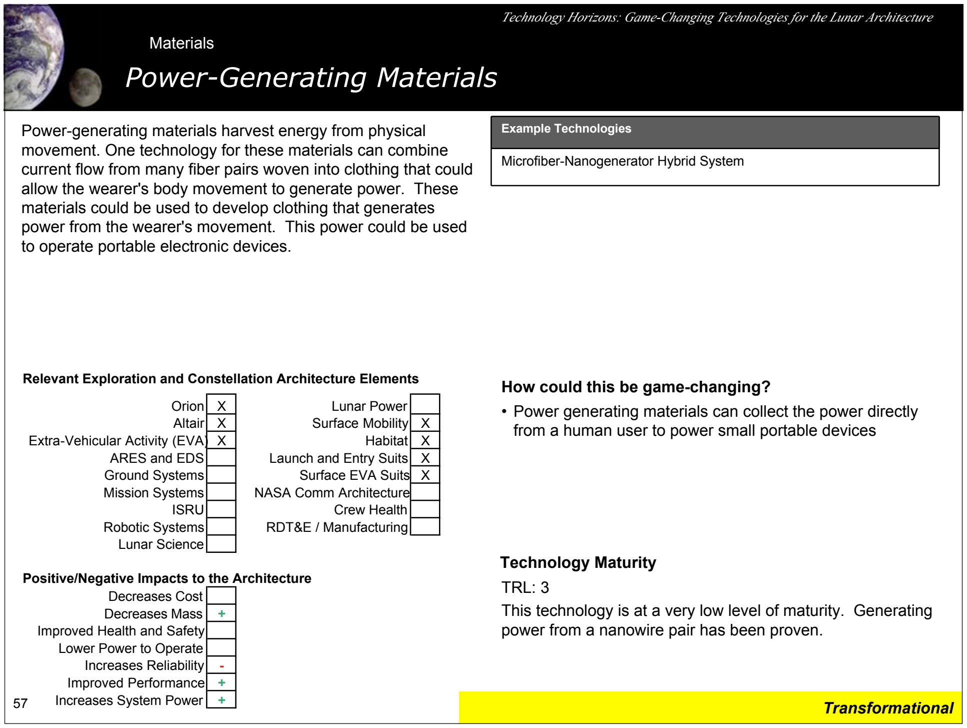
- Metamaterials is an early stage technology with potential across many application areas
- Coatings from these materials can improve the efficiency of solar cells by decreasing the amount of light reflected
- Increases the information stored on optical storage devices like DVDs
- Acoustic metamaterials could redirect sound waves and dampen noise within habitable volumes
- Metamaterials may potentially be designed for some radiation protection properties

Technology Maturity

TRL: 4

The use of metamaterials is still in its early stages. Researchers from several universities and the DoD have demonstrated the use of metamaterials in cloaking devices, lenses and optical fiber signal transmission efficiency.

Transformational



Materials

Power-Generating Materials

Power-generating materials harvest energy from physical movement. One technology for these materials can combine current flow from many fiber pairs woven into clothing that could allow the wearer's body movement to generate power. These materials could be used to develop clothing that generates power from the wearer's movement. This power could be used to operate portable electronic devices.

Example Technologies
Microfiber-Nanogenerator Hybrid System

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA	X	Habitat	X
ARES and EDS		Launch and Entry Suits	X
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU		Crew Health	
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	
Lower Power to Operate	
Increases Reliability	-
Improved Performance	+
Increases System Power	+

How could this be game-changing?

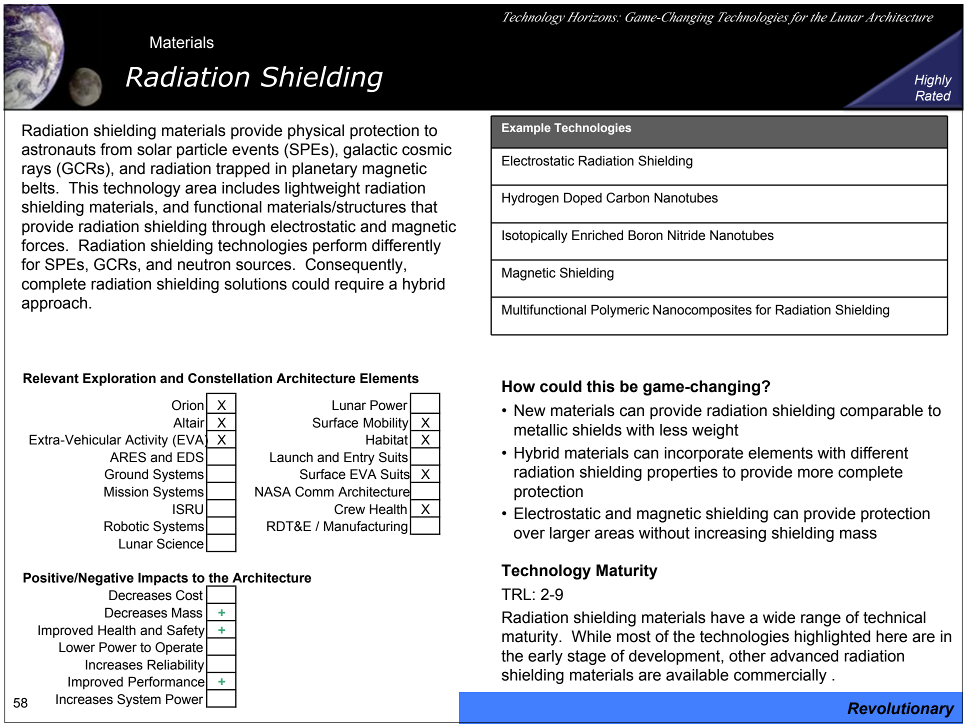
- Power generating materials can collect the power directly from a human user to power small portable devices

Technology Maturity

TRL: 3

This technology is at a very low level of maturity. Generating power from a nanowire pair has been proven.

Transformational



Materials

Radiation Shielding

Highly Rated

Radiation shielding materials provide physical protection to astronauts from solar particle events (SPEs), galactic cosmic rays (GCRs), and radiation trapped in planetary magnetic belts. This technology area includes lightweight radiation shielding materials, and functional materials/structures that provide radiation shielding through electrostatic and magnetic forces. Radiation shielding technologies perform differently for SPEs, GCRs, and neutron sources. Consequently, complete radiation shielding solutions could require a hybrid approach.

Example Technologies
Electrostatic Radiation Shielding
Hydrogen Doped Carbon Nanotubes
Isotopically Enriched Boron Nitride Nanotubes
Magnetic Shielding
Multifunctional Polymeric Nanocomposites for Radiation Shielding

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA	X	Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU		Crew Health	X
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	
Improved Performance	+
Increases System Power	

How could this be game-changing?

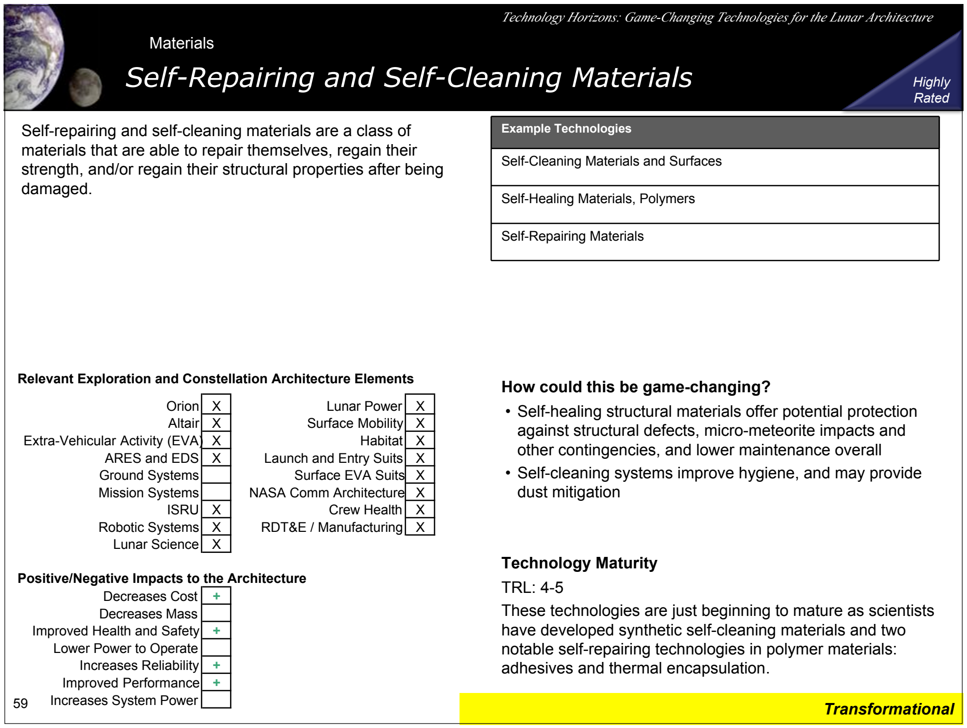
- New materials can provide radiation shielding comparable to metallic shields with less weight
- Hybrid materials can incorporate elements with different radiation shielding properties to provide more complete protection
- Electrostatic and magnetic shielding can provide protection over larger areas without increasing shielding mass

Technology Maturity

TRL: 2-9

Radiation shielding materials have a wide range of technical maturity. While most of the technologies highlighted here are in the early stage of development, other advanced radiation shielding materials are available commercially .

Revolutionary



Materials

Self-Repairing and Self-Cleaning Materials

Highly Rated

Self-repairing and self-cleaning materials are a class of materials that are able to repair themselves, regain their strength, and/or regain their structural properties after being damaged.

Example Technologies
Self-Cleaning Materials and Surfaces
Self-Healing Materials, Polymers
Self-Repairing Materials

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	X
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	X
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	

How could this be game-changing?

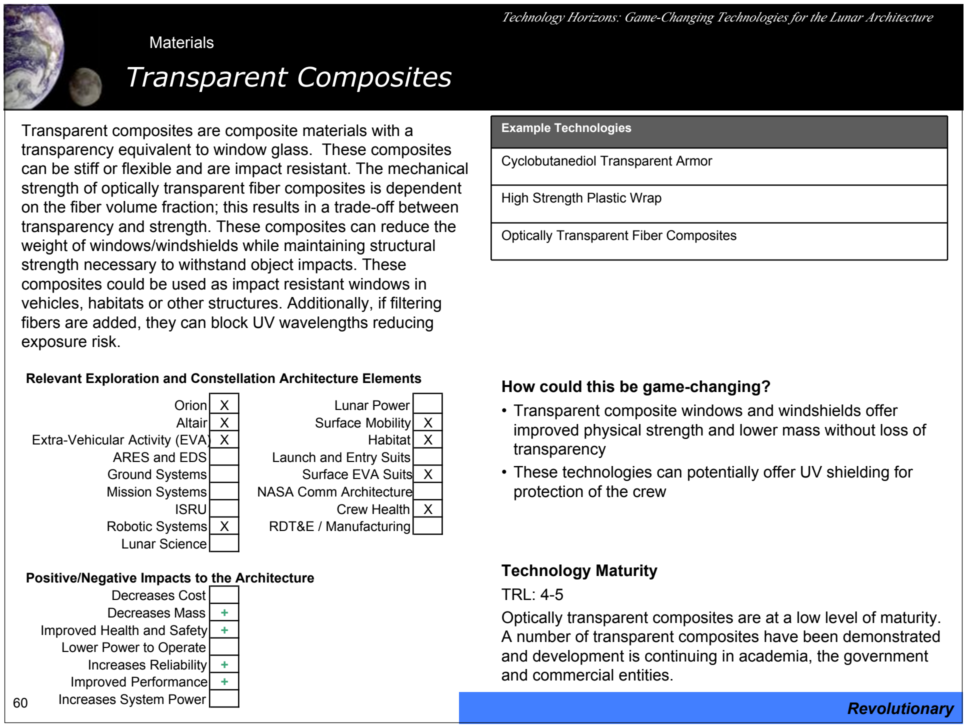
- Self-healing structural materials offer potential protection against structural defects, micro-meteorite impacts and other contingencies, and lower maintenance overall
- Self-cleaning systems improve hygiene, and may provide dust mitigation

Technology Maturity

TRL: 4-5

These technologies are just beginning to mature as scientists have developed synthetic self-cleaning materials and two notable self-repairing technologies in polymer materials: adhesives and thermal encapsulation.

Transformational



Materials

Transparent Composites

Transparent composites are composite materials with a transparency equivalent to window glass. These composites can be stiff or flexible and are impact resistant. The mechanical strength of optically transparent fiber composites is dependent on the fiber volume fraction; this results in a trade-off between transparency and strength. These composites can reduce the weight of windows/windshields while maintaining structural strength necessary to withstand object impacts. These composites could be used as impact resistant windows in vehicles, habitats or other structures. Additionally, if filtering fibers are added, they can block UV wavelengths reducing exposure risk.

Example Technologies
Cyclobutanediol Transparent Armor
High Strength Plastic Wrap
Optically Transparent Fiber Composites

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU		Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	

How could this be game-changing?

- Transparent composite windows and windshields offer improved physical strength and lower mass without loss of transparency
- These technologies can potentially offer UV shielding for protection of the crew

Technology Maturity

TRL: 4-5

Optically transparent composites are at a low level of maturity. A number of transparent composites have been demonstrated and development is continuing in academia, the government and commercial entities.

Revolutionary

Power and Energy

Embedded Power Technologies
Energy Storage Technologies
Long-Distance Power Transmission
Near Field Wireless Energy Transmission
Next Generation Fuel Cell Technologies
Next Generation Solar Cells
Nuclear Power Technologies
Power Generation from Organic Structures

Power and Energy

Embedded Power Technologies

Embedded power technologies liberate electronic devices from the need for external power, by integrated power generation capabilities. Potential examples include instruments that convert ambient heat into electricity through the use of thermoelectric materials incorporated in the design, or portable electronics designed with integrated photovoltaics. These technologies could simplify operations and power architectures when used in devices by astronauts in pressurized volumes. For full benefits, systems would need fully independent components, a longer term proposition.

Example Technologies
Converter Chip to Enable Energy Harvesting
Embedded Power

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improves Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improved Performance	
Increases System Power	+

How could this be game-changing?

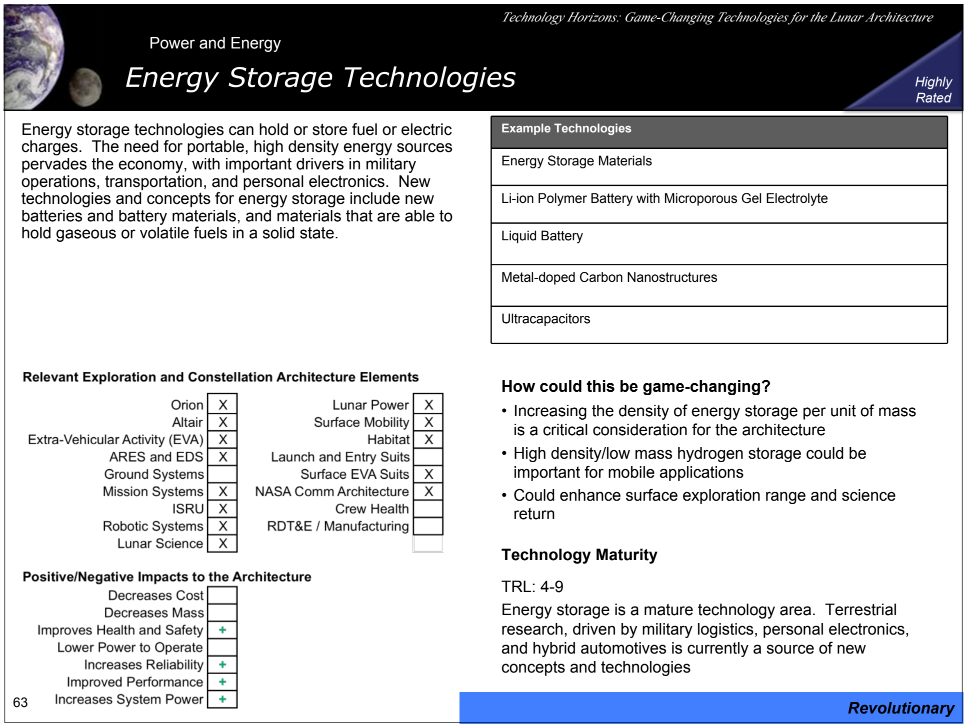
- Embedded power technologies would simplify operations and logistics associated with electronic devices and equipment
- Offers efficiencies by reducing wiring mass
- Creates system design challenges

Technology Maturity

TRL: 4-9

Embedded power technologies are commercially available, but the power generated by these chips and devices are far short of making the device energy independent

Revolutionary



Power and Energy

Energy Storage Technologies

Highly Rated

Energy storage technologies can hold or store fuel or electric charges. The need for portable, high density energy sources pervades the economy, with important drivers in military operations, transportation, and personal electronics. New technologies and concepts for energy storage include new batteries and battery materials, and materials that are able to hold gaseous or volatile fuels in a solid state.

Example Technologies
Energy Storage Materials
Li-ion Polymer Battery with Microporous Gel Electrolyte
Liquid Battery
Metal-doped Carbon Nanostructures
Ultracapacitors

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems	X	NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improves Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	+

How could this be game-changing?

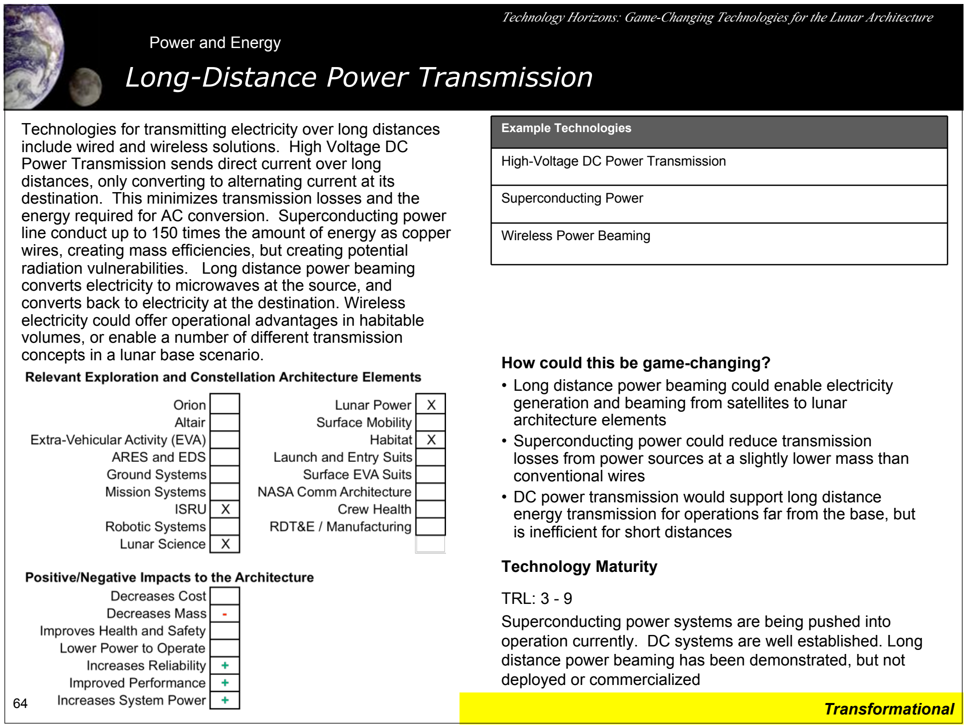
- Increasing the density of energy storage per unit of mass is a critical consideration for the architecture
- High density/low mass hydrogen storage could be important for mobile applications
- Could enhance surface exploration range and science return

Technology Maturity

TRL: 4-9

Energy storage is a mature technology area. Terrestrial research, driven by military logistics, personal electronics, and hybrid automotives is currently a source of new concepts and technologies

Revolutionary



Power and Energy

Long-Distance Power Transmission

Technologies for transmitting electricity over long distances include wired and wireless solutions. High Voltage DC Power Transmission sends direct current over long distances, only converting to alternating current at its destination. This minimizes transmission losses and the energy required for AC conversion. Superconducting power line conduct up to 150 times the amount of energy as copper wires, creating mass efficiencies, but creating potential radiation vulnerabilities. Long distance power beaming converts electricity to microwaves at the source, and converts back to electricity at the destination. Wireless electricity could offer operational advantages in habitable volumes, or enable a number of different transmission concepts in a lunar base scenario.

Example Technologies
High-Voltage DC Power Transmission
Superconducting Power
Wireless Power Beaming

Relevant Exploration and Constellation Architecture Elements

Orion		Lunar Power	X
Altair		Surface Mobility	
Extra-Vehicular Activity (EVA)		Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems		NASA Comm Architecture	
ISRU	X	Crew Health	
Robotic Systems		RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	-
Improves Health and Safety	
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	+

How could this be game-changing?

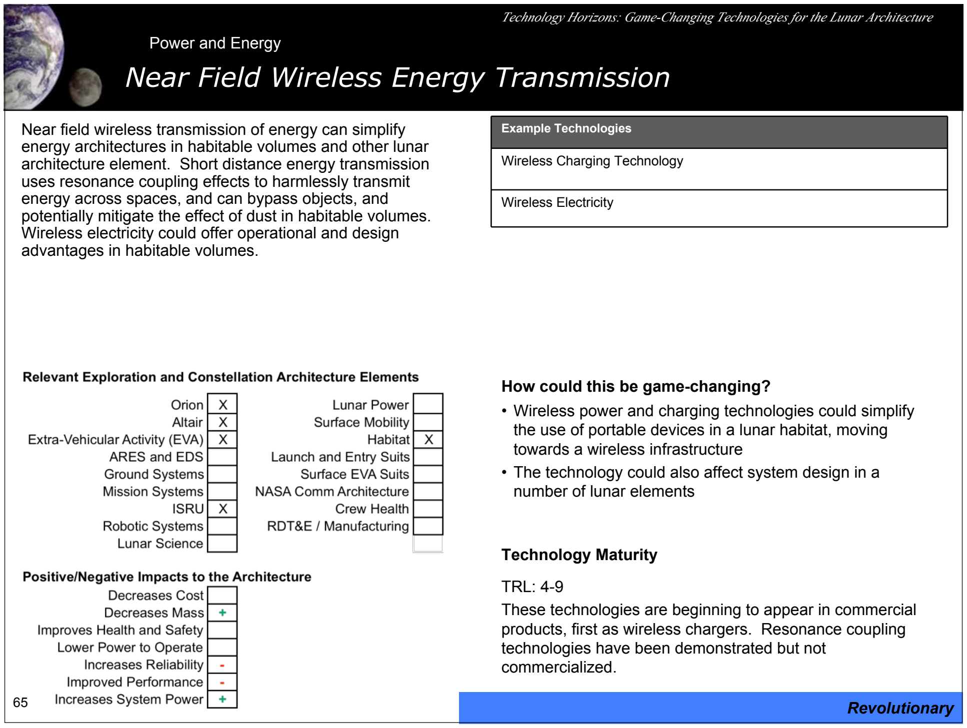
- Long distance power beaming could enable electricity generation and beaming from satellites to lunar architecture elements
- Superconducting power could reduce transmission losses from power sources at a slightly lower mass than conventional wires
- DC power transmission would support long distance energy transmission for operations far from the base, but is inefficient for short distances

Technology Maturity

TRL: 3 - 9

Superconducting power systems are being pushed into operation currently. DC systems are well established. Long distance power beaming has been demonstrated, but not deployed or commercialized

Transformational



Power and Energy

Near Field Wireless Energy Transmission

Near field wireless transmission of energy can simplify energy architectures in habitable volumes and other lunar architecture element. Short distance energy transmission uses resonance coupling effects to harmlessly transmit energy across spaces, and can bypass objects, and potentially mitigate the effect of dust in habitable volumes. Wireless electricity could offer operational and design advantages in habitable volumes.

Example Technologies
Wireless Charging Technology
Wireless Electricity

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems		NASA Comm Architecture	
ISRU	X	Crew Health	
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improves Health and Safety	
Lower Power to Operate	
Increases Reliability	-
Improved Performance	-
Increases System Power	+

How could this be game-changing?

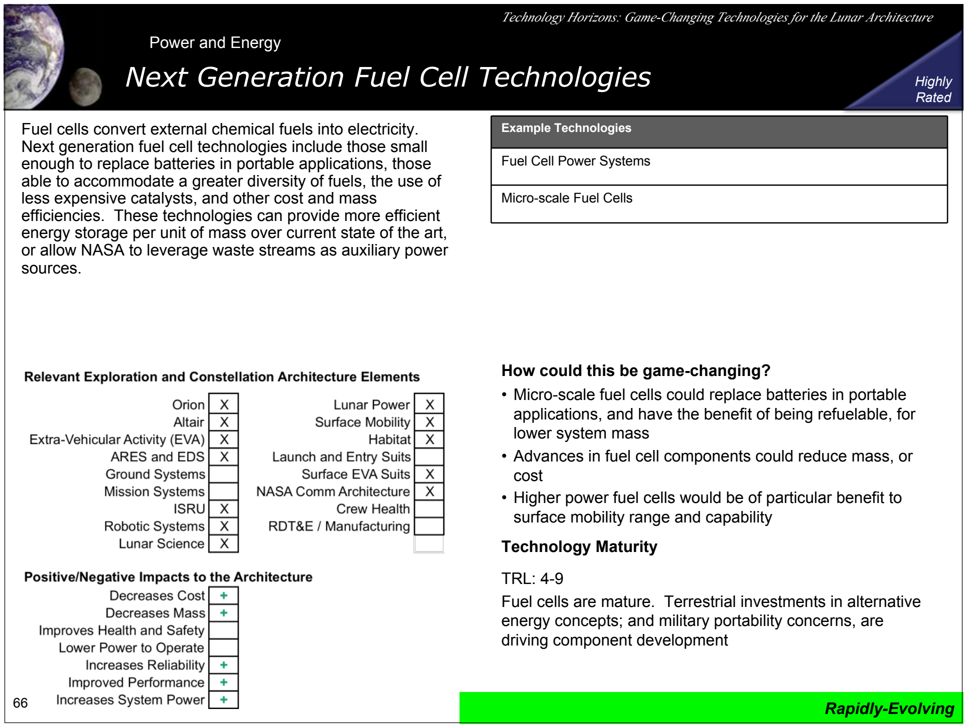
- Wireless power and charging technologies could simplify the use of portable devices in a lunar habitat, moving towards a wireless infrastructure
- The technology could also affect system design in a number of lunar elements

Technology Maturity

TRL: 4-9

These technologies are beginning to appear in commercial products, first as wireless chargers. Resonance coupling technologies have been demonstrated but not commercialized.

Revolutionary



Power and Energy

Next Generation Fuel Cell Technologies

Highly Rated

Fuel cells convert external chemical fuels into electricity. Next generation fuel cell technologies include those small enough to replace batteries in portable applications, those able to accommodate a greater diversity of fuels, the use of less expensive catalysts, and other cost and mass efficiencies. These technologies can provide more efficient energy storage per unit of mass over current state of the art, or allow NASA to leverage waste streams as auxiliary power sources.

Example Technologies
Fuel Cell Power Systems
Micro-scale Fuel Cells

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improves Health and Safety	
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	+

How could this be game-changing?

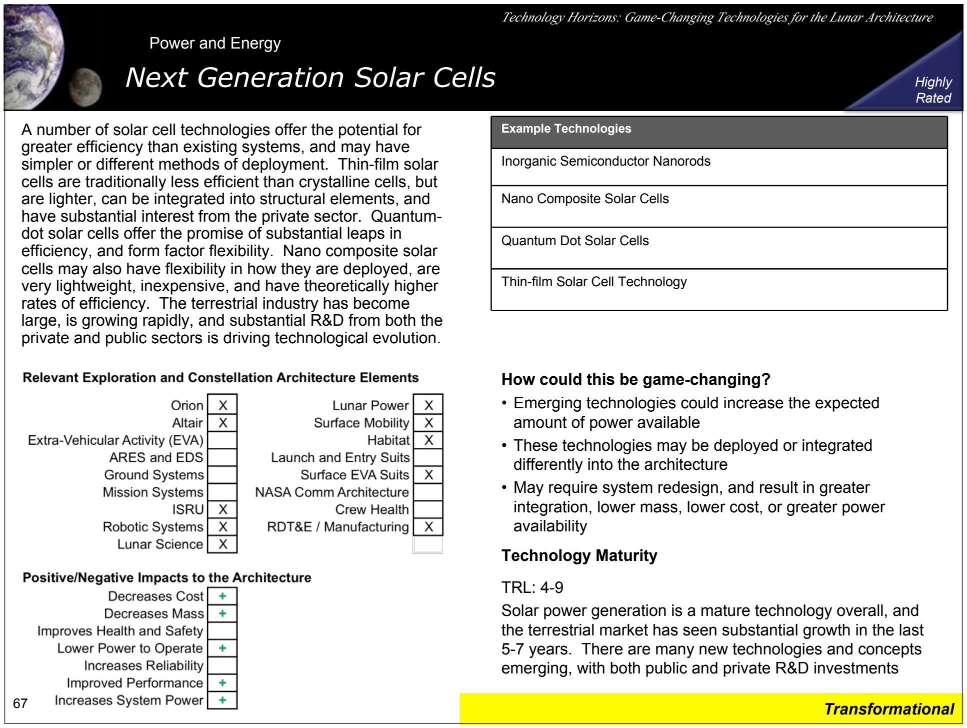
- Micro-scale fuel cells could replace batteries in portable applications, and have the benefit of being refuelable, for lower system mass
- Advances in fuel cell components could reduce mass, or cost
- Higher power fuel cells would be of particular benefit to surface mobility range and capability

Technology Maturity

TRL: 4-9

Fuel cells are mature. Terrestrial investments in alternative energy concepts; and military portability concerns, are driving component development

Rapidly-Evolving



Technology Horizons: Game-Changing Technologies for the Lunar Architecture

Power and Energy

Next Generation Solar Cells

Highly Rated

A number of solar cell technologies offer the potential for greater efficiency than existing systems, and may have simpler or different methods of deployment. Thin-film solar cells are traditionally less efficient than crystalline cells, but are lighter, can be integrated into structural elements, and have substantial interest from the private sector. Quantum-dot solar cells offer the promise of substantial leaps in efficiency, and form factor flexibility. Nano composite solar cells may also have flexibility in how they are deployed, are very lightweight, inexpensive, and have theoretically higher rates of efficiency. The terrestrial industry has become large, is growing rapidly, and substantial R&D from both the private and public sectors is driving technological evolution.

Example Technologies
Inorganic Semiconductor Nanorods
Nano Composite Solar Cells
Quantum Dot Solar Cells
Thin-film Solar Cell Technology

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)		Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improves Health and Safety	
Lower Power to Operate	+
Increases Reliability	
Improved Performance	+
Increases System Power	+

How could this be game-changing?

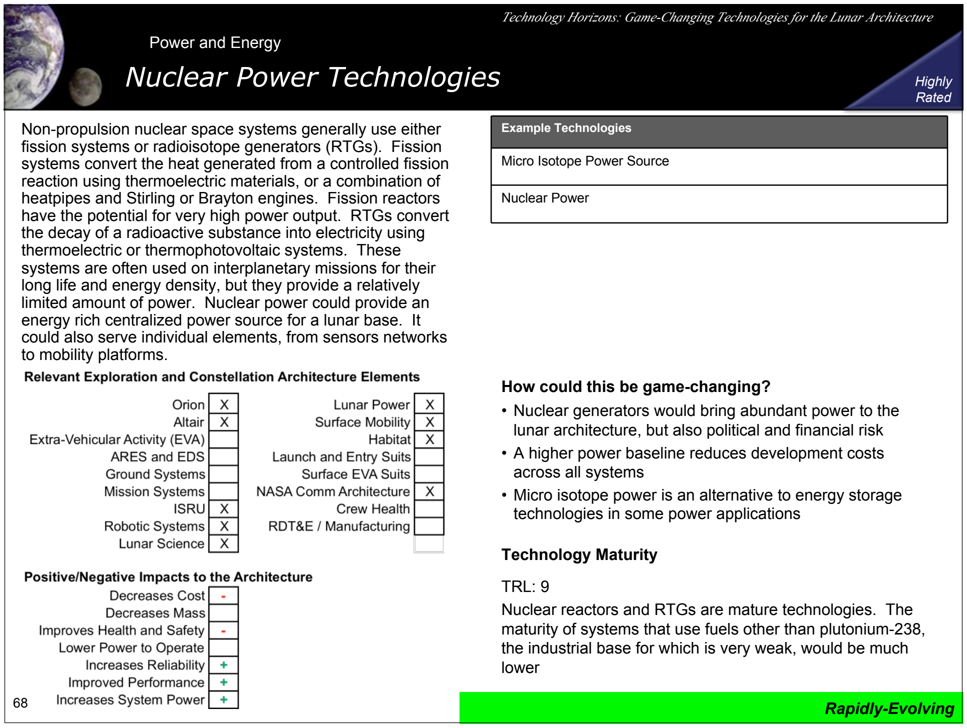
- Emerging technologies could increase the expected amount of power available
- These technologies may be deployed or integrated differently into the architecture
- May require system redesign, and result in greater integration, lower mass, lower cost, or greater power availability

Technology Maturity

TRL: 4-9

Solar power generation is a mature technology overall, and the terrestrial market has seen substantial growth in the last 5-7 years. There are many new technologies and concepts emerging, with both public and private R&D investments

Transformational



Technology Horizons: Game-Changing Technologies for the Lunar Architecture

Power and Energy

Nuclear Power Technologies

Highly Rated

Non-propulsion nuclear space systems generally use either fission systems or radioisotope generators (RTGs). Fission systems convert the heat generated from a controlled fission reaction using thermoelectric materials, or a combination of heatpipes and Stirling or Brayton engines. Fission reactors have the potential for very high power output. RTGs convert the decay of a radioactive substance into electricity using thermoelectric or thermophotovoltaic systems. These systems are often used on interplanetary missions for their long life and energy density, but they provide a relatively limited amount of power. Nuclear power could provide an energy rich centralized power source for a lunar base. It could also serve individual elements, from sensors networks to mobility platforms.

Example Technologies
Micro Isotope Power Source
Nuclear Power

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)		Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems		NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	-
Decreases Mass	
Improves Health and Safety	-
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	+

How could this be game-changing?

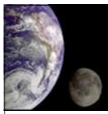
- Nuclear generators would bring abundant power to the lunar architecture, but also political and financial risk
- A higher power baseline reduces development costs across all systems
- Micro isotope power is an alternative to energy storage technologies in some power applications

Technology Maturity

TRL: 9

Nuclear reactors and RTGs are mature technologies. The maturity of systems that use fuels other than plutonium-238, the industrial base for which is very weak, would be much lower

Rapidly-Evolving



Power and Energy

Power Generation from Organic Sources

Several technologies are able to convert biological materials into fuel sources. One method is the use of a catalyst or bacteria to breakdown the chemicals in organic substances such that they can be used as a fuel cell feedstock. Another method is the identification of enzymes and microorganisms that convert or metabolize cellulose into biofuels. In either instance, NASA could use these technologies to leverage organic waste as a usable power source. The amount of power that could be generated from these sources is limited.

Example Technologies
Cellulolytic Enzymes
Hydrogen Producing Catalyst
Microbial Fuel Cells (MFCs)

Relevant Exploration and Constellation Architecture Elements

Orion	☐	Lunar Power	☒
Altair	☐	Surface Mobility	☒
Extra-Vehicular Activity (EVA)	☒	Habitat	☒
ARES and EDS	☐	Launch and Entry Suits	☐
Ground Systems	☐	Surface EVA Suits	☒
Mission Systems	☐	NASA Comm Architecture	☐
ISRU	☒	Crew Health	☒
Robotic Systems	☐	RDT&E / Manufacturing	☐
Lunar Science	☐		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	
Improves Health and Safety	
Lower Power to Operate	
Increases Reliability	
Improved Performance	+
Increases System Power	+

How could this be game-changing?

- The generation of power from waste streams could leverage previously disposable material to increase available power to the architecture
- Could impact 'feedstock' design, so that packaging, containers, and structures could be designed with biologically reducible materials

Technology Maturity

TRL: 3-4

These technologies are in development. The military is investigating these technologies for in-situ power generation. There are also related, larger scale technologies in this group for the global alternative energy supply

Transformational

Propulsion

Advanced Chemical Propulsion

Advanced Cryogenic Technologies

Advanced Electric Propulsion

Scalable Micro-Propulsion

Propulsion

Advanced Chemical Propulsion

Advanced chemical propulsion increases the performance, storage capabilities, or environmental friendliness of rocket performance. Metastable intermolecular composites are a class of energetic compounds with nanostructured fuels and oxidizers, for higher and/or greater customization in performance. Functionalized carbon nanotubes may improve ignition systems, or enable higher powered, easier to store propellants. ADN is a solid, organic oxidizer that, in not containing chloride or metals, leaves a reduced signature and less environmental damage. CL-20 is cited as the most explosive non-nuclear material known, consisting of a ring of nitrogen and oxygen atoms. Greater energetic performance from fuels increases the amount of mass NASA is able to afford across the architecture

Example Technologies
Ammonium Dinitramide (ADN)
CL-20 (Hexanitrohexazaiaowurtzitane)
Nanoenergetics: Functionalized Carbon Nanotubes for Energetic Applications
Nanoenergetics: Metastable Intermolecular Composites (MIC)

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	
Extra-Vehicular Activity (EVA)	X	Habitat	
ARES and EDS	X	Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems		NASA Comm Architecture	X
ISRU		Crew Health	
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improves Health and Safety	
Lower Power to Operate	
Increases Reliability	+
Improved Performance	+
Increases System Power	

How could this be game changing?

- Increased propulsion performance increases payload mass for a given launch vehicle
- High performance storable propellants or explosives may have applications in ISRU, robotics, or science missions
- "Green" oxidizers reduce environmental damage on Earth

Technology Maturity

TRL: 3-9

CL-20 and ADN are used in military applications, with ADN having been used in Soviet systems since the early 90s. MICs, and functionalized carbon nanotubes remain in development

Revolutionary

Propulsion

Advanced Cryogenic Technologies

Advanced cryogenic fuel management technologies have the capability to greatly enhance crewed and robotic space missions. In-orbit fuel transfer systems enable the use of propellant depots in LEO, which would allow for architectures that greatly increase the amount of mass landed on the Moon, or larger structures in orbit. Advanced cryogenic storage and cryocooler technologies enable not just the use of propellant depots, but also the use of cryogenic propellants on long duration interplanetary missions. The lower mass and volume of cryogenic propellants allows a higher amount of spacecraft mass and volume devoted to payloads. This may be critical for missions such as Mars sample return.

Example Technologies
Cryogenic and LOX Based Propulsion Systems for Robotic Planetary Missions
In-Orbit Cryogenic Fuel Transfer
Ultra Low-temperature Cryocooler

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	
Extra-Vehicular Activity (EVA)		Habitat	
ARES and EDS	X	Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems		NASA Comm Architecture	
ISRU		Crew Health	
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improves Health and Safety	
Lower Power to Operate	-
Increases Reliability	
Improved Performance	+
Increases System Power	

How could this be game-changing?

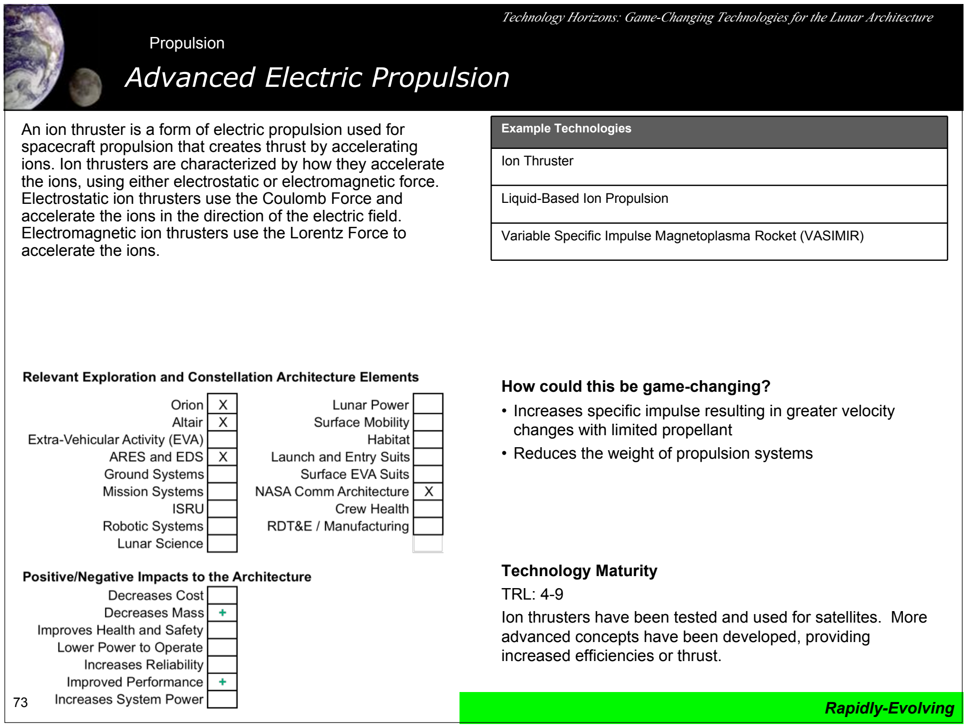
- Decreases the percentage of weight devoted to propulsion systems relative to payload on interplanetary missions
- Increases the lifetime of stored cryogenic propellants
- Allows for on-orbit propellant depots, which would affect and add flexibility to architecture design

Technology Maturity

TRL: 5-9

New USAF Cryocoolers have been designed and deployed in recent years. A design for a low thrust advanced cryogenic propulsion system has been developed. Additional research would be necessary for safe storage of cryogenic propellants indefinitely.

Transformational



Propulsion

Advanced Electric Propulsion

An ion thruster is a form of electric propulsion used for spacecraft propulsion that creates thrust by accelerating ions. Ion thrusters are characterized by how they accelerate the ions, using either electrostatic or electromagnetic force. Electrostatic ion thrusters use the Coulomb Force and accelerate the ions in the direction of the electric field. Electromagnetic ion thrusters use the Lorentz Force to accelerate the ions.

Example Technologies
Ion Thruster
Liquid-Based Ion Propulsion
Variable Specific Impulse Magnetoplasma Rocket (VASIMIR)

Relevant Exploration and Constellation Architecture Elements

Orion	☒	Lunar Power	☐
Altair	☒	Surface Mobility	☐
Extra-Vehicular Activity (EVA)	☐	Habitat	☐
ARES and EDS	☒	Launch and Entry Suits	☐
Ground Systems	☐	Surface EVA Suits	☐
Mission Systems	☐	NASA Comm Architecture	☒
ISRU	☐	Crew Health	☐
Robotic Systems	☐	RDT&E / Manufacturing	☐
Lunar Science	☐		

Positive/Negative Impacts to the Architecture

Decreases Cost	☐
Decreases Mass	+
Improves Health and Safety	☐
Lower Power to Operate	☐
Increases Reliability	☐
Improved Performance	+
Increases System Power	☐

How could this be game-changing?

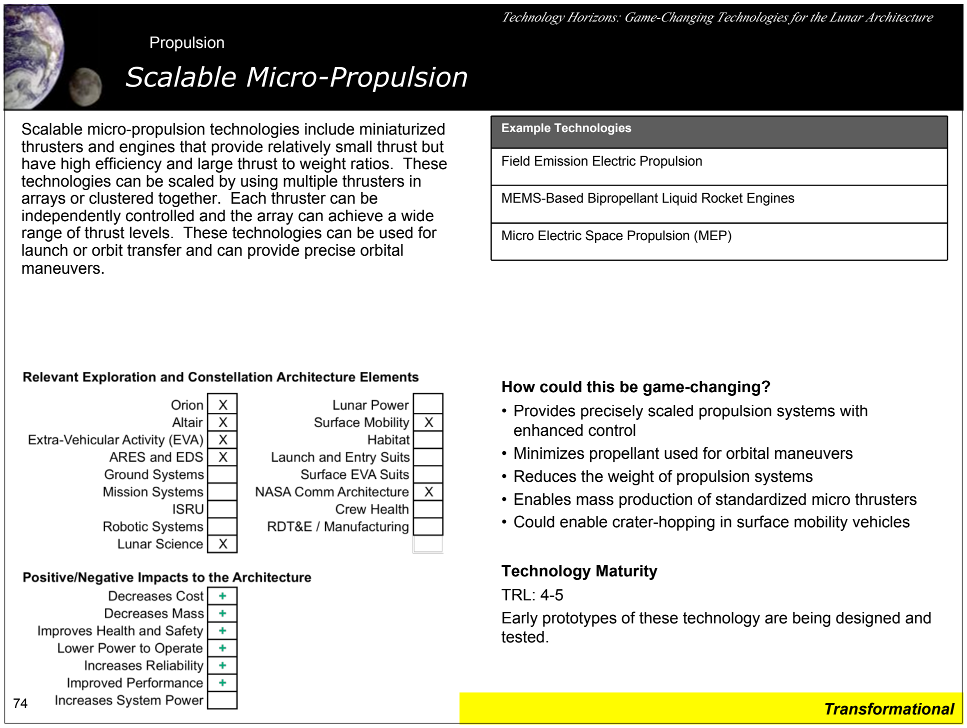
- Increases specific impulse resulting in greater velocity changes with limited propellant
- Reduces the weight of propulsion systems

Technology Maturity

TRL: 4-9

Ion thrusters have been tested and used for satellites. More advanced concepts have been developed, providing increased efficiencies or thrust.

Rapidly-Evolving



Propulsion

Scalable Micro-Propulsion

Scalable micro-propulsion technologies include miniaturized thrusters and engines that provide relatively small thrust but have high efficiency and large thrust to weight ratios. These technologies can be scaled by using multiple thrusters in arrays or clustered together. Each thruster can be independently controlled and the array can achieve a wide range of thrust levels. These technologies can be used for launch or orbit transfer and can provide precise orbital maneuvers.

Example Technologies
Field Emission Electric Propulsion
MEMS-Based Bipropellant Liquid Rocket Engines
Micro Electric Space Propulsion (MEP)

Relevant Exploration and Constellation Architecture Elements

Orion	☒	Lunar Power	☐
Altair	☒	Surface Mobility	☒
Extra-Vehicular Activity (EVA)	☒	Habitat	☐
ARES and EDS	☒	Launch and Entry Suits	☐
Ground Systems	☐	Surface EVA Suits	☐
Mission Systems	☐	NASA Comm Architecture	☒
ISRU	☐	Crew Health	☐
Robotic Systems	☐	RDT&E / Manufacturing	☐
Lunar Science	☒		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	+
Improves Health and Safety	+
Lower Power to Operate	+
Increases Reliability	+
Improved Performance	+
Increases System Power	☐

How could this be game-changing?

- Provides precisely scaled propulsion systems with enhanced control
- Minimizes propellant used for orbital maneuvers
- Reduces the weight of propulsion systems
- Enables mass production of standardized micro thrusters
- Could enable crater-hopping in surface mobility vehicles

Technology Maturity

TRL: 4-5

Early prototypes of these technology are being designed and tested.

Transformational

Robotics

Service Robotics

Robotics

Service Robotics

Highly Rated

Service robotics include single-application robots and related systems (including autonomous vehicles) implemented in a wide range of civil and defense applications. Development of these technologies could offer lessons learned for robotics concepts used across the spectrum of space systems. They would have applications in robotics generally, and in tasks supporting human life in space.

Example Technologies
Service Robotics
Front-End Robotics Enabling Near-term Demonstration (FREND)
Independent Robotic Manufacturing

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)		Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems		NASA Comm Architecture	
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	+
Improved Performance	
Increases System Power	

How could this be game-changing?

- Innovations in service robotics could inform the design of living quarters and operations
- Terrestrial experience with service robotics could change the “culture” of robotic and human relationships

Technology Maturity

TRL: 5-9

A few early examples of commercial service robots can vacuum floors and mow lawns. Products are expected to proliferate.

Revolutionary

Sensors

Advanced Optical Sensor Technologies
Biomimetic Sensor Technologies
Dust Penetrating Sensors
Intelligent Radiation Detectors
Smart Wireless Sensor Networks

Sensors

Advanced Optical Sensor Technologies

Advanced optical sensor technologies include active pixel sensor technologies, terahertz technologies and hyperspectral imagers. Active pixel sensors (APS) have an integrated circuit containing an array of pixel sensors each containing a photodetector and amplifier. These sensors can be used in the same applications as traditional passive sensors but provide improved performance and lower power. Multi-spectral active sensors can provide high precision remote sensing from high orbits and terahertz imaging can image human soft tissue and can identify materials from molecular spectra giving them the ability to detect concealed objects.

Example Technologies
CMOS Active Pixel Sensors
Multi-Spectral Active Optical Sensors
Terahertz Radiation Imaging

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems		NASA Comm Architecture	
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	+
Decreases Mass	
Improved Health and Safety	+
Lower Power to Operate	+
Increases Reliability	+
Improved Performance	+
Increases System Power	

How could this be game-changing?

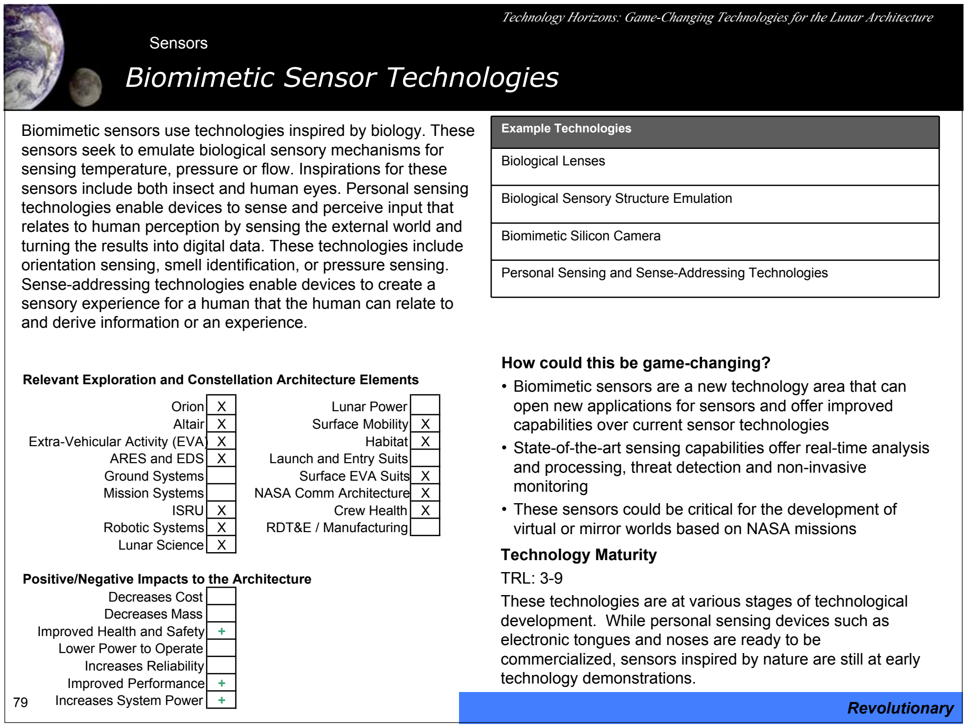
- Advanced optical sensor offer better resolution, low power operation, lower mass, higher speed and simplified operation
- Terhertz imaging can view the soft tissue of the body and concealed objects. It has applications from biosensing to food inspection

Technology Maturity

TRL: 4-8

These technologies are at various stages of development. NASA-sponsored research has developed several applications of CMOS APS. While detectors for terahertz imaging have recently been demonstrated.

Revolutionary



Sensors

Biomimetic Sensor Technologies

Biomimetic sensors use technologies inspired by biology. These sensors seek to emulate biological sensory mechanisms for sensing temperature, pressure or flow. Inspirations for these sensors include both insect and human eyes. Personal sensing technologies enable devices to sense and perceive input that relates to human perception by sensing the external world and turning the results into digital data. These technologies include orientation sensing, smell identification, or pressure sensing. Sense-addressing technologies enable devices to create a sensory experience for a human that the human can relate to and derive information or an experience.

Example Technologies
Biological Lenses
Biological Sensory Structure Emulation
Biomimetic Silicon Camera
Personal Sensing and Sense-Addressing Technologies

Relevant Exploration and Constellation Architecture Elements

Orion ☒
Altair ☒
Extra-Vehicular Activity (EVA) ☒
ARES and EDS ☒
Ground Systems ☐
Mission Systems ☐
ISRU ☒
Robotic Systems ☒
Lunar Science ☒
Lunar Power ☐
Surface Mobility ☒
Habitat ☒
Launch and Entry Suits ☐
Surface EVA Suits ☒
NASA Comm Architecture ☒
Crew Health ☒
RDT&E / Manufacturing ☐

Positive/Negative Impacts to the Architecture

Decreases Cost ☐
Decreases Mass ☐
Improved Health and Safety +
Lower Power to Operate ☐
Increases Reliability ☐
Improved Performance +
Increases System Power +

How could this be game-changing?

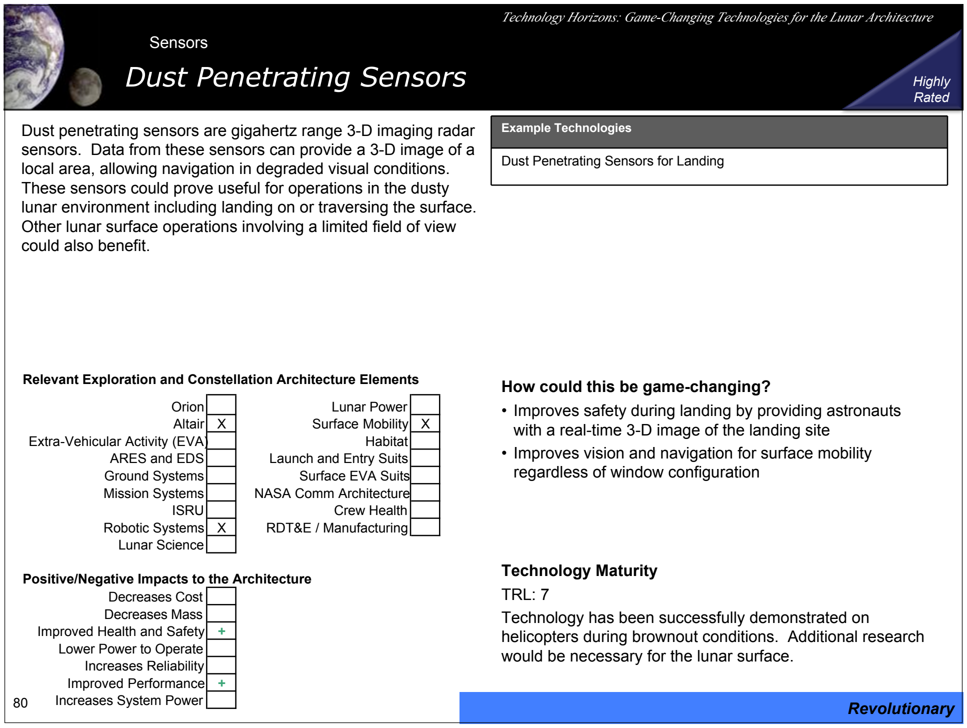
- Biomimetic sensors are a new technology area that can open new applications for sensors and offer improved capabilities over current sensor technologies
- State-of-the-art sensing capabilities offer real-time analysis and processing, threat detection and non-invasive monitoring
- These sensors could be critical for the development of virtual or mirror worlds based on NASA missions

Technology Maturity

TRL: 3-9

These technologies are at various stages of technological development. While personal sensing devices such as electronic tongues and noses are ready to be commercialized, sensors inspired by nature are still at early technology demonstrations.

Revolutionary



Sensors

Dust Penetrating Sensors

Highly Rated

Dust penetrating sensors are gigahertz range 3-D imaging radar sensors. Data from these sensors can provide a 3-D image of a local area, allowing navigation in degraded visual conditions. These sensors could prove useful for operations in the dusty lunar environment including landing on or traversing the surface. Other lunar surface operations involving a limited field of view could also benefit.

Example Technologies
Dust Penetrating Sensors for Landing

Relevant Exploration and Constellation Architecture Elements

Orion ☐
Altair ☒
Extra-Vehicular Activity (EVA) ☐
ARES and EDS ☐
Ground Systems ☐
Mission Systems ☐
ISRU ☐
Robotic Systems ☒
Lunar Science ☐
Lunar Power ☐
Surface Mobility ☒
Habitat ☐
Launch and Entry Suits ☐
Surface EVA Suits ☐
NASA Comm Architecture ☐
Crew Health ☐
RDT&E / Manufacturing ☐

Positive/Negative Impacts to the Architecture

Decreases Cost ☐
Decreases Mass ☐
Improved Health and Safety +
Lower Power to Operate ☐
Increases Reliability ☐
Improved Performance +
Increases System Power ☐

How could this be game-changing?

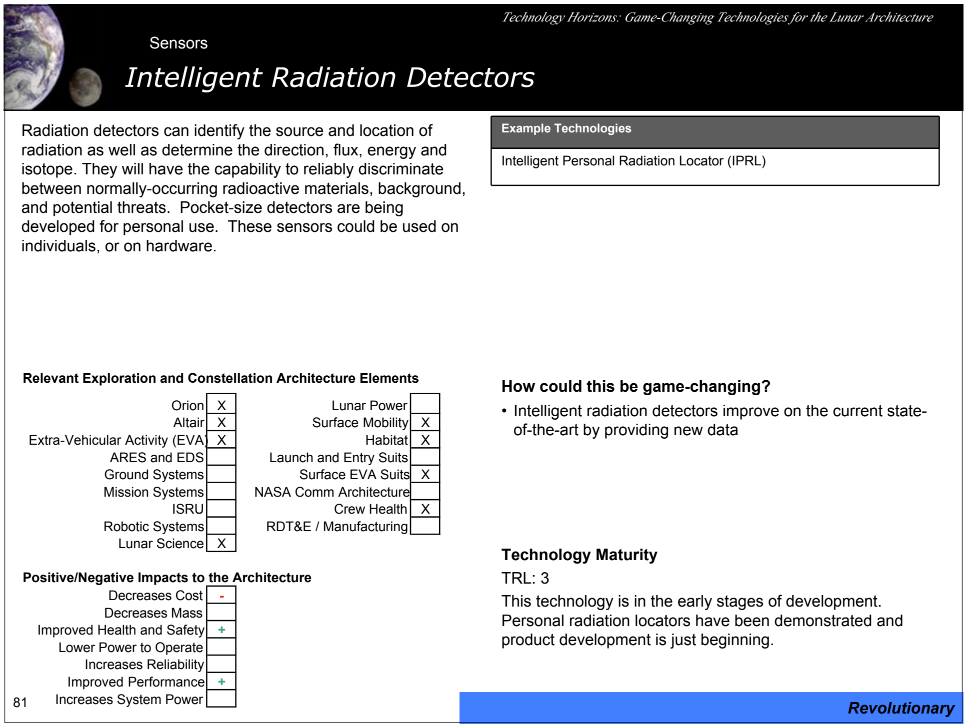
- Improves safety during landing by providing astronauts with a real-time 3-D image of the landing site
- Improves vision and navigation for surface mobility regardless of window configuration

Technology Maturity

TRL: 7

Technology has been successfully demonstrated on helicopters during brownout conditions. Additional research would be necessary for the lunar surface.

Revolutionary



Sensors

Intelligent Radiation Detectors

Radiation detectors can identify the source and location of radiation as well as determine the direction, flux, energy and isotope. They will have the capability to reliably discriminate between normally-occurring radioactive materials, background, and potential threats. Pocket-size detectors are being developed for personal use. These sensors could be used on individuals, or on hardware.

Example Technologies
Intelligent Personal Radiation Locator (IPRL)

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	
ISRU		Crew Health	X
Robotic Systems		RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	-
Decreases Mass	
Improved Health and Safety	+
Lower Power to Operate	
Increases Reliability	
Improved Performance	+
Increases System Power	

How could this be game-changing?

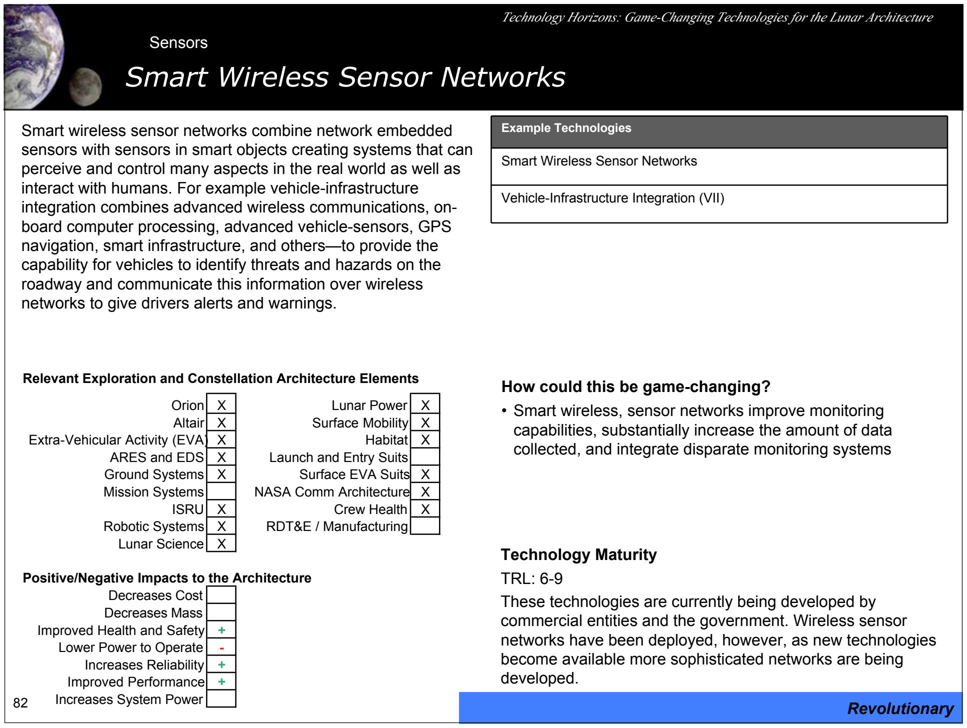
- Intelligent radiation detectors improve on the current state-of-the-art by providing new data

Technology Maturity

TRL: 3

This technology is in the early stages of development. Personal radiation locators have been demonstrated and product development is just beginning.

Revolutionary



Sensors

Smart Wireless Sensor Networks

Smart wireless sensor networks combine network embedded sensors with sensors in smart objects creating systems that can perceive and control many aspects in the real world as well as interact with humans. For example vehicle-infrastructure integration combines advanced wireless communications, on-board computer processing, advanced vehicle-sensors, GPS navigation, smart infrastructure, and others—to provide the capability for vehicles to identify threats and hazards on the roadway and communicate this information over wireless networks to give drivers alerts and warnings.

Example Technologies
Smart Wireless Sensor Networks
Vehicle-Infrastructure Integration (VII)

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems	X	Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	X
ISRU	X	Crew Health	X
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improved Health and Safety	+
Lower Power to Operate	-
Increases Reliability	+
Improved Performance	+
Increases System Power	

How could this be game-changing?

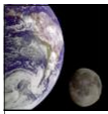
- Smart wireless, sensor networks improve monitoring capabilities, substantially increase the amount of data collected, and integrate disparate monitoring systems

Technology Maturity

TRL: 6-9

These technologies are currently being developed by commercial entities and the government. Wireless sensor networks have been deployed, however, as new technologies become available more sophisticated networks are being developed.

Revolutionary



Thermal Control

Advanced Heat Transfer Materials
Embedded Thermal Control Electronics
Entry Shields
Thermoelectric Materials

Thermal Control

Advanced Heat Transfer Materials

Heat transfer materials are those with a high thermal conductivity. These fluids can be used in heat pipes, to actively cool electronic or mechanical systems. Space systems commonly use ammonia, whereas terrestrial systems typically use water. New materials offer the potential for increased capabilities or reduced mass in NASA space systems.

Example Technologies
Nanoparticle Fluids for Heat Transfer

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	X
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improves Health and Safety	+
Lower Power to Operate	+
Increases Reliability	+
Improved Performance	
Increases System Power	+

How could this be game-changing?

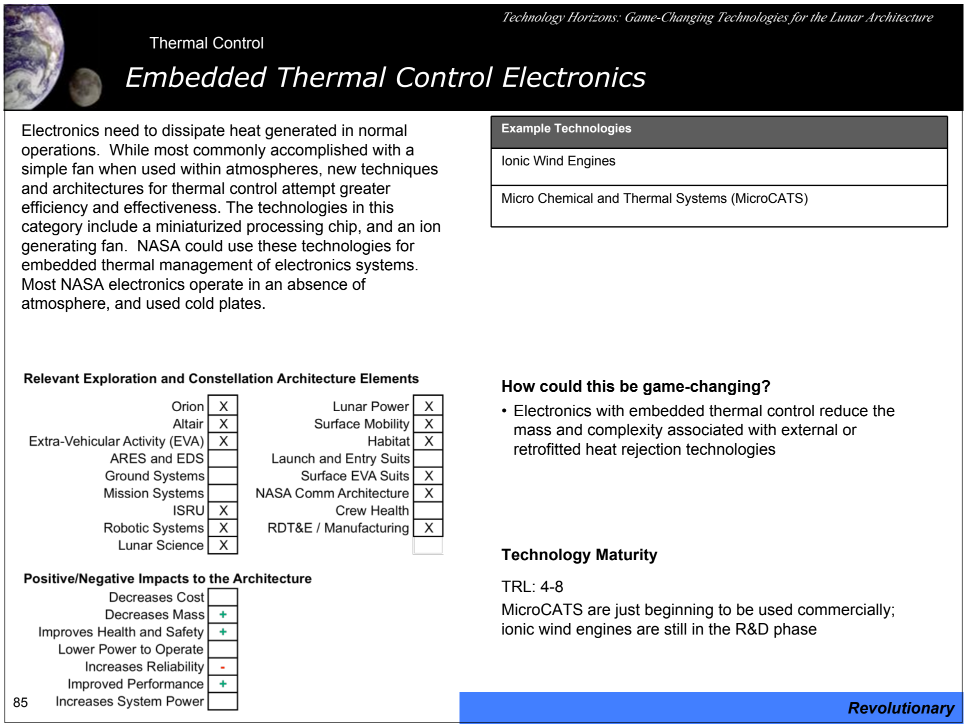
- Improved heat pipe materials increase performance or reduce mass of existing systems
- Early research shows as much as a 50% increase in heat capacity over current state-of-the-art
- Would reduce pump power and mass
- Could save power in ISRU by recycling heat

Technology Maturity

TRL: 4

These fluids are being developed and tested at a number of University centers

Revolutionary



Thermal Control

Embedded Thermal Control Electronics

Electronics need to dissipate heat generated in normal operations. While most commonly accomplished with a simple fan when used within atmospheres, new techniques and architectures for thermal control attempt greater efficiency and effectiveness. The technologies in this category include a miniaturized processing chip, and an ion generating fan. NASA could use these technologies for embedded thermal management of electronics systems. Most NASA electronics operate in an absence of atmosphere, and used cold plates.

Example Technologies
Ionic Wind Engines
Micro Chemical and Thermal Systems (MicroCATS)

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	X
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	+
Improves Health and Safety	+
Lower Power to Operate	
Increases Reliability	-
Improved Performance	+
Increases System Power	

How could this be game-changing?

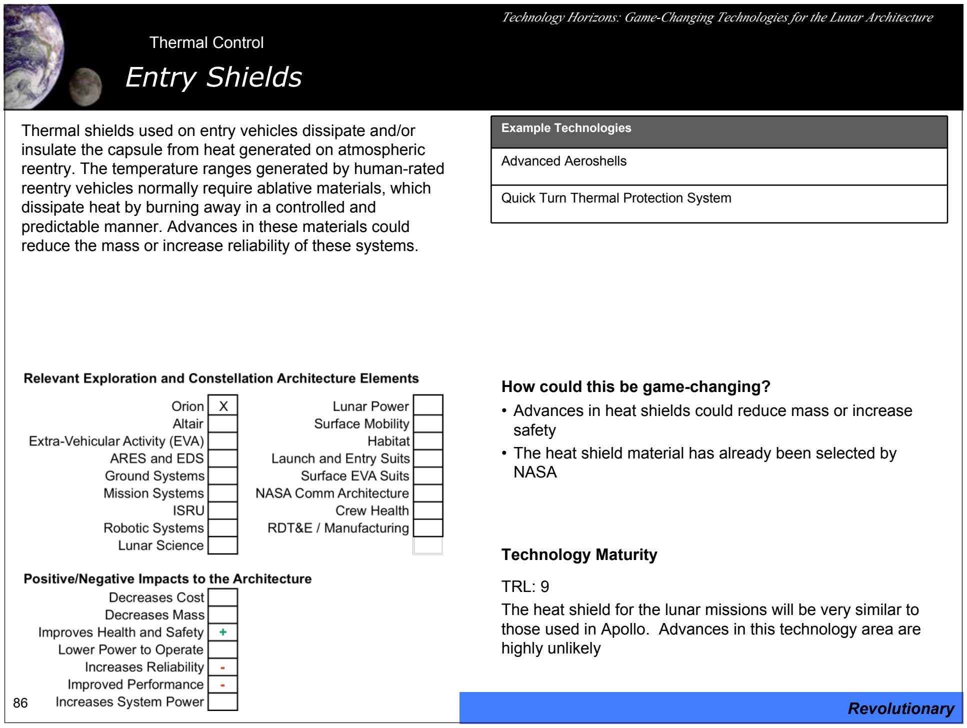
- Electronics with embedded thermal control reduce the mass and complexity associated with external or retrofitted heat rejection technologies

Technology Maturity

TRL: 4-8

MicroCATS are just beginning to be used commercially; ionic wind engines are still in the R&D phase

Revolutionary



Thermal Control

Entry Shields

Thermal shields used on entry vehicles dissipate and/or insulate the capsule from heat generated on atmospheric reentry. The temperature ranges generated by human-rated reentry vehicles normally require ablative materials, which dissipate heat by burning away in a controlled and predictable manner. Advances in these materials could reduce the mass or increase reliability of these systems.

Example Technologies
Advanced Aeroshells
Quick Turn Thermal Protection System

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	
Altair		Surface Mobility	
Extra-Vehicular Activity (EVA)		Habitat	
ARES and EDS		Launch and Entry Suits	
Ground Systems		Surface EVA Suits	
Mission Systems		NASA Comm Architecture	
ISRU		Crew Health	
Robotic Systems		RDT&E / Manufacturing	
Lunar Science			

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improves Health and Safety	+
Lower Power to Operate	
Increases Reliability	-
Improved Performance	-
Increases System Power	

How could this be game-changing?

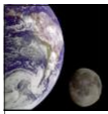
- Advances in heat shields could reduce mass or increase safety
- The heat shield material has already been selected by NASA

Technology Maturity

TRL: 9

The heat shield for the lunar missions will be very similar to those used in Apollo. Advances in this technology area are highly unlikely

Revolutionary



Thermal Control

Thermoelectric Materials

Thermoelectric materials convert heat to electricity; leveraging the Seebeck effect, the Peltier effect, or the Thomson effect. New thermoelectric technologies are generally focused on materials development to increase the efficiency of heat conversion. New technologies structure existing materials to maximize thermoelectric properties, or develop new nano-enabled materials with novel capabilities. NASA could use thermoelectric materials in electronics or propulsion subsystems to capture waste heat as an auxiliary heat source. Thermoelectric materials are also used in radioisotope thermoelectric generators (RTGs).

Relevant Exploration and Constellation Architecture Elements

Orion	X	Lunar Power	X
Altair	X	Surface Mobility	X
Extra-Vehicular Activity (EVA)	X	Habitat	X
ARES and EDS	X	Launch and Entry Suits	
Ground Systems		Surface EVA Suits	X
Mission Systems		NASA Comm Architecture	X
ISRU	X	Crew Health	
Robotic Systems	X	RDT&E / Manufacturing	
Lunar Science	X		

Positive/Negative Impacts to the Architecture

Decreases Cost	
Decreases Mass	
Improves Health and Safety	
Lower Power to Operate	
Increases Reliability	
Improved Performance	+
Increases System Power	+

Example Technologies
Nanostructured Bismuth Antimony Telluride Thermoelectric Material
Solid State Waste Heat Recovery System
Thermoelectric Material -- Lead, Antimony, Silver, Tellurium, and Tin (LAST/T)
Thin-film Superlattice Thermoelectric Materials
Nanovoid Thermoelectric Materials
Skutterudite-Based Thermoelectric Materials

How could this be game-changing?

- Advances in thermoelectric materials increase available power and support heat rejection
- In ISRU situations, these materials could aid heat/power recovery for high temperature systems, or reduce power for water or product separation

Technology Maturity

TRL: 3-9

These materials are well established, but composite and nanostructured materials offer improvements over the current state of the art

Revolutionary

Appendix B: Sources

- National Intelligence Council, Disruptive Civil Technologies, Six Technologies with Potential Impacts on U.S. Interests Out to 2025, 2008
- MIT-NASA Workshop: Transformational Technologies, 2005
- SRI Consulting Business Intelligence, Technology List
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- Defense Intelligence Agency, Avoiding Surprise in an Era of Global Technology Advances, 2005
- The Aerospace Corporation, Advanced Space System Concepts and Technologies: 2010-2030+, 2003
- National Research Council, Space Technology for the New Century, 1998
- Other works:
    - DTIC, 3rd Annual Disruptive Technology Conference, 2006
    - NATO Assessment of Possible Disruptive Technologies for Defense and Security
    - Terry C. Pierce, Warfighting and Disruptive Technologies: Disguising Innovation (London, England: Frank Cass Publishers, 2004)
    - Daniel Talmage, Forecasting Future Disruptive Technologies, http://www8.nationalacademies.org/cp/projectview.aspx?key=48795, in progress

Appendix C: Initial List of Technologies

- >100kW solid-state lasers
- 3-D air traffic control
- 3-D Printing
- 3-D TV
- Affective Computing
- Aging Population
- ALBEDO engineering
- Alternative food production
- Animal BMIs
- Artificial muscles
- Atmosphere seeding
- Augmented reality
- Autonomous and semi-autonomous vehicles
- Biodiesel from algae
- Biofuels and Bio-Based Chemicals
- Biomedical Imaging
- Biometrics
- Biomimetic adhesives
- Bioprinting
- Biorefineries and bioreactors
- Carbon capture
- Carbon nanotubes
- Cellulosic biomass conversion to biofuels
- Clean Coal
- CO2 conversion (to fuels, chemicals etc)
- Coal gassification/liquids
- Commercial UWB radio
- Computer models of humans
- Computer security technology
- Converter chip to enable energy harvesting
- Crowdsourcing Technologies
- Digital money
- Embedded power
- Emotions Technologies
- Energy Storage Materials
- Enhanced geothermal systems
- Event recorders and GPS tracking devices
- Femininization of the Educated Workforce
- Flexible displays
- Gallium Nitride
- Gesture recognition
- Global food supply network
- Glonass
- Graphene
- Green Buildings
- Handheld technologies
- Biogerontechnology
- High voltage DC power transmission
- Human augmentation
- Human Behavioral Modeling
- Human brain-machine interfaces
- Human embryonic stem cells
- Hydrogen infrastructures
- Illegal drug production/detection
- Improved desalination technology, esp. membranes
- Innovative commercial aircraft
- Internet of Things
- Internet recommender software
- and influence engines
- LED illumination
- Machine dialog
- Marine cloud formation
- Massive Data Capturing and Processing
- MEMS/lab-on-a-chip/point-of-care testing
- Metamaterials
- Mirror worlds
- Mixed Reality
- Molecular Electronics
- Molecular Manufacturing
- Nanorobots
- Neurotechnology
- Neurotronics
- Nuclear fusion
- Nuclear power
- Nuclear waste management
- Obesity
- Ocean energy
- OLED lighting
- Online Maps and Cartography
- Optical computing
- Paper-like displays
- Paperless payment/ transaction technology
- People recognition based on RFID and/or machine vision
- Service Robotics
- Plug-in Electric Vehicles
- Popularization of the technology of modern weapons/explosives, and terrain-specific, and adaptive

military tactics
Prediction and forecasting tools
Printed Electronics
Quantum Computing
Quantum-dot light-emitting-diode displays
Quantum-dot solar cells
Renewable energy and resources
Robot Construction
Satellite broadband Internet connections
SED TV
Self-cleaning materials and surfaces
Self-repairing materials
Sensing and sense-addressing technologies
Shape memory plastics
Sleep technology
Smart shelf technology
Smart wireless sensor networks
Subsea technology
Superconducting power
Swarm technology
Synthetic Biology
Synthetic biology for improved biofuels
Systems Biology
Telepresecnce
Terahertz radiation/detection
Thin-film Solar Cell Technology
Tissue engineering/ regenerative medicine
Translation devices
Ubiquitous positioning
Ultrasound diagnostics and treatment
Ultrasound processing
Vaccines
Vehicle-Infrastructure Integration (VII)
Vehicle-to-vehicle (V2V) communications
Very light jets
Video recognition
Virtual worlds
Wireless charging technology
Robust Autonomous Systems that are Self Aware
Next Generation On-Orbit, Surface, and Subsurface Robotic Systems
Micro Chemical and Thermal Systems (MicroCATS)
Collective Vision for Optical Technology
Modular Stability Tools for Distributed Computation and Control
Why Cutting Paths are Different from Robotic Paths: Sensor and Navigation
Avogadro-Scale Engineering
Staged Development of Complex Systems
Extensibility in Space Transportation
Modular Reusable Space Architecture
Lean Aerospace Initiative
Safety Engineering Environments
Using the ISS as an Engineering Technology Research Laboratory for Space-Based Telescopes
Advanced Nuclear Technology for Space Exploration
Nuclear Technology for Project Prometheus
MEMS-Based Bipropellant Liquid Rocket Engines
Laser Propulsion Systems
Advanced Plasma Propulsion
Electromagnetic Formation Flight
Electric Propulsion Testbed on the ISS New Space
New Space Communications Architectures
Alternative Concepts for Communications
Communications Technologies for Space
Peer-to-Peer Networks
Quantum-dot solar cells
Metamaterials
Personalized Medical Monitors
Single-Cell Analysis
Optical Antennas for Computing
Neuron Control
Nanohealing
Compressive Sensing
Augmented Reality
Surprise Modeling
Probabilistic Chips (PCMOS)
NanoRadio
Wireless Electricity
Atomic Magnetometers
Offline Web Applications
Graphene Transistors
Connectomics
Reality Mining
Cellulolytic Enzymes
Biosecurity
Nanotechnology
Neurotechnology
Computational Imaging
Quantum Computing

High value manufacturing
Advanced materials.
--Structural materials.
--Functional materials.
--Multi-functional materials.
--Biomaterials.
--Cross cutting areas
Nanotechnology.
Bioscience.
Electronics, photonics and electrical systems.
Information and communication technology.
A new space robot end-effecter for on-orbit reflector assembly
A new concept of synthetic aperture instrument for High Resolution Earth Observation from high orbits
Deployable hexapod using tape-springs
Silicon Carbide technology: a revolution for space optical payloads
Magnetic actuator in space and application for high precision formation flying
Micro-thrust measurement and drag free on ground test
Gossamer space structures : a technology leap
Fuzzy logic controller for small satellites navigation
Reconfigurable computing architecture for on-board image processing
Very high-performance embedded computing will allow ambitious space science investigation
CMOS snapshot active pixel sensor for spaceborne Earth observation applications
High-end CMOS active pixel sensors for space-borne imaging instruments
The CMOS breakthrough for space optical detection: recent advances and short term perspectives
Recent breakthrough in high-speed photon detectors, THz mixers and quantum information processing circuits in LTS and HTS superconductors
New technological developments for far infrared bolometer arrays
Large-format science-grade monolithic CMOS active pixel sensor for extreme ultra violet spectroscopy and imaging
A single-chip CDS and 16 bit ADC CCD video processing ASIC
Low noise, low power sensor interface circuits for spectroscopy in standard CMOS technology operating at 4k
Ion thruster systems
Fusion reactions and matter-antimatter annihilation for space propulsion
Cryogenic and LOX based propulsion systems for robotic planetary missions
High power electric propulsion system for NEP
Helium high pressure tanks at EADS Transportation. New technology with thermoplastic liner
Optical wireless communications onboard the spacecraft
Optical free space communications open new borders for future civilian and defense systems
Low phase noise fiber optic links for space applications
Diffuse optical data bus development for spacecraft (IRCOMM)
High-throughput optical interconnect technology for future on-board digital processors
High-throughput optical interconnect technology for future on-board digital processors
Automatic in-flight repair of FPGA cosmic ray damage
Potentialities of HTS superconductor technology in domain of telecommunication satellites
NBN Josephson and tunnel junctions for space THz observation and signal processing
Potential impacts of micro and nano technologies on space transportation systems
Comparative Interactomics
Nanomedicine
Epigenetics
Cognitive Radio
Nuclear Reprogramming
Diffusion Tensor Imaging
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Brain/Neurologics
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Superempowered Individuals
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Biotechnology

Energetics
Quantum Physics
Digital Swarming
Motion Displays Fusion
Fuel Cell Power Systems
Advanced Capability Electric Propulsion
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Direct Contact Miniature Medical Sensor with Wireless Transmission
Nano-fiber Bleeding Sensor: Multifunctional Sensing Textiles
Nano-fiber Bleeding Sensor: Integrated Sensing and Silicon Circuitry
Nano-fiber Bleeding Sensor and Clotting Agent: Mechanically Active Textiles
Coordination Tools for Autonomous Vehicle Teams
Self-healing Materials, Polymers
Nano Composite Solar Cell
Inorganic Semiconductor Nanorods
Micro-scale Fuel Cell--Catalytic Micro-combustors
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Tunable Synthetic Aperture Radar
Metal Organic Framework-177
Intelligent Personal Radiation Locator (IPRL)
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Adaptive Wing Structures
Biological Sensory Structure Emulation
Biological Lenses
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Trauma Pod
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