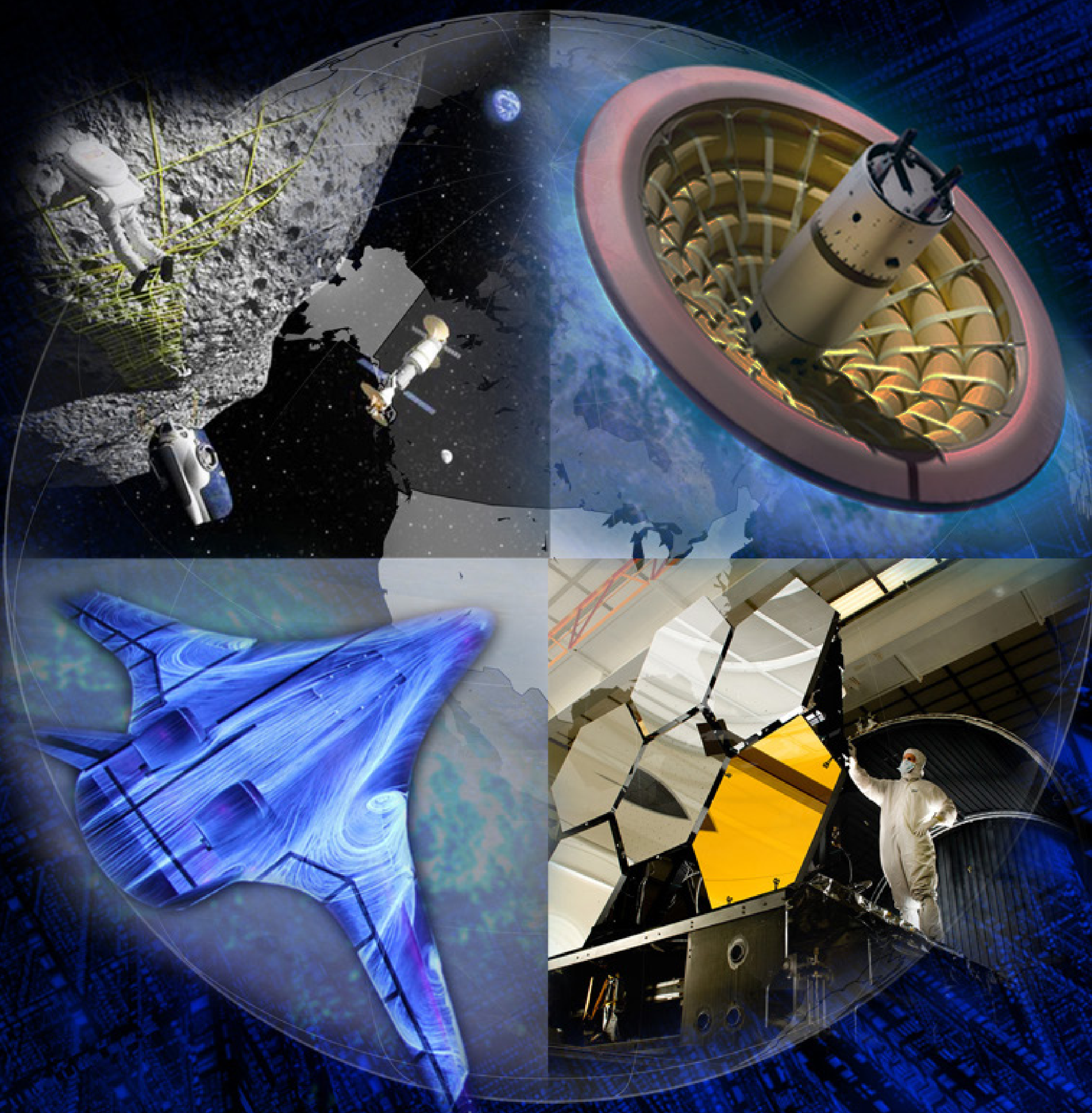
National Aeronautics and Space Administration

NASA Technology Roadmaps
TA 3: Space Power and Energy Storage



May 2015 Draft

Foreword

NASA is leading the way with a balanced program of space exploration, aeronautics, and science research. Success in executing NASA's ambitious aeronautics activities and space missions requires solutions to difficult technical challenges that build on proven capabilities and require the development of new capabilities. These new capabilities arise from the development of novel cutting-edge technologies.

The promising new technology candidates that will help NASA achieve our extraordinary missions are identified in our Technology Roadmaps. The roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years. The roadmaps are a foundational element of the Strategic Technology Investment Plan (STIP), an actionable plan that lays out the strategy for developing those technologies essential to the pursuit of NASA's mission and achievement of National goals. The STIP provides prioritization of the technology candidates within the roadmaps and guiding principles for technology investment. The recommendations provided by the National Research Council heavily influence NASA's technology prioritization.

NASA's technology investments are tracked and analyzed in TechPort, a web-based software system that serves as NASA's integrated technology data source and decision support tool. Together, the roadmaps, the STIP, and TechPort provide NASA the ability to manage the technology portfolio in a new way, aligning mission directorate technology investments to minimize duplication, and lower cost while providing critical capabilities that support missions, commercial industry, and longer-term National needs.

The 2015 NASA Technology Roadmaps are comprised of 16 sections: The Introduction, Crosscutting Technologies, and Index; and 15 distinct Technology Area (TA) roadmaps. Crosscutting technology areas, such as, but not limited to, avionics, autonomy, information technology, radiation, and space weather span across multiple sections. The introduction provides a description of the crosscutting technologies, and a list of the technology candidates in each section.

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Executive Summary

This is Technology Area (TA) 3: Space Power and Energy Storage, one of the 16 sections of the 2015 NASA Technology Roadmaps. The Roadmaps are a set of documents that consider a wide range of needed technologies and development pathways for the next 20 years (2015-2035). The roadmaps focus on "applied research" and "development" activities.

Many state of the art (SOA) power systems are too heavy, bulky, or inefficient to meet future mission requirements, and some cannot operate in some extreme environments. The technology developments presented in this roadmap can produce power systems with significant mass and volume reductions, increased efficiency, and capability for operation across a broad temperature range and in intense radiation environments. The different components of a power system—power generation, energy storage, and power management and distribution (PMAD)—each require technological improvements to meet these requirements. Most of the power technologies discussed in this roadmap are used, in some form, on current crewed or robotic missions. These technologies need incremental and unique improvements in performance and mission durability in order to enable or enhance the missions currently in NASA's plans. However, in a circumstance that is unique for the power and propulsion TAs (TA 1 Launch Propulsion Systems, TA 2 In-Space Propulsion Technologies, and TA 3 Space Power and Energy Storage), there are some low technology readiness level (TRL) power technologies that could (often when integrated with certain advanced propulsion technologies) offer NASA radically improved mission capabilities.

Goals

Power systems are enabling for every robotic and crewed mission, for both science and human exploration. They typically comprise up to a third of a spacecraft's mass. Power systems are made up of power generation, energy storage, and PMAD subsystems. Any technology improvement that reduces the mass needed for a given power level enhances all missions using that technology and in many cases enables a mission. Other power system attributes that can enable missions include affordable life cycle; design, development, test, and evaluation (DDT&E) and modular hardware cost for new systems; potential for reuse on other missions; conversion efficiency; volumetric energy density; robust operation in deep space or surface environments; and effective integration with other systems.

The top-level goals for power systems that drive electric propulsion are an increase in power capability from tens of kilowatts (kW) to multiple megawatts (MW) and a simultaneous reduction in specific mass from tens of kilograms (kg)/kW_e down to single digit kg/kW_e. These top-level goals may be met by different combinations of subsystem sub-goals, such as an increase in heat engine conversion efficiency toward 50 percent, an increase in photovoltaic (PV) conversion efficiency toward 50 percent, an increase in power electronics conversion efficiency to greater than 95 percent, and an increase in operating temperature for power electronics to 300o Celsius (C). Sub-goals for 100 W_e to 500 W_e radioisotope power systems center on increasing specific power from today's 3 W_e/kg up to 8 W_e/kg, with far-term disruptive technologies that could achieve more than 200 W_e/kg. Additional sub-goals for photovoltaics and power electronics include tolerance to Jovian radiation levels. Further, reducing the cost of very high power solar arrays for electric propulsion is crucial, as is developing inherently safe batteries with very high specific energy.

A key consideration of all of these goals is to ensure that if one performance metric is improved, all other mission requirements are still met. For example, a technology that reduces the mass of the power system, but also decreases safety or reliability, or significantly increases mission cost, may not enhance the mission and may not be adopted by mission planners.

Table 1. Summary of Level 2 TAs

3.0 Space Power and Energy Storage	Goals:	Develop power systems with significant mass and volume reductions, increased efficiency, and capability for operation across a broad temperature range and in intense radiation environments.
3.1 Power Generation	Sub-Goals:	Provide the highest possible specific power with sufficient durability in the mission environment.
3.2 Energy Storage	Sub-Goals:	Store energy at the highest possible specific energy with sufficient durability in the mission environment and, in the case of rechargeable storage, sufficient cycle life.
3.3 Power Management and Distribution	Sub-Goals:	Reliably support high-power electric propulsion missions into deep space. Support low-power operations in extreme environments such as the Venus surface.
3.4 Cross Cutting Technologies	Sub-Goals:	Cross Cutting Technologies are referred to in other technology roadmaps.

Benefits

Technology advances in space power and energy storage offer significant benefits to spacecraft, launch vehicles, landers, rovers, spacesuits, tools, habitats, communication networks, and anything that requires power and energy. New missions are enabled when a breakthrough in power generation or energy storage is attained. For instance, if a novel photovoltaic system is developed that can operate in low-intensity, low-temperature conditions, space systems can be solar powered farther from the sun. If a nuclear power system is developed that, along with a high-power electric thruster, is cost effective and lightweight, human space exploration will not depend on solar energy; and short-duration missions to Mars and beyond could be enabled. Scientific understanding of the outer planets also could be rapidly advanced. Incrementally improved power systems enable in-situ resource utilization (ISRU) systems for operations on lunar and planetary surfaces. They enable more efficient use of expensive radioisotope and fission energy sources and thereby enable more science missions in deep space. They enhance the capabilities of crewed exploration vehicles (for low-Earth orbit (LEO), high-Earth orbit (HEO), near-Earth asteroids (NEAs), and Mars missions) and crewed surface habitats. Advances in power system durability and life enable missions in intense radiation and extreme temperature environments (e.g., Venus, Europa, Mars polar, and lunar polar science missions). Miniaturization of power systems, improving impact tolerance for landing, and creating novel power system architectures enables nanosatellites and small planetary probes. Advanced power and energy storage technology can enable missions that are limited only by our imagination.

Space power technology also offers benefits to other national needs. These include systems such as unmanned aerial vehicles (fuel cells, batteries, wireless power transmission), unmanned underwater vehicles (batteries, fuel cells, PMAD), and soldier-portable power systems (PV, batteries, wireless power, PMAD). Another visible national need is for energy independence and green energy. NASA's work on batteries, fuel cells, and power management could yield spin-offs to all-electric and hybrid automobiles. Grid-scale energy storage systems would benefit from improved batteries, electrolyzers, fuel cells, flywheels, and PMAD. Novel systems would include waste heat utilization (i.e., energy harvesting) using thermoelectric materials to further improve energy efficiency. The "Smart Grid" would take advantage of PMAD and analytical tools developed to design planetary outpost power systems, and terrestrial solar power systems would benefit from high-efficiency solar cells, advanced arrays, solar concentrators, and Stirling convertors. Remote, off-grid power systems could be patterned after NASA's crewed vehicles and habitats.

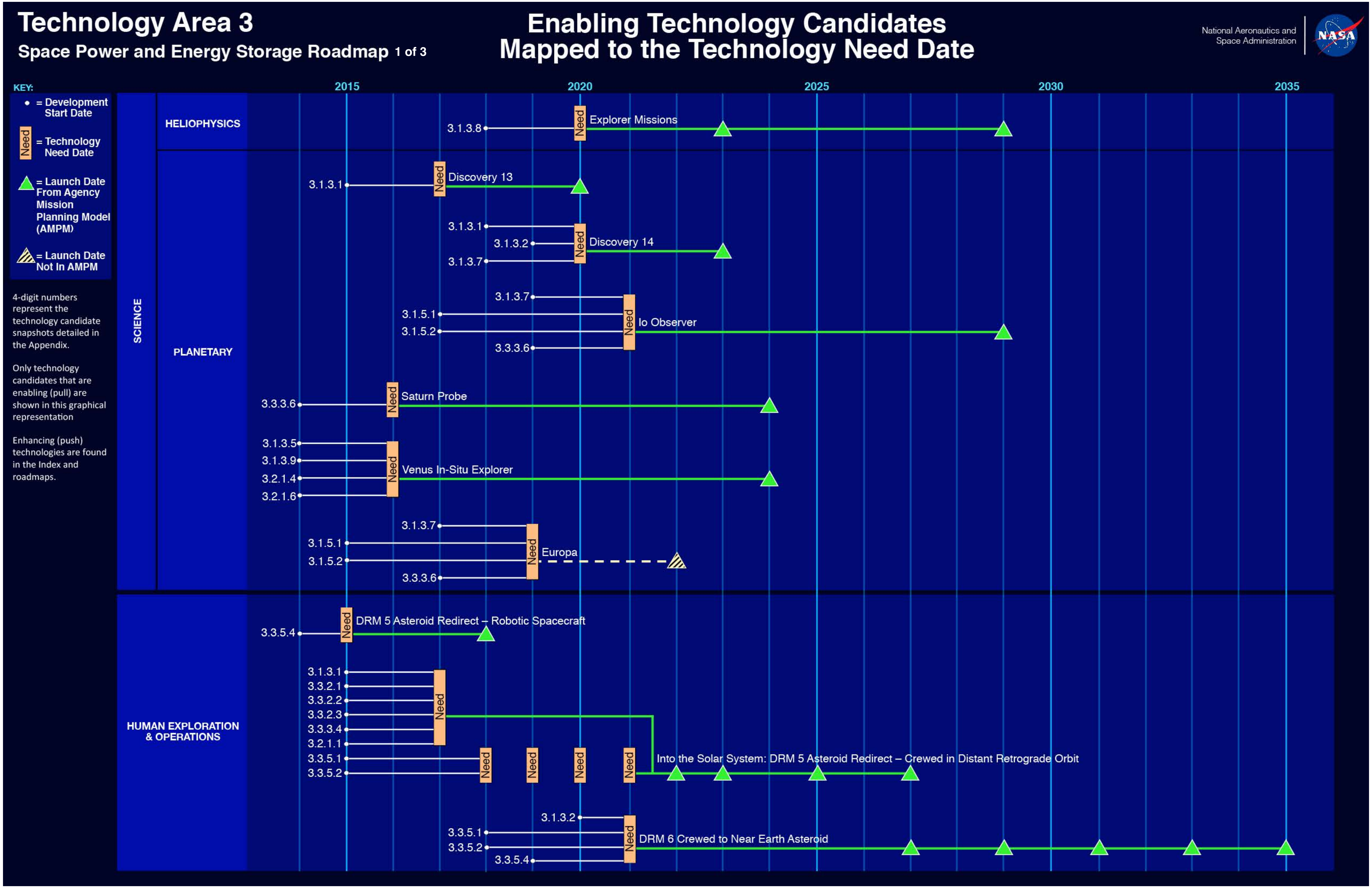


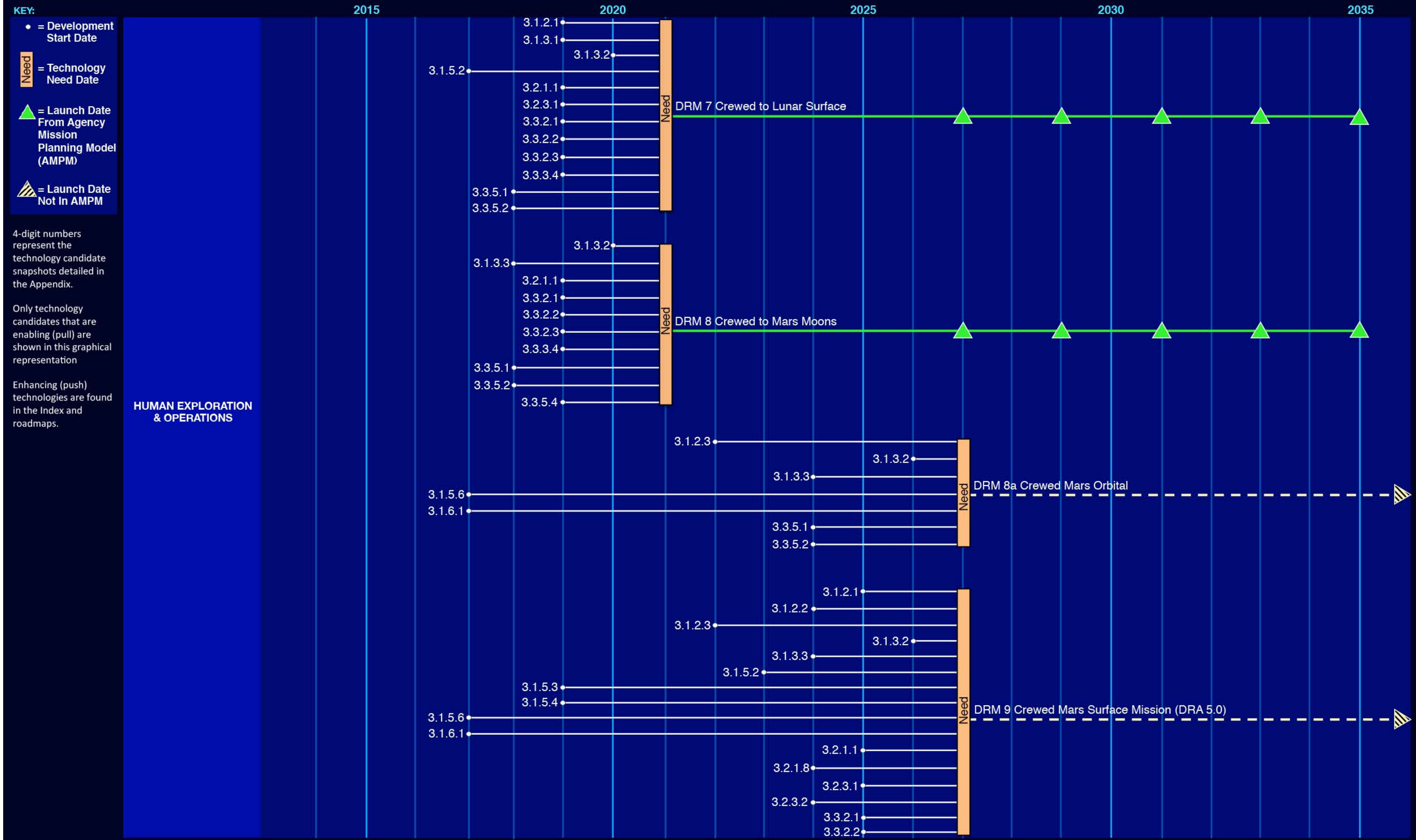
Figure 1. Technology Area Strategic Roadmap

Technology Area 3

Space Power and Energy Storage Roadmap 2 of 3

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration



4-digit numbers represent the technology candidate snapshots detailed in the Appendix.

Only technology candidates that are enabling (pull) are shown in this graphical representation

Enhancing (push) technologies are found in the Index and roadmaps.

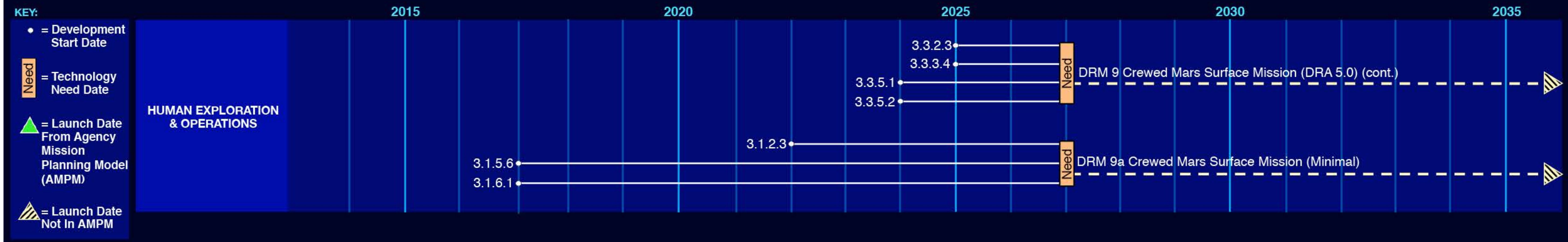
Figure 1. Technology Area Strategic Roadmap (Continued)

Technology Area 3

Space Power and Energy Storage Roadmap 3 of 3

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration



4-digit numbers represent the technology candidate snapshots detailed in the Appendix.

Only technology candidates that are enabling (pull) are shown in this graphical representation

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Figure 1. Technology Area Strategic Roadmap (Continued)

Introduction

The purpose of this document is to describe the state of the art in space power and energy storage technologies and formulate a technology roadmap that can guide NASA's developments to assure the timely development and delivery of innovative and enabling power and energy storage systems for future space missions. The major power subsystems are: (1) Power Generation, (2) Energy Storage, and (3) Power Management and Distribution (PMAD). Technology development efforts are identified as either "enabling," which are advancements that have been identified by architectural studies of planned missions as being necessary to enable those missions, or "enhancing," which are either incremental technology advancements that may lower the cost of or augment the capabilities of a class of missions, or disruptive advancements that may enable entirely new and vastly more capable mission architectures.

This roadmap lays out general technical approaches for advancing the state of the art in power generation, energy storage, and PMAD toward NASA's needs. Crosscutting technology areas (TAs) are addressed in other TA roadmaps. The Technology Area Breakdown Structure (TABS) for Space Power and Energy Storage is shown in Figure 2.

TA 3 — **Space Power and Energy Storage**

3.1	3.2	3.3	3.4
Power Generation	**Energy Storage**	**Power Management and Distribution**	**Cross Cutting Technology**
3.1.1 Energy Harvesting	**3.2.1** Batteries	**3.3.1** Fault Detection, Isolation, and Recovery	3.4.1 Analytical Tools
3.1.2 Chemical	**3.2.2** Flywheels	**3.3.2** Management and Control	3.4.2 Green Energy Impact
3.1.3 Solar	**3.2.3** Regenerative Fuel Cells	**3.3.3** Distribution and Transmission	3.4.3 Multi-Functional Structures
3.1.4 Radioisotope	**3.2.4** Capacitors	**3.3.4** Wireless Power Transmission	3.4.4 Alternative Fuels
3.1.5 Fission		**3.3.5** Conversion and Regulation	
3.1.6 Fusion			

Figure 2. Technology Area Breakdown Structure Technology Areas for Space Power and Energy Storage

NASA's technology area breakdown structure (TABS) is in wide use in technology organizations around the globe. Because of this, any sections that were previously in the structure have not been removed, although some new areas have been added. Within these roadmaps, there were some sections of the TABS with no identified technology candidates. This is either because no technologies were identified which coupled with NASA's mission needs (either push or pull) within the next 20 years, or because the technologies which were previously in this section are now being addressed elsewhere in the roadmaps. These sections are noted in gray above and are explained in more detail within the write-up for this roadmap.

3.1 Power Generation

Power generation subsystems include solar arrays, radioisotope power generators, fission and fusion nuclear reactors, and fuel cells. This area includes methods of generating power from chemical, solar, and nuclear sources, along with the corresponding energy conversion and harvesting technologies. These technologies are grouped into the following general categories:

- **3.1.1 Energy Harvesting:** Also known as power harvesting or energy scavenging, energy harvesting involves obtaining power from sources that are used for other purposes (e.g., waste heat utilization).
- **3.1.2. Chemical:** Chemical power sources relevant to NASA's future power needs include fuel cells, which harness electrochemical redox reactions.
- **3.1.3 Solar:** Solar power technologies relevant to NASA's needs focus on photovoltaic cells and the associated mechanical and structural technologies for the array.
- **3.1.4 Radioisotope:** The power needs of NASA's science missions may be met by certain energy conversion technologies (thermoelectric and Stirling) at a range of power levels, all harnessing decay energy from the plutonium-238 (^{238}Pu) radioisotope. Alphavoltaic direct conversion of decay energy may yield a disruptive increase in capability for these missions.
- **3.1.5 Fission:** Applications of fission with thermoelectric or Stirling heat engine conversion at a ~1 kW_e power level support NASA's science missions, while small 1-10 kW_e fission systems and larger 10-100 kW_e fission systems are needed for Mars surface missions. Also, multi-MW_e systems are promising options for advanced propulsion vehicles to support human exploration missions.
- **3.1.6 Fusion:** Harnessing aneutronic fusion reactions with direct energy conversion could yield a disruptive increase in capability for human exploration missions.

3.2 Energy Storage

The electric energy storage options for space missions include batteries, regenerative fuel cells, and flywheels. This area considers these methods of storing energy after it has been generated from solar, chemical, and nuclear sources if the energy is not needed immediately.

- **3.2.1 Batteries:** Advancements in lithium-based and other battery chemistries (both primary and secondary and particularly in terms of specific energy and safety) are required to support the broad range of NASA missions: science, human exploration, and aeronautics.
- **3.2.2 Flywheels:** Once materials challenges are met, flywheel technology can offer energy storage density on par with chemical batteries with much higher cycle life. They can also offer spacecraft a novel system for combining attitude control (replacing momentum wheels) and energy storage (replacing batteries), reducing the overall mass of the combined systems.
- **3.2.3 Regenerative Fuel Cells:** Regenerative fuel cell technology, in either solid oxide or proton exchange membrane chemistry, offers large-scale energy storage at specific energy levels well beyond that possible with chemical batteries.
- **3.2.4 Capacitors:** A capacitor is a passive, two-terminal electrical component used to store energy electrostatically in an electric field. Capacitors can provide pulse power capability at low temperatures for spacecraft and avionics.

3.3 Power Management and Distribution

The electric energy storage options for space missions include batteries, regenerative fuel cells, and flywheels. This area considers these methods of storing energy after it has been generated from solar, chemical, and nuclear sources if the energy is not needed immediately.

- **3.3.1 Fault Detection, Isolation, and Recovery (FDIR):** FDIR technologies include the control algorithms, models, and sensors needed to detect, isolate, and repair systems failures. These are considered in TA 3.3.2 along with other system Management and Control technologies.
- **3.3.2 Management and Control:** This area includes the control algorithms, models, and sensors needed to control a spacecraft or aircraft power bus.
- **3.3.3. Distribution and Transmission:** This area includes the switchgear, wiring, and other passive components necessary for electric power transmission. Certain NASA missions require improvements in high-temperature and radiation tolerance in these subsystems, and advances in carbon nanotube wiring would enhance many NASA missions.
- **3.3.4 Wireless Power Transmission:** This area describes needed enhancements in short-range, low-power wireless power transmission for battery charging and instrumentation and in longer range, high-power surface element applications.
- **3.3.5 Conversion and Regulation:** This area describes needed improvements in temperature and radiation tolerance and voltage capability required by NASA missions for capacitors and power electronics semiconductors.

3.4 Cross Cutting Technologies

Cross cutting technologies are complementary to the power and energy storage technologies while not being directly in line with delivery of an advanced power system itself. These technologies can be grouped into the following general categories:

- **3.4.1 Analytical Tools:** Power systems engineering uses analytical tools that are not fundamentally different than those in other disciplines.
- **3.4.2 Green Energy Impact:** This area describes enhancements needed in aviation fuels to mitigate environmental impacts.
- **3.4.3 Multi-Functional Structures:** Multi-functional structures can include materials that enable electric current to be carried or electrical energy to be stored.
- **3.4.4 Alternative Fuels:** This area describes options for more efficient aviation fuels.

TA 3.1: Power Generation

Power generation subsystems include such technologies as photovoltaic arrays, radioisotope power generators, fission and fusion nuclear reactors, and fuel cells. This area identifies the methods of generating power from chemical, solar, and nuclear sources, as well as energy conversion and harvesting technology. The state of the art for each of the energy source technologies varies widely.

Sub-Goals

The primary sub-goal for any space power generation technology is to provide the highest possible specific power with sufficient durability in the mission environment. The limitations on this capability are generally driven by the limitations of the energy source itself. For example, the maximum specific power possible from a solar array decreases with the square of the spacecraft's distance from the Sun. The specific power of a fission system is limited by the Carnot efficiency associated with the maximum operating temperature of the nuclear fuel elements and by the maximum heat rejection temperature available to the radiators.

Materials generally drive limitations on the durability of a power generation system. For example, the durability of a solar array is driven in part by the effect of space radiation on the photovoltaic cells. Such environments vary widely among missions and thus can drive technology developments in different directions. One cannot develop a single power generation solution that meets the requirements of all of NASA's space missions, and some missions require power generation technologies that are entirely unique.

Table 2. Summary of Level 3.1 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
3.0 Space Power and Energy Storage	Goals:	Develop power systems with significant mass and volume reductions, increased efficiency, and capability for operation across a broad temperature range and in intense radiation environments.
Level 2		
3.1 Power Generation	Sub-Goals:	Provide the highest possible specific power with sufficient durability in the mission environment.
Level 3		
3.1.1 Energy Harvesting	Objectives:	Produce multi-kW power over a period of years in Earth or Jovian orbit.
	Challenges:	Durability of tether material.
	Benefits:	Produces energy for orbiting spacecraft for missions of indefinite length.
3.1.2 Chemical	Objectives:	Reliable operation using oxygen (O_2) and hydrogen (H_2) or methane (CH_4) for 10,000 hours with high efficiency.
	Challenges:	Balance-of-plant components (regulators, valves, circulation pumps). Operation with reactants stored at gas at up to 2,000 pounds per square inch (psi) or as cryogens. Durability during thermal cycling and high efficiency operation when operating with hydrocarbon fuels.
	Benefits:	Enables reliable, Sun-independent electrical power generation for crew transportation systems and surface systems.
3.1.3 Solar	Objectives:	Increased specific mass and stowed volume efficiency, low cost, radiation tolerance, with good low intensity, low temperature (LILT) and high intensity, high temperature (HIHT) performance.
	Challenges:	Effective operation in the vicinity of the plasma generated by the electric thrusters used for solar electric propulsion (SEP), while passing through the Van Allen Belt perhaps numerous times, in intense radiation environments, and while operating at high voltages.
	Benefits:	Enables the use of SEP to cost-effectively carry cargo and/or crew for human exploration missions to Mars. Enables higher power delivery to inner and outer planetary missions thus increasing the number or capability of science missions. Enhances the manufacture of fuels and water in-situ for lunar and Mars surface missions.

Table 2. Summary of Level 3.1 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
3.1.4 Radioisotope	Objectives:	Increase conversion efficiency to improve the total power level, specific power, and efficiency of radioisotope systems.
	Challenges:	Reliability and durability in energy conversion systems.
	Benefits:	Radioisotope power systems (RPSs) in the 0.1–1,000 W_e power range enable advanced science missions, new capabilities, and support human exploration missions, including long-life subsurface probes; high specific power RPSs enable radioisotope electric propulsion for deep-space missions.
3.1.5 Fission	Objectives:	Develop multi-kW fission power systems for science and exploration. Develop multi-MW fission power for in-space propulsion.
	Challenges:	High-temperature reactor fuels and materials; high-temperature, high-efficiency power conversion; lightweight, high-temperature radiators; and integration into a safe, reliable, affordable system.
	Benefits:	High-power fission systems (MW-class) can benefit nuclear electric propulsion missions, potentially including cargo and crewed missions to Mars, and other destinations.
3.1.6 Fusion	Objectives:	Develop aneutronic fusion (p-^{11}B) reactors with direct power conversion for high-energy charged particle product beams, and high-voltage (~1 MV), high-efficiency PMAD.
	Challenges:	Stable confinement of plasmas with ions of sufficient energy to produce high-energy yield. Traveling wave direct energy conversion (TWDEC) for direct conversion of high-energy alpha particles produced in the fusion reactions.
	Benefits:	Aneutronic fusion offers in-space power at low specific mass with no neutron shielding requirements and no generation of radioactive waste, thus enabling rapid exploration missions to Mars and beyond.

TA 3.1.1 Energy Harvesting

Technical Capability Objectives and Challenges

This area treats methods of harvesting electric power, often at mW levels, from the space environment for use on CubeSat class vehicles. A range of technologies is considered in this area, from electrodynamic tethers to scavenged energy from a planetary magnetic field to low temperature thermoelectrics to convert low quality waste heat to electricity.

In the example of the electrodynamic tether, a 20 kilometer (km) tethered satellite system experiment has demonstrated > 2 kW power generation in LEO.

The objective for electrodynamic tether technology is to produce, for a period of years, multi-kW power with a 1 km tether at ~1 amp (A) in the Earth magnetosphere or 5 A in the Jovian magnetosphere. The primary challenge for this is the durability of the tether material.

Benefits of Technology

Electrodynamic tethers can produce energy for orbital spacecraft for missions of indefinite length.

Table 3. TA 3.1.1 Technology Candidates – not in priority order

TA	Technology Name	Description
3.1.1.1	Electrodynamic Tether Energy Harvesting	An electrodynamic tether is essentially a long conducting wire extended from a spacecraft. The gravity gradient field pulls the tether taut and tends to orient the tether along the vertical direction. As the tether orbits around the Earth (or other planet), it crosses the body's magnetic field lines at orbital velocity (7 to 8 kilometers per second). The motion of the conductor across the magnetic field induces a voltage along the length of the tether. This voltage, which is called the "motional electromagnetic force (EMF)," can be up to several hundred volts per kilometer. Within the ionosphere, free electrons are collected by the tether, producing useful power of up to several kilowatts at the expense of the spacecraft orbital altitude, from which the energy is derived.

TA 3.1.2 Chemical

Technical Capability Objectives and Challenges

This area discusses hydrogen-oxygen and hydrocarbon-oxygen fuel cells used to generate electrical power for crewed spacecraft and surface mobility systems. Fuel cells generally provide the maximum specific energy solution for crewed spacecraft (non-propulsion) loads when solar power is unavailable.

Every crewed U.S. spacecraft since the Gemini program has used fuel cells to generate electrical power for vehicle loads. The last fuel cell to fly in a crewed spacecraft is the alkaline hydrogen-oxygen fuel cell used on the Space Shuttle Orbiter. This alkaline fuel cell was sized to generate 2-12 kW_e with reagent-quality hydrogen and oxygen, utilizing active pumps and water separators to manage the product water. These external components limited the life of the fuel cell to about 5,000 hours before requiring refurbishment. The alkaline separator for this fuel cell required asbestos, which is now unavailable, and leakage of the caustic potassium hydroxide (KOH) electrolyte limited the power plant's life. When clean hydrogen is available as a fuel, commercial systems in terrestrial applications now use proton exchange membrane (PEM) technology for systems ranging from < 1 kW_e for portable applications to 400 kW_e for stationary power. PEM fuel cells for terrestrial transportation systems range from 1 kW_e to 100 kW_e. Rather than using corrosive pure oxygen as an oxidant, they use air and rely on gravity and external components to expel product water. The effects of variable hydration and heat on the PEM membrane typically limit the operational life of these plants to ~5,000 hours. To reduce recurring cost, the PEM membranes in commercial systems typically operate at low voltage (i.e., low efficiency) to reduce the amount of platinum catalyst required.

Solid oxide fuel cells (SOFCs) are now commercially available for terrestrial applications. Their high-temperature operations enable compatibility with fuel reformed from such hydrocarbons as natural gas, but also create challenges for reliable operation, notably with thermal transients during on-off cycling. Commercial systems can also be heavy, while space operations require kilowatts of electrical power generation without a substantial mass penalty.

NASA has three primary applications that require advancements in fuel cell technology:

1. Electrical power generation from oxygen and hydrogen to power crewed transportation systems including landers and rovers. These systems need to produce nominally 40 kW_e at 120 volts (V). Balance-of-plant components (regulators, valves, circulation pumps) are the source of most failure modes in fuel cell power plants of any chemistry, so passive reactant management systems could dramatically improve the reliability of fuel cell systems by eliminating the most common sources of failure. System mass can be reduced by new stack bipolar plate designs and materials, and system efficiency and durability can be improved by new catalyst and membrane materials. The primary objective for PEM fuel cells is to demonstrate reliable operation for > 10,000 hours with high efficiency (> 75 percent) when operating with propellant-grade hydrogen and oxygen. These fuel cell systems must also operate with reactants stored at nominally 2,000 psi, which requires either a reliable compressor or fuel cell stack that does not leak at elevated pressures.
2. Fuel cell systems that can directly process residual propellants from landers and fuels generated from ISRU systems will enable the ability to establish sustainable outposts. Power can effectively be produced from liquid methane-oxygen propulsion storage via high-temperature (e.g., solid oxide) fuel cells, bipropellant turbines or Stirling engines, or a combination thereof. Further, high-temperature SOFCs enable heat rejection systems that are greatly reduced in mass. High-temperature fuel cells (e.g., solid oxide) must reliably operate with systems that are cycled on and off up to 10 times, and therefore must demonstrate durability during thermal cycling and high efficiency operation (> 70 percent) when operating with hydrocarbon fuels such as methane.
3. Electrical power generation from oxygen and hydrogen or methane carbon monoxide (CO) generated by electrolysis as part of a regenerative fuel cell system is needed for surface applications. These subsystems are addressed in TA 3.2.3.

Benefits of Technology

The technology advancements described above will enable reliable electrical power generation for crew transportation systems and surface systems. Such advances are particularly advantageous when integrated with ISRU systems.

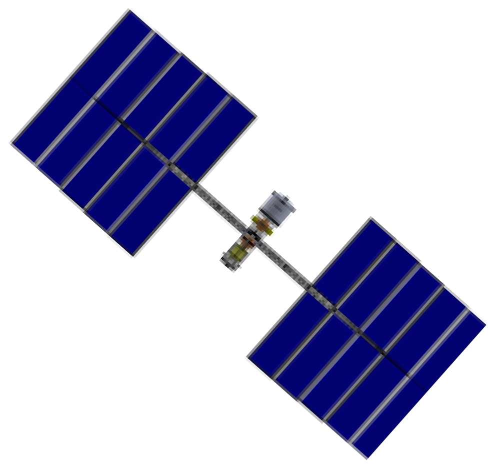
Table 4. TA 3.1.2 Technology Candidates – not in priority order

TA	Technology Name	Description
3.1.2.1	Polymer Electrolyte Membrane Fuel Cells (PEMFC)	Fuel cell system that employs a hydrogen ion conducting PEM and is capable of operating on hydrogen and oxygen at a temperature of < 100° C.
3.1.2.2	Solid Oxide Fuel Cells (SOFC)	High-temperature (700-1,000° C) fuel cell system that employs a sold oxide electrolyte and is capable of operating on propellant grade hydrogen (H_2) or methane (CH_4) and oxygen (O_2).
3.1.2.3	Very High Efficiency Fuel Cells	Fuel cell system that employs advanced membrane to provide efficiency substantially higher than existing PEM, alkaline, or solid oxide fuel cells.

TA 3.1.3 Solar

Technical Capability Objectives and Challenges

This area describes photovoltaic arrays that provide electrical power for spacecraft and surface systems. Commercial satellites and NASA science missions fly solar arrays that provide up to ~10 kW_e at 32-105 V to power communications and science payloads. Solar arrays at up to ~20 kW_e have also been flown to power small solar electric propulsion spacecraft, and much larger (> 100 kW_e) array sets power the International Space Station (ISS). Solar arrays up to ~1.5 kW_e (at 1 Astronomical Unit (A.U.)) have been used on the surface of Mars.



MW-Class Solar Array Structure

The majority of these missions use triple-junction solar cells, which provide up to 29 percent conversion efficiency at 1 A.U. and 20° C at the array's beginning of life. In most cases, these arrays use rigid-panel, honeycomb structures that require a significant amount of manual work to lay down the photovoltaic cells, interconnects, and cover glasses during array manufacture. Because these honeycomb structures are relatively thick (typically ~0.5 inch), stowed volume efficiency during launch is typically 10 kW-m^3. With the exception of the few solar arrays that have been deployed on the surface of Mars, there are few loads on these arrays while in operation, so their deployed strength and stiffness requirements are low, typically 0.005 grams (g) and > 0.05 Hertz (Hz). The high cost of labor to manufacture these arrays coupled with the high cost of high-efficiency, radiation-tolerant photovoltaic cells yields costs on the order of $1,000/Watts (W) for arrays used on NASA missions. NASA missions to the outer and inner planets require the screening of individual photovoltaic cells for those that perform best at LILT and HIHT, respectively, further adding to the cost.

NASA has two primary classes of mission that require advancements in solar array technology.

1. Spacecraft using high-power SEP require very large solar arrays for cis-lunar and deep-space missions. For near-term missions, solar arrays for SEP must be large enough to provide > 40 kW_e with stowed packing efficiencies > 40 kW/m^3 to enable the cost-effective use of launch vehicles while meeting strength and stiffness requirements of 0.1 g and > 0.1 Hz to enable the arrays to remain deployed during propulsive maneuvers. For crewed missions to the surface of Mars, these arrays must provide > 250 kW_e while meeting the same volume, strength, and stiffness requirements. In addition, these arrays must operate

effectively in the vicinity of the plasma generated by the electric thrusters used for SEP, while passing through the Van Allen Belt perhaps numerous times, and while operating at high voltages. Because these arrays are the largest component of cost for SEP spacecraft, there is a need to substantially reduce both the recurring and non-recurring cost of the photovoltaic blanket.

The focus of solar array technology development for SEP is on lightweight, deployable structures using flexible blankets with photovoltaics amenable to automated manufacturing processes. Development challenges include structural designs that can provide very high power (> 250 kW) while providing > 0.05 g strength and > 0.1 Hz stiffness with > 40 kW/m^3 stowed volume efficiency and > 100 W/kg specific power for future crewed missions to the Mars surface. Technologies that can reduce the cost of these arrays, and of similar arrays in the 40 kW – 125 kW class, are of high interest. These technologies may reduce the cost of individual photovoltaic cells, the cost of blanket lay-up, or the number of cells through the use of concentrator arrays.

2. Planetary missions may require high-efficiency photovoltaic power conversion far from the sun with LILT. Inner-planet missions require photovoltaic power in HIHT and acid environments (e.g., the Venus atmosphere). Intense radiation tolerance is also required. The focus of photovoltaics for LILT and HIHT applications is on improving the conversion efficiency of the cells at temperatures < -130° C and > 250° C, respectively, with solar illumination at > 5 A.U. and < 0.35 A.U., respectively.

Benefits of Technology

The technology advancements described above will enable SEP to cost effectively carry cargo and/or crew for human exploration missions to Mars; will enable higher power delivery to inner and outer planetary missions to increase the number or capability of science missions; and will enhance the manufacture of fuels and water in-situ for lunar and Mars surface missions.

Table 5. TA 3.1.3 Technology Candidates – not in priority order

TA	Technology Name	Description
3.1.3.1	25 – 150 kW$_e$-class Solar Array Structures	Deployable structures sized to carry enough photovoltaic cells to generate up to ~150 kW$_e$ per wing.
3.1.3.2	250 kW$_e$-class Solar Array Structures	Deployable structures sized to carry enough photovoltaic cells to generate ~250 kW$_e$ per wing.
3.1.3.3	MW$_e$-class Solar Array Structures	Deployable structures sized to carry enough photovoltaic cells to generate ~500 kW$_e$ per wing.
3.1.3.4	Reliably Retractable Solar Arrays	Solar arrays that can be retracted in-flight and redeployed multiple times.
3.1.3.5	Acid-Resistant Solar Array Structures	Structures that support photovoltaic blankets to provide power to vehicles on high-altitude Venus missions.
3.1.3.6	Reduced-Cost Photovoltaic Blankets	Reduce the cost of photovoltaic blankets by lower-cost photovoltaic cell technologies and/or automated manufacturing processes to assemble cells, interconnects, and/or coverglasses.
3.1.3.7	Low-Intensity, Low-Temperature (LILT) Radiation Tolerant Photovoltaic Blankets	High-efficiency LILT photovoltaic cells integrated into solar array substrates with interconnects and coverglasses for radiation-tolerant operation.
3.1.3.8	High-Temperature, Radiation-Tolerant Photovoltaic Blankets	High-temperature, radiation-tolerant photovoltaic cells, interconnects, and coverglasses integrated into solar array substrates.
3.1.3.9	Acid-Resistant, High-Temperature, Radiation-Tolerant Photovoltiac Blankets	Acid-resistant photovoltaic cells, interconnects, and coverglasses integrated into solar array substrates.
3.1.3.10	Ultra-High-Efficiency Photovoltaic Blankets	High-efficiency photovoltaic cells integrated into solar array substrates.

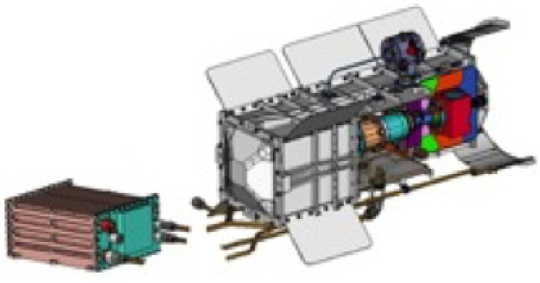
Table 5. TA 3.1.3 Technology Candidates – not in priority order - Continued

TA	Technology Name	Description
3.1.3.11	Solar Concentrator Systems	Reflectors and lenses to concentrate solar radiation on high-efficiency PV cells or heat collection elements.
3.1.3.12	Full-Spectrum Hybrid Solar-Thermal Systems	Hybrid solar-thermal systems to utilize the full-solar-spectrum in high-efficiency, high-energy systems for both electric power and dispatchable heat.

TA 3.1.4 Radioisotope

Technical Capability Objectives and Challenges

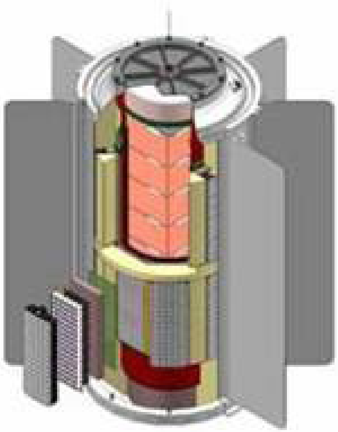
This area describes subsystems that use radioisotopes as an energy source and convert the energy released by radioactive decay into electricity. Radioisotope power systems (RPS) based on plutonium-238 (^{238}Pu) and thermoelectric conversion have been used in space since 1961, with typical performance metrics of 3-5 W_e/kg, 6 percent efficiency, and over a 30-year (demonstrated) life. RPSs operate independent of solar proximity or orientation. In addition to enabling sophisticated science missions throughout the solar system, RPSs were used on Apollo missions 12-17 and the Viking landers.



Stirling Radioisotope Generator

The radioisotope of choice is ^{238}Pu, which has excellent power density and lifetime, and minimal radiation emissions. However, this isotope remains in short supply. NASA and another government agency have initiated the refurbishment of the domestic capability to produce new ^{238}Pu. The first new domestic supply of ^{238}Pu oxide will be delivered in this decade and should ramp up to support the deep space science mission manifest in the coming decades.

NASA's deep-space science missions are the primary pull for advancements in radioisotope power generation. The total power level, specific power, and efficiency of radioisotope systems can all be improved through more efficient heat engine conversion, either by enhanced thermoelectrics or by high-efficiency Stirling engines. While Stirling engines will offer more efficient conversion than thermoelectrics, the availability of larger amounts of high-quality waste heat (i.e., heat available at higher temperatures to provide the driving potential needed to maintain common equipment temperature limits) renders thermoelectrics an attractive solution for some vehicle architectures, when given a discrete set of radioisotope power generation options.



Large Segmented RSRM Test

RPS work should focus on making efficient use of available ^{238}Pu and developing a milliwatt-class radioisotope heat source that could be used on a variety of missions, including sub-surface probes. Power conversion technologies that have the potential to meet the requirements of planned missions include advanced Stirling and advanced thermoelectric systems. Development must focus on improving conversion efficiency (beyond 12 percent) and specific power (beyond 8 W_e/kg) while ensuring long life (minimum 14 years). It should be noted that, while ^{238}Pu has long been considered the isotope best suited for deep space science missions, other radioisotopes (e.g., Americium 241(^{241}Am)) might offer some mission enhancement due to their potentially greater availability and lower cost. However, the energy conversion options trade in essentially the same way regardless of the radioisotope chosen as energy source.

Direct conversion of radioisotope energy via alphavoltaics may deliver a disruptive improvement in efficiency and, especially, in specific power (to > 200 W_e/kg). However, this requires development in a very high-risk effort.

Benefits of Technology

Looking forward, RPSs in the 0.1-1,000 W_e power range could continue to enable advanced science missions and new capabilities, and could also be useful in supporting human exploration missions, including long-life subsurface probes. High specific power RPSs could enable radioisotope electric propulsion for deep-space missions, enhancing or enabling numerous NASA missions of interest.

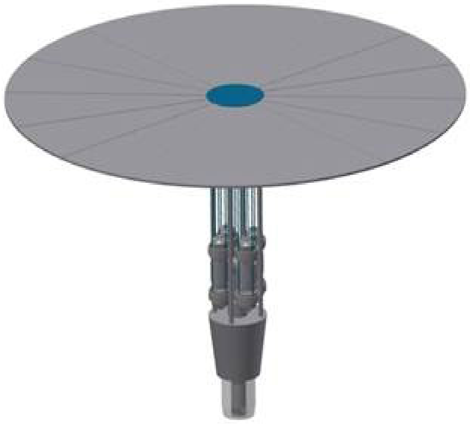
Table 6. TA 3.1.4 Technology Candidates – not in priority order

TA	Technology Name	Description
3.1.4.1	Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG-100)	Radioisotope thermoelectric generator (100 W) with general purpose heat source (GPHS) and high-efficiency thermoelectric converters (η ~10%).
3.1.4.2	Advanced Stirling Radioisotope Generator (ASRG-100)	Radioisotope power system (100 W) with general purpose heat source (GPHS) and high-efficiency Stirling engine converters (η ~30%).
3.1.4.3	High-Power Advanced Radioisotope Thermoelectric Generator (ARTG-500)	Radioisotope thermoelectric (TE) generator (500 W) with general purpose heat source (GPHS) and high-power, high-efficiency thermoelectric converters (η ~15%).
3.1.4.4	High Power Stirling Radioisotope Generator (ASRG-500)	Radioisotope power system (500 W) with general purpose heat source (GPHS) and high-efficiency and high-power Stirling engine converters (η ~30%).
3.1.4.5	mW-class Radioisotope Thermoelectric Generators (mW RTG)	mW Radioisotope thermoelectric generator that employs radioisotope heater unit (RHU) and high-efficiency thermoelectric converters.
3.1.4.6	Alphavoltaic Atomic Battery	Radioisotope power system that contains a radioactive isotope (such as ^{238}Pu or another alpha-emitter) and a semiconductor device that converts alpha radiation directly into electricity.

TA 3.1.5 Fission

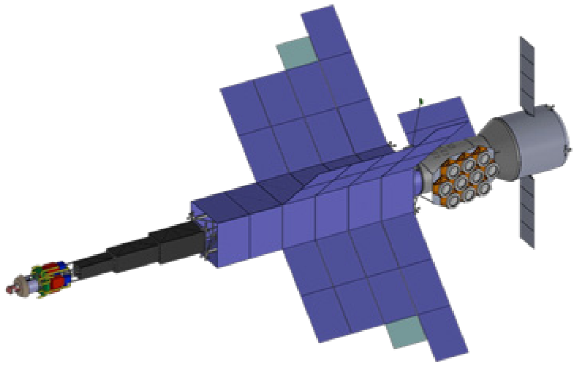
Technical Capability Objectives and Challenges

This area describes subsystems that use nuclear fission as an energy source and convert the heat energy released into electricity. Fission power reactors flown in space between 1965 and 1987 operated at coolant outlet temperatures and thermal powers comparable to those required by a 21st century concept for a 40 kW_e system. Space reactor programs have succeeded in developing high-temperature, high-performance fuels, materials, and heat transport systems, however, this hardware has not flown in space. The experience gained from nearly seven decades of terrestrial fission systems can benefit the design and development of future space fission systems. Fuel and materials technologies from terrestrial systems (e.g., the Fast Fission Test Facility and Experimental Breeder Reactor-II) are applicable, especially for first generation space fission systems. Smaller fission systems in the 1-10 kW_e range have the potential to provide an alternative to radioisotope power for science missions and a viable option for human outposts on Mars. High-temperature (~800 Kelvin (K)) fuels developed for terrestrial applications and test reactors also could be of use for ultra-compact, high-specific-power space systems.



1-10 kW_e "Kilopower" Fission Power System

Nuclear fission power sources are needed for in-space electric propulsion for human exploration missions and higher-power science missions. In this latter category, the extreme expense of certifying a nuclear fission core motivates development of a fission power system that can provide ~1 kW_e to a science mission spacecraft bus, and can be scaled to provide up to ~10 kW_e for a human exploration surface mission.


1-10 MW_e Space Fission Power System

At the other extreme, architectures for the human exploration of Mars identify requirements for fission power subsystems (driving electric propulsion subsystems) with power levels up to 10 MW_e from a 1,500 K fuel element and with subsystem specific mass below 15 kW_e/kg. Development of the high-temperature fuel element is a key challenge in meeting this objective.

To meet the requirements of current mission architectures, fission power development efforts should focus on three different power classes: (1) a 1-10 kW_e power module common to both science mission bus power and human exploration surface power; (2) a 10-100 kW_e "workhorse" system for human exploration surface power and for electric propulsion needs on "flexible path" missions, such as crewed missions to an asteroid; and (3) a 1-5 MW_e low-specific-mass system required for crewed missions to Mars. Current human exploration mission concepts may be vastly enhanced by developing technologies to enable very-high-power (> 5 MW_e), very-low-specific mass (< 5 kg/kW_e) space fission power for electric propulsion.

The top technical challenges for fission systems are application specific. A 1-10 kW_e fission system would require high-uranium-density fuel; simple, lightweight core-to-power conversion heat transfer; low mass power conversion (at low power); and design for safety, reliability, and minimum mass. Existing (or near-term) materials, fuels, power conversion, and waste-heat rejection technologies could be used. Simply put, the technologies exist for developing near-term, mission-enabling space fission systems. The major challenge for these initial systems is integrating the technologies into a safe, reliable, affordable system. For second-generation space fission systems (and beyond), the major challenge is developing technologies to further improve performance. Specific technologies include high-temperature reactor fuels and materials; high-temperature, high-efficiency power conversion; and lightweight, high-temperature radiators. For example, at high power levels (> 100 kW_e), space fission power systems' performance would benefit from advanced fuels, advanced power conversion, and lightweight radiator technologies. Innovative reactor designs would also improve performance. Specific technologies needed to provide multi-MW systems of specific mass under 5 kW_e/kg include development of high-temperature (~1,800 K) cermet fuels (e.g., Tungsten-Uranium Nitride (W-UN)) and advanced power conversion technologies with conversion efficiencies > 20 percent. Lightweight radiators capable of operating at temperatures between 600 and 1,000 K also could benefit integrated system performance.

Benefits of Technology

Fission power is required for the sustainable human exploration of Mars. Fission systems can also support science missions in the ~1 kW_e power range. The workhorse 10-100 kW_e fission systems can support surface and robotic missions. High-power fission systems (MW-class) can benefit nuclear electric propulsion missions, potentially including cargo and crewed missions to Mars and other destinations. The report "Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration," released in May 2014, notes that surface nuclear power is one of eleven Primary Mission Elements to achieve a human Mars mission. Also, in NASA Administrator Bolden's "Pioneering Space: NASA's Next Steps on the Path to Mars," he notes that advanced surface power generation is a key technology area for Mars missions.

Table 7. TA 3.1.5 Technology Candidates – not in priority order

TA	Technology Name	Description
3.1.5.1	1-4 kW_e Thermoelectric Fission Power System	1 to 4 kW_e fission power systems scalable from a common fission core for outer planetary and electric propulsion missions. System uses thermoelectric power conversion.
3.1.5.2	1-10 kW_e Stirling Fission Power System	1 to 10 kW_e fission power systems scalable from a common fission core for outer planetary and electric propulsion missions. Power conversion system options include Stirling and Brayton engines.
3.1.5.3	10-100 kW_e Fission Power System with Stirling Conversion	10-100 kW_e fission power system with Stirling conversion capable of providing full power independent of available sunlight.
3.1.5.4	10-100 kW_e Fission Power System with Solid State Conversion	10-100 kW_e fission power system with solid state energy conversion capable of providing full power independent of available sunlight.
3.1.5.5	1–10 MW_e Space Fission Power Systems	1-10 MW_e space fission power system capable of providing abundant energy anywhere in the solar system. Primary use would be nuclear electric propulsion to decrease launch mass requirements or mission duration for human missions to Mars.
3.1.5.6	>10 MW_e Space Fission Power System	Low-specific-mass space fission power systems for supporting fast-transit human Mars missions.by providing power for nuclear electric propulsion systems.

TA 3.1.6 Fusion

Technical Capability Objectives and Challenges

Fusion power has long been considered to be most readily attainable through heating and confinement of a deuterium-tritium (D-T) plasma until the condition at which the plasma can heat itself (ignition) is reached. The D-T reaction releases most (80 percent) of its energy in the form of neutrons, so a D-T fusion reactor requires heavy shielding and heat-based energy conversion to produce electricity. Since the 1960s, fusion research has focused on the D-T reaction, as it appears to be the least challenging from the perspective of plasma confinement and reactor technology for utility grid power generation. Steady progress toward the objective of net fusion power generation continues to be made, with most development devoted to the magnetic plasma confinement approach. The primary effort currently underway is a very large magnetic confinement device, which is projected to lead to net power generation in the 2030s with $\alpha > 200$ kg/kW_e at ηconv < 0.4 and 10 gigawatt (GW). A power system with this specific mass is not useful in a spacecraft application.

Enabling a "step function" decrease in initial mass in LEO (IMLEO) and mission duration for the human exploration of Mars requires an in-space power-propulsion system with specific mass well under 3 kg/kW_e. This cannot be accomplished within the limitations of the heat engine conversion required by fission or D-T fusion energy sources. Such a low specific mass requires harnessing the aneutronic fusion reaction p-^{11}B with direct energy conversion.

The international fusion development program currently underway is the result of focusing on the most direct route to terrestrial fusion energy technologies. D-T fusion has been seen as this route, as it is the "easiest" to achieve from a physics perspective (its fusion cross section peak is at a relatively low collision energy). However, engineering a D-T fusion power plant has proven to be a very challenging and expensive undertaking, and focus on this direction has caused neglect of the more "difficult" (i.e., higher energy cross section) reactions such as p-^{11}B, even though their capability for direct conversion would result in a power plant with much lower specific mass. Since this low specific mass is less important in terrestrial power applications, relatively little has been developed in engineering a plasma confinement that would enable harnessing this reaction or on the direct conversion systems that it would use.

Aneutronic fusion power sources with direct conversion can enable crewed missions to Mars under one year in duration and 350 metric ton (mT) total IMLEO if they provide a power system of specific mass < 3 kg/kW_e.

Accomplishing this requires developing a non-Maxwellian plasma confinement for the p-^{11}B reaction with Q (Power-out/Power-in) > 6 and of traveling wave direct energy conversion (TWDEC) systems of efficiency > 70 percent.

Fusion power generation technology development should focus on ~50 MWthermal (MWt) aneutronic fusion (p-^{11}B) reactors, on direct power conversion (e.g., TWDEC) for high-energy charged particle product beams, and on high-voltage (~1 MV), high-efficiency PMAD. Related propulsion work should focus on developing plasma thrusters in which the plasma is heated directly by the high-energy charged particle beam from an aneutronic fusion reactor.

The primary technical challenge in aneutronic fusion remains demonstrating stable confinement of plasmas with ions of sufficient energy to produce high-energy yield. With presently known magnetic confinement configurations, Maxwellian plasmas of sufficient energy to sustain these reactions cannot be confined for a sufficient time and, at the required plasma temperature, radiation losses would exceed the power output of the fusion reaction. Therefore, sustaining non-Maxwellian "colliding beam" plasmas appears a more viable solution, yet these have many unknowns. Other challenges include developing systems (e.g., TWDEC) for direct conversion of high-energy alpha particles produced in the fusion reactions. It should also be noted that a propulsion-power system with a total specific mass (αT) < 1.0 kg/kW is realistically possible only if a thrust-producing propellant jet can be generated from the energy of the fusion products of the reactor.

Benefits of Technology

For the terrestrial electric power grid, aneutronic fusion would be disruptive. It offers energy from an abundant fuel with no emissions of carbon and no generation of radioactive waste. Aneutronic fusion power with electric propulsion would "disrupt" decades-old mission architecture concepts. It could support human missions to Mars with round-trip times under one year and large, high-power robotic missions throughout the solar system.

Table 8. TA 3.1.6 Technology Candidates – not in priority order

TA	Technology Name	Description
3.1.6.1	Aneutronic Fusion In-Space Power	Non-Maxwellian plasma confinement of p-^{11}B fusion plasma with traveling wave direct energy conversion.

TA 3.2: Energy Storage

This area describes methods of storing energy after it has been generated from solar, chemical, or nuclear sources. The two basic methods for such storage in spacecraft are chemical (batteries and regenerative fuel cells) and mechanical (flywheels). While the vast majority of energy storage technologies of interest to spacecraft design are at TRL 3 or higher for spacecraft applications, the state of the art (SOA) of each varies widely. The SOA of most energy storage technologies needs improvement in specific energy, as well as safety, reliability, and durability. Further development is required to provide technology that meets all requirements.

Sub-Goals

The primary sub-goal for any space energy storage technology is to provide power at the highest possible specific energy with sufficient durability in the mission environment and, in the case of rechargable storage, sufficent cycle life. The limitations on this capability are generally driven by either chemical reaction kinetics and efficiency or the mechanical strength of materials. For example, the maximum specific energy possible for a lithium battery is driven by the electrochemical potential available from the redox reaction support by the chemical reactants in the cell. The specific energy of a flywheel is limited at first order by the tensile strength of the rotor material.

Limitations on the durability of an energy storage system are generally driven by material and environmental issues and by operating mode. For example, the cycle life of a lithium-ion rechargeable battery can be severely decreased as the depth of discharge on each cycle increases, whereas flywheel cycle life is often not so significantly affected by depth of discharge. Also, the cycle life of any chemical battery is affected by environmental temperature. Such environments and operating modes vary among missions and thus can drive technology developments in different directions. One cannot develop a single energy storage solution that meets the requirements of all of NASA's space missions, and some missions require energy storage technologies that are entirely unique.

Table 9. Summary of Level 3.2 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
3.0 Space Power and Energy Storage	Goals:	Develop power systems with significant mass and volume reductions, increased efficiency, and capability for operation across a broad temperature range and in intense radiation environments.
Level 2		
3.2 Energy Storage	Sub-Goals:	Provide power at the highest possible specific energy with sufficient durability in the mission environment and, in the case of rechargeable storage, sufficient cycle life
Level 3		
3.2.1 Batteries	Objectives:	Develop high specific energy, high energy density batteries tolerant to electrical, thermal, and mechanical abuse with no fire or thermal runaway.
	Challenges:	High-specific-capacity cathode and anode nanomaterials; high-voltage and highly conductive electrolytes with flame retardant capabilities and overcharge protection additives; scale-up of these materials; and integration of components into functioning, high performing, safe cells.
	Benefits:	Enable the next generation of deep-space extravehicular activity (EVA) suits that require advanced life support, communications, and computing equipment. Enable energy storage for science missions in extreme environments.

Table 9. Summary of Level 3.2 Sub-Goals, Objectives, Challenges, and Benefits

Level 3		
3.2.2 Flywheels	Objectives:	Provide high specific energy flywheels with increased cycle life and total lifetime.
	Challenges:	Store energy for kWh and MWh systems at a specific energy of up to 2,700 Wh/kg with carbon nanofiber rotors and attain a charge life of greater than 50,000 cycles and lifetime of greater than 20 years with high reliability and safety.
	Benefits:	Nanoengineered material flywheels have the potential to be the highest specific energy storage medium (2,700 Wh/kg theoretically).
3.2.3 Regenerative Fuel Cells (RFCs)	Objectives:	Develop high specific energy regenerative fuel cells (RFCs) with high round trip efficiency and long life.
	Challenges:	Optimization for multi-gravity and vacuum environment operations. Operate with reactants stored at nominally 2,000 psi.
	Benefits:	RFCs only require larger storage containers and additional reactants to extend their operational period. RFCs can maximize use of in-situ reactants by effective integration with surface ISRU systems.
3.2.4 Capacitors	Objectives:	Improve specific energy while retaining or improving specific power at low temperatures.
	Challenges:	Improving the specific energy of supercapacitors, while retaining or improving specific power at low temperatures.
	Benefits:	Provide pulse power capability at low temperatures for spacecraft and avionics. Supercapacitors, hybridized with batteries or used for stand-alone energy storage, support high power loads, such as communications, radar, actuation, and electric thrusters.

TA 3.2.1 Batteries

Technical Capability Objectives and Challenges

Batteries are used in virtually all space missions. Primary batteries (single discharge batteries) are used in missions that require one-time use of electrical power for a few minutes to several hours. Primary batteries have been used in planetary probes, sample return capsules, and rovers. Secondary batteries (rechargeable batteries) have been used mainly for load-leveling and providing electrical power for survival during eclipse periods on solar-powered missions and as the source of power for extravehicular activity (EVA) suits. They have been used in orbital missions (ISS, surveyors, and observers), as well as Mars landers and rovers.

State of the art primary and secondary batteries are heavy and bulky, and safety concerns exist with some of the primary lithium (Li) and rechargeable Li-Ion batteries.

While the highest possible specific energy is an objective for most any battery, this objective must be traded off against other mission requirements, resulting in a variety of technology directions. For example, batteries for eclipse storage on Earth-orbiting satellites require 200 Wh/kg with 50,000 (< 30 percent depth of discharge (DOD)) charge-discharge cycles, whereas human EVA missions can accept many fewer cycles in exchange for higher specific energy capability with extreme (90 percent) DOD on each cycle. Planetary mission requirements trade lower specific energy for the ability to operate at extreme temperatures: up to 450° C for inner planet missions, down to -150° C for outer planet missions.

The major technical challenges to developing these advanced space batteries include developing high-specific-capacity cathode and anode nanomaterials; high-voltage and highly conductive electrolytes with flame retardant capabilities and overcharge protection additives; and scale-up of these materials and integration of these components into functioning high performing and safe cells.

Benefits of Technology

Batteries that can safely store very large amounts of energy in small, low-mass packages enable the next generation of deep-space EVA suits that require advanced life support, communications, and computing equipment. All other missions are enhanced by having additional electrical power available without a mass penalty.

Table 10. TA 3.2.1 Technology Candidates – not in priority order

TA	Technology Name	Description
3.2.1.1	High-Specific-Energy, Human-Rated Lithium (Li) Secondary Batteries	Li secondary batteries employing high specific-capacity electrodes and low-flammability electrolyte.
3.2.1.2	Long-Life Lithium (Li)-Ion Secondary Batteries	Long-cycle-life Li-Ion batteries employing high-specific-capacity electrode materials and stable electrolytes.
3.2.1.3	Very Low-Temperature Secondary Lithium (Li)-Ion Batteries	Low-temperature Li-Ion batteries employing electrode materials and electrolytes with improved low temperature performance (-60° C).
3.2.1.4	High-Temperature Secondary Batteries	High-temperature Li rechargeable batteries employing electrode materials and electrolytes with high temperature performance capability (200-450° C).
3.2.1.5	Ultra-Low-Temperature Primary Batteries	Low-temperature Li primary batteries employing electrode materials and electrolytes with ultra-low-temperature performance capability (-150° C).
3.2.1.6	High-Temperature Primary Batteries	High-temperature Li primary batteries employing electrode materials and electrolytes with high-temperature performance capability (200-450° C).
3.2.1.7	Battery Physics-Based Models	Physics-based models that incorporate detailed component geometry and materials to predict the behavior of advanced battery designs under changing environmental conditions.
3.2.1.8	Extended Shelf-Life Batteries	High-reliability batteries (or easily assembled battery components) with shelf life in excess of 15 years.

TA 3.2.2 Flywheels

Technical Capability Objectives and Challenges

Flywheels offer spacecraft a novel system for combining attitude control (replacing momentum wheels) and energy storage (replacing batteries), which reduces the overall mass of the combined systems. Flywheels have the advantage of being able to quickly deliver their energy; they can be fully discharged repeatedly without harming the system and they have the lowest self-discharge rate of any electrical energy storage medium.

NASA has fabricated and successfully ground-tested engineering units in the 25-30 Wh/kg size range. Further reductions in mass are needed to make these systems significantly more attractive than batteries and momentum wheels for applications such as use on the ISS.

Flywheel technology development for energy storage applications should focus on flywheel component miniaturization, nanotechnology-based rotors, magnetic bearings, reliability, and system development and demonstration. The major challenges are to advance flywheel technology to store energy for kWh and MWh systems at a specific energy of up to 2,700 Wh/kg with carbon nanofiber rotors and to attain a charge life of greater than 50,000 cycles and lifetime of greater than 20 years with high reliability and safety. Bearing technology development, such as superconducting magnetic bearings and advanced generators, would also advance flywheel technology.

Benefits of Technology

With the application of nanoengineered materials, flywheels have the potential to be the highest specific energy storage medium (2,700 Wh/kg, theoretically).

Table 11. TA 3.2.2 Technology Candidates – not in priority order

TA	Technology Name	Description
3.2.2.1	Large Energy Storage Flywheels	Mechanical energy storage system using high-speed, magnetically-suspended composite wheels and a motor generator to charge and discharge.
3.2.2.2	High Specific Energy, High Temperature Flywheels	Mechanical energy storage system using magnetically-suspended carbon nantotube fiber or graphene wheels and a motor generator to charge and discharge.
3.2.2.3	Energy Storage Flywheels for Low-Temperature Applications	Mechanical energy storage system using high-speed magnetically-suspended composite wheels and a motor generator to charge and discharge.

TA 3.2.3 Regenerative Fuel Cells

Technical Capability Objectives and Challenges

This area describes the major subsystems of a RFC system (fuel cell, electrolyzer, reactant storage, thermal management, and control) and their integrated operation.

Air-based terrestrial RFCs (recycling only hydrogen and water) are being developed for commercial and military applications. RFC systems for space exploration have no air available and thus must be designed to also recycle oxygen, a corrosive element. Furthermore, RFC systems for space applications must be optimized for multi-gravity environment operations (from 0 gravity (g) to launch loads) and also for thermal and water management in space thermal vacuum environments. Space-quality RFC technology feasibility demonstrators have been assembled and tested to demonstrate technology viability and to determine system operations.

Two RFC chemistries are of interest in space applications: PEM and solid oxide. The components needed for a PEM RFC are under development to operate with water management by wicking alone (e.g., non-flow-through mode), thereby eliminating the balance-of-plant elements that are most prone to failure. Non-flow-through PEM fuel cells suitable for use in an RFC are at TRL 4 and non-flow-through PEM electrolyzers are at TRL 3. A solid oxide RFC is a more complex system in that the hydrocarbon fuel must be formed when in the “charge” operational mode. Solid oxide RFCs may thus be part of a broader ISRU-based architecture in missions on the Mars surface, wherein the carbon dioxide (CO_2) produced in the discharge mode is vented to the atmosphere and wherein CO_2 from the Martian atmosphere is formed into CH_4 in the charge mode via Sabatier reactors. Solid oxide water electrolysis is also compatible with ISRU soil processing, where product steam can be electrolyzed and stored for fuel cell operation and/or life support. Such systems are under consideration in broader Mars architecture studies, and solid oxide components for space RFC systems are at TRL 2 to 3. These fuel cells and electrolyzers must also operate with reactants stored at nominally 2,000 psi, which requires either a reliable compressor or fuel cell and electrolyzer stacks that do not leak at elevated pressures.

Large-scale energy storage capabilities would be enhanced by RFCs with high specific energy (up to 1,500 Wh/kg), high charge-discharge efficiency (up to 70 percent), high reliability, and long life capability (~10,000 hours). In order to develop such RFCs, development efforts should focus on such objectives as high-efficiency fuel cells and electrolyzers, as well as improved water and thermal management subsystems.

Benefits of Technology

RFC systems are attractive for space missions that require large-scale energy storage on the order of several MWh. This is especially important for applications like space habitats and planetary surface systems requiring tens of kilowatts of electrical power. Unlike batteries, which become very large when designed for long periods of operation, RFCs only require larger storage containers and additional reactants to extend their operational period. RFCs can also be effectively integrated with surface ISRU systems to maximize use of in-situ reactants.

Table 12. TA 3.2.3 Technology Candidates – not in priority order

TA	Technology Name	Description
3.2.3.1	Hydrogen (H_2)/Oxygen (O_2)-Based Regenerative Fuel Cell (RFC)	Regenerative fuel cells produce power and water from energy stored as oxygen and hydrogen and store energy by drawing power to electrolyze stored water into hydrogen and oxygen.
3.2.3.2	Methane (CH_4)/Carbon Dioxide (CO_2)-Based Regenerative Fuel Cell (RFC)	Regenerative fuel cells produce power, water, and carbon dioxide from energy stored as methane, oxygen, and water. The carbon dioxide can be exhausted into the Martian atmosphere. These units then store energy by drawing power to electrolyze water into hydrogen and oxygen and drawing hydrogen and power to convert atmospheric carbon dioxide into methane.

TA 3.2.4 Capacitors

Technical Capability Objectives and Challenges

The key objective is improving the specific energy of capacitors while retaining or improving specific power at low temperatures. Current technologies feature relatively low specific energy, which limits applicability.

Benefits of Technology

Capacitors can provide pulse power capability at low temperatures for spacecraft and avionics. Supercapacitors can be hybridized with batteries or used for standalone energy storage and can support high power loads, such as communications, radar, actuation, and electric thrusters.

Table 13. TA 3.2.4 Technology Candidates – not in priority order

TA	Technology Name	Description
3.2.4.1	High Specific Energy and Power, Wide Temperature Supercapacitors	Supercapacitors with high specific energy and power over wide operating temperatures, for pulse power applications.

TA 3.3: Power Management and Distribution (PMAD)

This area describes the technologies required to manage and control electric power generated from a source. The SOA for these technologies is limited in its ability to tolerate deep-space radiation. Additionally, component operating temperature ranges are so narrow as to require substantial thermal management, including heaters for cold temperature operation and substantial radiator mass and cooling systems for high-temperature environments. In addition, the components currently available cannot support the high temperature and high power needs of electric propulsion. Further, system control schemes require substantial human intervention. All of these limitations must be removed to enable NASA's missions beyond LEO.

Sub-Goals

The primary sub-goal for PMAD is to reliably support high-power electric propulsion missions into deep space. Other sub-goals include supporting low-power operations in extreme environments, such as the Venus surface. Meeting all of these sub-goals requires that component operating temperatures be raised up toward 300° C and that voltage and current carrying capability both be raised substantially. Equally important is tolerance of radiation environments, such as those of the Jovian region.

Table 14. Summary of Level 3.3 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
3.0 Space Power and Energy Storage	Goals:	Develop power systems with significant mass and volume reductions, increased efficiency, and capability for operation across a broad temperature range and in intense radiation environments.
Level 2		
3.3 Power Management and Distribution	Sub-Goals:	Reliably support high-power electric propulsion missions into deep space. Support low-power operations in extreme environments such as the Venus surface.
Level 3		
3.3.1 Fault Detection, Isolation, and Recovery	Objectives:	Detect faults early enough to reduce the amount of catastrophic failures in a spacecraft without raising too many false alarms.
	Challenges:	Monitoring thousands of unique electrical components.
	Benefits:	Early detection of faults for improved system robustness.
3.3.2 Management and Control	Objectives:	Develop intelligent management and control systems, which can operate independently from ground station control.
	Challenges:	Non-invasive voltage and current sensors with wireless connections; extreme-temperature-capable, radiation-tolerant avionics components. High-fidelity system simulations; intelligent control algorithm verification, and validation of interfaces with the overall vehicle mission manager.
	Benefits:	Enables more reliable power for long-duration, long-distance crewed and uncrewed space missions.
3.3.3 Distribution and Transmission	Objectives:	Develop radiation-hardened, extreme-temperature components and interconnects for power distribution and transmission.
	Challenges:	Extreme-temperature, radiation-hardened, high-voltage (300 V) components. High voltage capability often works against radiation tolerance.
	Benefits:	Tolerates deep-space radiation without excessive radiator mass for heat rejection.

Table 14. Summary of Level 3.3 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
3.3.4 Wireless Power Transmission	Objectives:	Remove the need for power wiring to low-power instruments and enable “connector-less” charging of batteries in dusty surface environments. ”Off-board” power sources for spacecraft propulsion and/or power, thus enabling mass savings.
	Challenges:	Beam control, pointing, and tracking systems.
	Benefits:	Increases reliability for human exploration missions in a dusty environment (e.g., the Martian surface). Increases launch and space vehicle performance.
3.3.5 Conversion and Regulation	Objectives:	Develop radiation-hardened, extreme-temperature components and interconnects for power conversion and regulation.
	Challenges:	Current operating temperature ranges are so narrow as to require substantial thermal management, thus increasing the specific mass of the power and propulsion system. High voltage capabilities often work against radiation-tolerance.
	Benefits:	Reduces requirement for thermal management, thus decreasing the specific mass of the power and propulsion system. Manages current for high power electric thrusters without deep-space radiation degradation of components.

TA 3.3.1 Fault Detection, Isolation, and Recovery

Technical Capability Objectives and Challenges

FDIR technologies include autonomous fault detection, which involves detecting the presence of anomalous system behaviors. Fault isolation involves identifying likely fault candidates that would explain anomalous system behaviors. Estimating the remaining useful operating time of power system components after fault detection is also an important function of FDIR.

Spacecraft have thousands of unique electrical components that can fail. Fault detection and isolation algorithms must be sensitive enough to detect faults early (before catastrophic failures occur), but must also be robust enough to avoid raising too many false alarms. Spacecraft may also have fault cases that still allow the spacecraft to function, but it is case dependent on how long operations can be sustained with the degraded system. FDIR algorithms are required for such controls.

Benefits of Technology

Fault detection and isolation algorithms may detect faults early enough to reduce the amount of catastrophic failures in a spacecraft.

Table 15. TA 3.3.1 Technology Candidates – not in priority order

TA	Technology Name	Description
3.3.1.1	Autonomous Fault Detection and Isolation for Complex Power Systems	Autonomous fault detection amounts to detecting the presence of anomalous system behaviors. Fault isolation involves the identification of likely fault candidates that would explain anomalous system behaviors.
3.3.1.2	Remaining Useful Life Prediction After Fault Detection	Estimation of the remaining useful operating time of power system components after fault detection.

TA 3.3.2 Management and Control

Technical Capability Objectives and Challenges

State of the art power management and control systems for spacecraft require "human-in-the-loop" control (e.g., human systems integration) from ground stations and current and voltage sensors that are invasive, offer fault paths, and must be hardwired. Current simulations to verify control and FDIR performance lack the fidelity necessary for long-duration, remote space missions, such as deep-space science missions or crewed missions to Mars. Onboard distributed computing elements, including processors, memories, and interconnects capable of running these models and determining power system and load status, state, and condition at the required temperature ranges and radiation and power levels do not currently exist.

Both science and human exploration missions pull intelligent management and control systems, which can operate independently from ground station control. Increased reliability can be obtained by developing non-invasive voltage and current sensors with wireless connections to the data bus, as well as the extreme-temperature-capable, radiation-tolerant avionics components needed to support the distributed model-based processing system, including processors, memories and interconnects. High-fidelity system simulations are also required to support reliable control. Intelligent control systems require new algorithm development, verification, and validation of interfaces with the overall vehicle mission manager.

Smart Grids, with a multitude of interconnected sources and loads, require advanced power flow control algorithms that promise more efficient and reliable power system operations. These same concepts can be developed into space power systems. In addition, power system control algorithms need to be highly reliable, but also be resilient when faults do occur to enable the long-term autonomous operation that interplanetary space systems or surface power systems would need. Terrestrial Smart Grid technologies are advancing in this direction.

Benefits of Technology

Better management and control systems will enable more reliable power for long-duration, long-distance crewed and uncrewed space missions. The algorithms and sensors developed could apply to "Smart Grid" technologies being developed for terrestrial green energy applications.

Table 16. TA 3.3.2 Technology Candidates – not in priority order

TA	Technology Name	Description
3.3.2.1	Hierarchical Control of a Power System	Autonomous management of power generation and energy storage, power distribution, and detected faults.
3.3.2.2	Advanced Power Sensors	Development of non-invasive voltage and current sensors linked with standards-based wireless data links to provide a data-rich environment for power system control and health monitoring.
3.3.2.3	Multi-processor Real-Time Power Simulation	Networked processors that run distributed, high-fidelity models of power components in real-time systems that provide an input and output environment to evaluate and verify advanced control performance.

TA 3.3.3 Distribution and Transmission

Technical Capability Objectives and Challenges

Power distribution systems currently certified for spacecraft are limited to 180 V (used on the ISS). Also, there are no passive components or interconnects certified for the extreme temperature ranges (-200 to +300° C) needed to minimize thermal management system overhead or for the intense radiation environments that deep-space science and human exploration missions will encounter.

Both science and human exploration missions pull on radiation-hardened, extreme-temperature components and interconnects for power distribution and transmission. A chief challenge in meeting this objective is the small demand that NASA can create to meet these specialized requirements.

The driving challenges of NASA missions involve providing extreme-temperature, radiation-hardened, high-voltage (300 V) components.

Benefits of Technology

Improvement in this technology is enabling for NASA's deep-space missions. The state of the art cannot tolerate deep-space radiation, and the low operating temperature requires excessive radiator mass for heat rejection.

Table 17. TA 3.3.3 Technology Candidates – not in priority order

TA	Technology Name	Description
3.3.3.1	High-Conductivity Carbon Nanotube Wire	Ultra-low loss (low resistance) wiring that utilizes woven carbon nanotube fiber.
3.3.3.2	Aluminum Wiring and Connectors	Low-mass wiring.
3.3.3.3	Modular High- and Low-Power Switchgear	Modular switch using a combination of intelligent semiconductors, flexible mechanical components, and standard thermal interfaces to enable reusability; basic switching element can be reconfigured for multiple applications—both high power and low power. Interface and performance standards are enforced to provide maximum commonality and eliminate proprietary interfaces.
3.3.3.4	High-Voltage Power Distribution, High-Voltage Semiconductors, Passive Components	Develop new power distribution components to enable reliable operation in a high-voltage environment.
3.3.3.5	High-Temperature Semiconductors, Passive Components, and Interconnects	Develop new high-temperature semiconductor switches, switch drivers diodes, high-temperature capacitors, and magnetic wire and interconnection techniques to permit the high-temperature operation of switchgear and permit reduction in the heat rejection system.
3.3.3.6	Extreme Radiation-Hardened Power Distribution	Develop new power semiconductors and drivers to enable radiation-hard power distribution system.

TA 3.3.4 Wireless Power Transmission

Technical Capability Objectives and Challenges

NASA's requirements in this field involve not only low-power applications (such as instrumentation and battery charging), but also high-power interfaces for ground, launch, and exploration systems. The space-certified SOA for these functions involves hard-wired connections, though the technology does exist to power everything from mW-class small electronics chargers to 2.5-kW systems for diesel-electric locomotives. Both crewed and science mission capabilities would be enhanced by the availability of this wireless power transmission technology, particularly in dusty environments where conventional connectors can be fouled, or in situations where instrumentation must be moved or added within an existing spacecraft in orbit.

Wireless power transmission could significantly reduce spacecraft mass by removing the need for power wiring to low-power instruments. Such technology could also enhance operating reliability by enabling "connectorless" charging of batteries in dusty surface environments. Low-current, short-distance power transmission systems are available in the commercial electronics field; NASA need only investigate these for space application. At the other extreme of power levels, launch and space vehicle performance could be greatly enhanced by the ability to beam power, via laser or microwave, from ground generation stations to vehicle propellant heating elements. Beam control, pointing, and tracking systems present a major challenge in this high power domain.

Benefits of Technology

Wireless battery charging and instrument power will increase reliability of human exploration missions in dusty environments (e.g., the Martian surface). High power beaming could increase launch and space vehicle performance.

Table 18. TA 3.3.4 Technology Candidates – not in priority order

TA	Technology Name	Description
3.3.4.1	Integrated Power Conversion for Wireless Power Transmission	Augment existing E or B field wireless charging to accommodate higher powers over longer throw distance.
3.3.4.2	Beaming Stations	Beaming stations are power sources that beam energy to small spacecraft for propulsion and/or power using lasers or microwaves. The technology can also be used for orbital debris removal with laser ablation. The stations can be ground based or space based. The beams can be continuous or pulse mode and provide more flux intensity than sunlight.

TA 3.3.5 Conversion and Regulation

Technical Capability Objectives and Challenges

Current space-certified metal-oxide-semiconductor field-effect transistors (MOSFET), diodes, and capacitors are only capable of operating at -55 to +150° C, up to 180 V, and are built into channels of < 10 kW capacity. They are not certified for the high temperatures (300° C) needed to minimize heat rejection radiator mass or for the intense radiation environments that deep-space science and human exploration missions will encounter. Such components also do not exist for the high voltage requirements of electric propulsion systems operating in the deep-space environment.

For conversion and regulation, both science and human exploration missions pull on radiation-hardened, extreme-temperature components and interconnects. The driving capabilities pulled by NASA missions center on extreme-temperature, radiation-hardened, high-voltage (1,200 V) components. Electric propulsion applications require a substantial increase (to > 1,200 V) in voltage tolerance.

Benefits of Technology

Improvements in this technology are needed for NASA's deep-space missions involving electric propulsion. Current operating temperature ranges are so narrow as to require substantial thermal management, thus increasing the specific mass of the power and propulsion system. High-voltage capability is required to manage current for high power electric thrusters. The deep-space radiation environment would rapidly degrade current components.

Table 19. TA 3.3.5 Technology Candidates – not in priority order

TA	Technology Name	Description
3.3.5.1	Very High-Voltage, High-Power Semiconductors	Semiconductor MOSFETS and diodes that are high-voltage, high-temperature, radiation-hardened, and exhibit low switching and conduction loss.
3.3.5.2	High-Temperature, High-Voltage Capacitors	Low equivalent series resistance (ESR), high-voltage capacitors that can operate in the intended space environment are critical to successful converter design.
3.3.5.3	Modular Power Converters	Modular power processing technology that can use a combination of intelligent embedded controls, advanced semiconductors, flexible mechanical components, and "smart" standard thermal and electrical interfaces to enable reusability; and highly-efficient power transfer.
3.3.5.4	Advanced Power Processing Units	Advanced power processing unit for a high-power electric propulsion system.

TA 3.4: Cross Cutting Technology

TA 3.4 Cross Cutting Technology areas are discussed in the following technology roadmaps:

3.4.1 Analytical Tools

Analytical Tools has been addressed within TA 11 Modeling, Simulation, Information Technology and Processing. For more information regarding Analytical Tools technologies, please refer to section TA 11.2.4 Science Modeling and 11.2.5 Frameworks, Languages, Tools and Standards.

3.4.2 Green Energy Impact

Green Energy Impact has been addressed within TA 15 Aeronautics. For more information regarding Green Energy Impact technologies, please refer to section TA 15.4.1 Introduction of Low Carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems.

3.4.3 Multi-Functional Structures

Multi-functional Structures have been addressed within TA 12 Materials, Structures, Mechanical Systems and Manufacturing and TA 10 Nanotechnology. For more information regarding Multi-Functional Structures technologies, please refer to section TA 12.1.1 Lightweight Structural Materials and section TA 10.2.2 Power Generation.

3.4.4 Alternative Fuels

Alternative Fuels has been addressed within TA 15 Aeronautics. For more information regarding Alternative Fuels technologies, please refer to section TA 15.4.2 Introduction of Alternative Propulsion Systems.

Appendix

Acronyms

AEM	Alkaline Exchange Membranes
ARTG	Advanced Radioisotope Thermoelectric Generator
ASRG	Advanced Stirling Radioisotope Generator
BOL	Beginning-Of-Life
DDT&E	Design, Development, Test, and Evaluation
DOD	Depth of Discharge
DRA	Design Reference Architecture
DRM	Design Reference Mission
EMF	ElectroMagnetic Force
eMMRTG	enhanced Multi-Mission Radioisotope Thermoelectric Generator
ESR	Equivalent Series Resistance
EVA	ExtraVehicular Activity
FDIR	Fault Detection, Isolation, and Recovery
GEO	GEosynchronous Orbit
GPHS	General Purpose Heat Source
HEO	High-Earth Orbit
HIHT	High Intensity, High Temperature
IMLEO	Initial Mass in Low-Earth Orbit
ISRU	In-Situ Resource Utilization
ISS	International Space Station
LEO	Low-Earth Orbit
LILT	Low Intensity Low Temperature
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
NASA	National Aeronautics and Space Administration
NEA	Near-Earth Asteroid
OCT	Office of the Chief Technologist
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PMAD	Power Management and Distribution
PV	PhotoVoltaic
RFC	Regenerative Fuel Cell
RHU	Radioisotope Heater Unit
RPS	Radioisotope Power System
RTG	Radioisotope Thermoelectric Generators
SEP	Solar Electric Propulsion
SOA	State Of the Art
SOFC	Solid Oxide Fuel Cell
SRG	Stirling Radioisotope Generator
STIP	Strategic Technology Investment Plan
TA	Technology Area

TABS	Technology Area Breakdown Structure
TE	Thermoelectric
TID	Total Ionizing Dose
TRL	Technology Readiness Level
TWDEC	Traveling Wave Direct Energy Conversion
U.S.	United States

Abbreviations and Units

Abbreviation	Definition
%	Percent
αT	Total Specific Mass kg/kW_e
A	Ampere
^{241}AM	Americium 241 (isotope)
A.U.	Astronomical Units
C	Battery C-rate
° C	Degrees Celsius
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
cm^3	Cubic Centimeter
Cu	Copper
DOD	Depth of Discharge
D-T	Deuterium – Tritium (fusion reaction)
F	Farad
g	Grams
g	Gravity
GW	Gigawatt
H_2	Hydrogen
Hz	Hertz
in	Inches
K	Kelvin
kg	Kilogram
km	Kilometer
KOH	Potassium Hydroxide
krad	Kilorads
kV	Kilovolt
kW	Kilowatt
kW_e	Kilowatt Electric
kWh	Kilowatt Hours
L	Liters
Li	Lithium
m	Mass
m^2	Square Meters
m^3	Cubic Meters
meV	Mega Electrovolt
msec	Millisecond

Abbreviation	Definition
mT	Metric Ton
mW	Milliwatt
MW_e	Megawatt Electricity
MWh	Megawatt Hours
η	Efficiency
O_2	Oxygen
p-^{11}B	Proton – Boron-11 (fusion reaction)
psi	Pounds per Square Inch
^{238}PU	Plutonium 238
Q	Power-Out/Power-In
SKD	Skutterrudite
UO_2	Uranium Dioxide
V	Volts
W	Watts
W_e	Watts Electricity
Wh	Watt Hours
W-UN	Tungsten Uranium Nitride
µF	Microfarads
µJ	Microjoules

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Technology Candidate Snapshots

3.1 Power Generation
3.1.1 Energy Harvesting

3.1.1.1 Electrodynamic Tether Energy Harvesting

TECHNOLOGY

Technology Description: An electrodynamic tether is essentially a long conducting wire extended from a spacecraft. The gravity gradient field pulls the tether taut and tends to orient the tether along the vertical direction. As the tether orbits around the Earth (or other planet), it crosses the body's magnetic field lines at orbital velocity (7 to 8 kilometers per second). The motion of the conductor across the magnetic field induces a voltage along the length of the tether. This voltage, which is called the "motional electromagnetic force (EMF)," can be up to several hundred volts per kilometer. Within the ionosphere, free electrons are collected by the tether, producing useful power of up to several kilowatts at the expense of the spacecraft orbital altitude, from which the energy is derived.

Technology Challenge: Long-life tether, high voltage, and high current control algorithms represent key challenges with this technology.

Technology State of the Art: The 20-kilometer Tethered Satellite System demonstrated high power operation in low-Earth orbit (LEO), operating at > 2 kW_e.

Parameter, Value:

Length: ~20 km;

Current: ~1 amp with duration of < 1 day

TRL: 5

Technology Performance Goal: Produce a long, lightweight conducting tether power system.

Parameter, Value:

Earth operational derived parameters: Length: > 1 kilometer;

Current > 1 amp with duration of months to years;

Jovian derived parameters:

Length: > 1 kilometer;

Current: > 5 amp with duration of months to years

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Nanotube Space Tether: TA 10.3.3

CAPABILITY

Needed Capability: Enable capability for on-demand, high-power energy harvesting.

Capability Description: Provide moderate to high power for Earth orbiting spacecraft (near-term) and high power for Jovian-bound spacecraft (long-term).

Capability State of the Art: Solar panels and batteries for continuous power and batteries or capacitors for burst power.

Parameter, Value:

Energy stored: ~80 kW/m^3

Capability Performance Goal: Produce burst power as needed.

Parameter, Value:

Energy stored: > 1 kW power on-demand

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years

3.1 Power Generation
3.1.2 Chemical

3.1.2.1 Polymer Electrolyte Membrane Fuel Cells (PEMFC)

TECHNOLOGY

Technology Description: Fuel cell system that employs a hydrogen ion conducting polymer electrolyte membrane and is capable of operating on hydrogen and oxygen at a temperature of < 100° C.

Technology Challenge: Challenges include performance on propellant-quality fuels, water management in zero-g; seals fabrication and materials selection, maintaining stack integrity, load swing cycle tolerance, long life, and high reliability.

Technology State of the Art: Advanced polymer electrolyte membrane fuel cell (PEMFC) for future human space missions with emphasis is on non-flow through PEMFC designs.

Parameter, Value:

Power: 1 kW;
Efficiency: 70%;
Lifetime: > 100 hours;
Operating temperature: < 100° C

TRL
4

Technology Performance Goal: High specific power, high specific energy, high conversion efficiency, long life, high reliability, and operational tolerance with propellant grade hydrogen and oxygen at an operating temperature of < 100° C.

Parameter, Value:

Power: 5 kW;
Specific power: 130 W/kg;
Efficiency: > 75%;
Lifetime: > 10,000 hours

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-power and long-life fuel cells for large robotic and human rovers.

Capability Description: Provide power for robotic and human rovers and habitable spacecraft.

Capability State of the Art: Alkaline fuel cells (H_2-O_2) have been successfully used to power spacecraft in the past.

Parameter, Value:

Alkaline fuel cells (H_2-O_2), nominal power: 5 kW;
Specific power: 50 W/kg;
Efficiency: 70%;
Lifetime: 2,500 hours;
Operating temperature: 70-90° C

Capability Performance Goal: Subsystem service in the designated application requires high specific power, high specific energy, high conversion efficiency, long life, and high reliability. Operation on propellant grade reactants. Operation in deep space and planetary surface environments.

Parameter, Value:

Power: 5 kW;
Specific power: 100 W/kg;
Lifetime: > 10,000 hours

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	2 years

3.1 Power Generation
3.1.2 Chemical

3.1.2.2 Solid Oxide Fuel Cells (SOFC)

TECHNOLOGY

Technology Description: High-temperature (700-1,000° C) fuel cell system that employs a sold oxide electrolyte and is capable of operating on propellant grade hydrogen (H_2) or methane (CH_4) and oxygen (O_2).

Technology Challenge: Temperature and pressure load swing cycle tolerance, interconnects, system integration and control, thermal management, seals, high reliability (no leaks, proper compression).

Technology State of the Art: CH_4-air solid oxide fuel cell (SOFC) systems for terrestrial mobile applications are being developed.

Parameter, Value:

Power: 300 W;

Specific power: 100 W_e/kg;

Efficiency: < 50%;

Lifetime: 3,000 hours

Operating temperature: 600-800° C; Integrated systems for space applications not yet built

TRL
2

Technology Performance Goal: High specific power, high specfic energy, high conversion efficiency, long life, and high reliability. Operation on propellant grade CH_4 and O_2.

Parameter, Value:

Power: 5 kW;

Specific power: 130 W/kg;

Efficiency: > 70%;

Lifetime: > 10,000 hours

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Nanoporous SOFC electrodes: TA 10.2.2

CAPABILITY

Needed Capability: High-power and long-life fuel cells for large robotic and human rovers.

Capability Description: Provide power for surface systems using residual fuel from liquid oxygen/methane landers.

Capability State of the Art: H_2-O_2 alkaline fuel cells have been used to power Apollo and Space Shuttle missions.

Parameter, Value:

Nominal power: 5 kW;

Specific power: 50 W/kg;

Efficiency: 70%;

Life: 2,500 hours;

Operating temperature: 70-90° C

Capability Performance Goal: Subsystem service in the designated application requires high specific power, high specific energy, high conversion efficiency, long life, and high reliability. Operation on propellant grade methane. Operation in planetary surface environments.

Parameter, Value:

Power: 5 kW;

Specific power: 100 W/kg;

Efficiency: > 75%;

Lifetime: > 10,000 hours

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

3.1 Power Generation
3.1.2 Chemical

3.1.2.3 Very High Efficiency Fuel Cells

TECHNOLOGY

Technology Description: Fuel cell system that employs advanced membrane to provide efficiency substantially higher than existing proton exchange membrane (PEM), alkaline, or solid oxide fuel cells.

Technology Challenge: Membrane durability and high reliability.

Technology State of the Art: Advanced proton and alkaline (OH-) exchange membranes (PEM and AEM).

Parameter, Value:

System has not yet been built, so parameter value is based on demonstrated component performance: 80% efficiency with PEMs

TRL 2

Technology Performance Goal: High specific power, high specfic energy, high conversion efficiency, long life, and high reliability. Operation on propellant grade hydrogen and oxygen.

Parameter, Value:

Power: 5 kW;

Specific power: > 150 W/kg;

Efficiency: > 80%;

Lifetime: > 10,000 hours

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Fuel cell membrane electrode assembly (MEA): TA 10.2.1

CAPABILITY

Needed Capability: High-power and long-life fuel cells for large robotic and human rovers.

Capability Description: Provide power for robotic and human rovers and surface systems with substantially reduced reactant tank volumes.

Capability State of the Art: H_2-O_2 alkaline fuel cells have been used to power Apollo and Space Shuttle missions.

Parameter, Value:

Power: 5 kW;

Specific power: 50 W/kg;

Efficiency: 70%;

Life: 2,500 hours;

Operating temperature: 70-90° C

Capability Performance Goal: Subsystem service in the designated application requires high specific power, high specific energy, high conversion efficiency, long life, and high reliability. Operation on propellant grade reactants. Operation in deep space and planetary surface environments.

Parameter, Value:

Power: 5 kW;

Specific power: 100 W/kg;

Efficiency: > 80%;

Lifetime: > 10,000 hours

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

3.1 Power Generation
3.1.3 Solar

3.1.3.1 25-150 kW_e-class Solar Array Structures

TECHNOLOGY

Technology Description: Deployable structures sized to carry enough photovoltaic cells to generate up to ~150 kW_e per wing.

Technology Challenge: Highly reliable deployment of large structures with high strength and stiffness that stow into small volumes.

Technology State of the Art: Autonomously-deployable, tensioned-membrane, flexible blanket solar arrays.

Parameter, Value:
Wing power: 20 kW;
Specific mass: 178 W/kg beginning-of-life (BOL);
Stowed volume efficiency: 40 kW/m^3 BOL;
Deployed strength: > 0.1 g;
Deployed stiffness: > 0.1 Hz

TRL 5

Technology Performance Goal: Solar arrays sized to produce 30-100 kW_e using 29% efficient cells with low mass, low stowed volume, and high strength and stiffness.

Parameter, Value:
Wing power: 25-150 kW_e;
Specific power: > 100 W/kg;
Stowed volume efficiency: > 40 Kw/m^3;
Deployed strength: > 0.1 g;
Depolyed stiffness: > 0.1 Hz

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Solar power up to ~300 kW_e.

Capability Description: Provide electrical power for planetary surface elements and for high-power solar electric propulsion stages.

Capability State of the Art: Low power, rigid panel solar array structures.

Parameter, Value:
Wing power: 10kW_e;
Specific power: 60 W/kg;
Stowed volume efficiency: 10 kW/m^3;
Deployed strength: 0.005 g;
Deployed stiffness: 0.05 Hz

Capability Performance Goal: Solar arrays sized to produce 30-100 kW_e using 29% efficient cells with low mass, low stowed volume, and high strength and stiffness.

Parameter, Value:
Wing power: 25-150 kW_e;
Specific power: > 100 W/kg;
Stowed volume efficiency: > 40 kW/m^3;
Deployed strength: > 0.1 g;
Depolyed stiffness: > 0.1 Hz

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	2 years
Discovery: Discovery 13	Enabling	--	2020	2017	2 years
Discovery: Discovery 14	Enabling	--	2023	2020	2 years

3.1 Power Generation
3.1.3 Solar

3.1.3.2 250 kW_e-class Solar Array Structures

TECHNOLOGY

Technology Description: Deployable structures sized to carry enough photovoltaic cells to generate ~250 kW_e per wing.

Technology Challenge: Highly reliable deployment of large structures with high strength and stiffness that stow into small volumes.

Technology State of the Art: Autonomously-deployable, tensioned-membrane, flexible blanket solar arrays.

Parameter, Value:

Wing power: 20 kW_e;
Specific mass: 178 W/kg beginning-of-life (BOL);
Stowed volume efficiency: 40 kW/m^3 BOL;
Deployed strength: > 0.1 g;
Deployed stiffness: > 0.1 Hz

TRL 5

Technology Performance Goal: Solar arrays sized to produce ~250 kW_e using 33% efficient cells with low mass, low stowed volume, and high strength and stiffness.

Parameter, Value:

Wing power: 300-800 kW_e;
Specific power: > 100 W/kg;
Stowed volume efficiency: > 40 kW/m^3;
Deployed strength: > 0.1 g;
Depolyed stiffness: > 0.1 Hz

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Solar power up to ~500 kW_e.

Capability Description: Provide electrical power for very high-power solar electric propulsion stages.

Capability State of the Art: Low-power, rigid-panel solar array structures.

Parameter, Value:

Wing power: 10kW_e;
Specific power: 60 W/kg;
Stowed volume efficiency: 10 kW/m^3;
Deployed strength: 0.005 g;
Deployed stiffness: 0.05 Hz

Capability Performance Goal: Solar arrays sized to produce ~250 kW_e using > 33% efficient cells operating at > 250 V with low mass, low stowed volume, and high strength and stiffness

Parameter, Value:

Wing power: 300-800 kW_e;
Specific power: > 100 W/kg;
Stowed volume efficiency: > 40 kW/m^3;
Deployed strengthss: > 0.05 g;
Deployed stiffness: > 0.1 Hz

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	1 year
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	1 year
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	1 year
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	1 year
Discovery: Discovery 14	Enabling	--	2023	2020	1 year

3.1 Power Generation
3.1.3 Solar

3.1.3.3 MW_e-class Solar Array Structures

TECHNOLOGY

Technology Description: Deployable structures sized to carry enough photovoltaic cells to generate ~500 kW_e per wing.

Technology Challenge: Highly reliable deployment of large structures with high strength and stiffness that stow into small volumes.

Technology State of the Art: Autonomously-deployable, tensioned-membrane, flexible blanket solar arrays.

Parameter, Value:

Wing power: 20 kW;
Specific power: 178 W/kg beginning-of-life (BOL);
Stowed volume efficiency: 41 kW/m^3 BOL;
Deployed strength: > 0.1 g;
Deployed stiffness: > 0.1 Hz

TRL 5

Technology Performance Goal: Solar arrays sized to produce ~500 kW_e using 33% efficient cells with low mass, low stowed volume, and high strength and stiffness.

Parameter, Value:

Wing power: > 500 kW_e;
Specific power: > 100 W/kg;
Stowed volume efficiency: > 40 kW/m^3;
Deployed strength: > 0.1 g;
Deployed stiffness: > 0.1 Hz

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Solar power ~1 MW_e.

Capability Description: Provide electrical power for ultra high-power solar electric propulsion stages.

Capability State of the Art: Low-power, rigid-panel solar array structures.

Parameter, Value:

Wing power: 10 kW_e;
Specific power: 60 W/kg;
Stowed volume efficiency: 10 kW/m^3;
Deployed strength: 0.005 g;
Deployed stiffness: 0.05 Hz

Capability Performance Goal: Solar arrays sized to produce ~500 kW_e using 33% efficient cells with low mass, low stowed volume, and high strength and stiffness.

Parameter, Value:

Wing power: > 500 kW_e;
Specific power: > 100 W/kg;
Stowed volume efficiency: > 40 kW/m^3;
Deployed strength: > 0.05 g;
Deployed stiffness: > 0.1 Hz

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

3.1 Power Generation
3.1.3 Solar

3.1.3.4 Reliably Retractable Solar Arrays

TECHNOLOGY

Technology Description: Solar arrays that can be retracted in-flight and redeployed multiple times.

Technology Challenge: Robust operation in deep-space environment.

Technology State of the Art: Demonstration model retractable solar array.

Parameter, Value:
Wing power: sized for 1.5 kW_e;
Specific power: 120 W/kg;
Number of retractions: > 100

TRL: 4

Technology Performance Goal: Solar arrays must accommodate a wide variety of cell blanket technology, using a lightweight, low stowed volume structure.

Parameter, Value:
Wing power: 1-10 kW_e;
Specific power: > 100 W/kg;
Number of retractions: > 10

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Solar arrays that retract reliably.

Capability Description: Provide re-stow capability in flight to permit maneuvers which require tight clearances.

Capability State of the Art: Once deployed, array retraction and redeployment is unreliable.

Parameter, Value:
Design number of retractions: 10 motorized deployments and retractions

Capability Performance Goal: Solar arrays must accommodate a wide variety of cell blanket technology, using a lightweight, low stowed volume structure.

Parameter, Value:
Wing power: 1-10 kW_e;
Specific power: > 100 W/kg;
Number of retractions: > 10

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	1 year
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	1 year
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	1 year
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	1 year
Living with a Star: Geospace Dynamics Constellation (GDC)	Enhancing	--	2030	2019	1 year
Discovery: Discovery 13	Enhancing	--	2020	2017	1 year

3.1 Power Generation
3.1.3 Solar

3.1.3.5 Acid-Resistant Solar Array Structures

TECHNOLOGY

Technology Description: Structures that support photovoltaic blankets to provide power to vehicles on high-altitude Venus missions.

Technology Challenge: Long life under acid attack, intense radiation, and at high temperatures.

Technology State of the Art: Commercial acid-tolerant coatings exist for terrestrial applications.

Parameter, Value:
No data on combined radiation effects.

TRL 1

Technology Performance Goal: Low structural strength degradation in high Venus altitude for one year.

Parameter, Value:
Strength reduction: < 10%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Acid-resistant structures.

Capability Description: Provide electrical power in high Venus altitude.

Capability State of the Art: Does not exist.

Parameter, Value:
Not applicable.

Capability Performance Goal: Low structural strength degradation in high Venus altitude for one year.

Parameter, Value:
Strength reduction: < 10%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years

3.1 Power Generation
3.1.3 Solar

3.1.3.6 Reduced-Cost Photovoltaic Blankets

TECHNOLOGY

Technology Description: Reduce the cost of photovoltaic blankets by lower-cost photovoltaic cell technologies and/or automated manufacturing processes to assemble cells, interconnects, and/or coverglasses.

Technology Challenge: Reducing manufacturing costs while maintaining robust deep-space performance.

Technology State of the Art: Several approaches, including: substrate reuse for Triple Junction and Inverted Metamorphic Multijunction cells, micro-fabricated cells, faster semiconductor growth times, better material utilization, and improved automation manufacturing techniques.

Parameter, Value:
Not applicable.

TRL 4

Technology Performance Goal: Low recurring costs for the photovoltaic blanket.

Parameter, Value:
Blanket cost: 25% of baseline

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low-cost solar arrays.

Capability Description: Reduce costs for very large solar arrays.

Capability State of the Art: Triple junction cells are robotically laid down onto rigid panels for < 10 kW solar arrays.

Parameter, Value:
Blanket cost: baseline

Capability Performance Goal: Low recurring costs to manufacture flexible photovoltaic blankets.

Parameter, Value:
Blanket cost: 25% of baseline

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years
Living with a Star: Geospace Dynamics Constellation (GDC)	Enhancing	--	2030	2019	2 years

3.1 Power Generation
3.1.3 Solar

3.1.3.7 Low-Intensity, Low-Temperature (LILT) Radiation-Tolerant Photovoltaic Blankets

TECHNOLOGY

Technology Description: High-efficiency low-intensity, low-temperature (LILT) photovoltaic cells integrated into solar array substrates with interconnects and coverglasses for radiation-tolerant operation.

Technology Challenge: High conversion efficiency at low insolation and long life under intense radiation.

Technology State of the Art: Bandgap-modified triple junction photovoltaic cells.

Parameter, Value: TRL

Not applicable. 2

Technology Performance Goal: High conversion efficiency at low temperature, long-duration, deep-space radiation tolerance.

Parameter, Value: TRL

Array efficiency of 30% at 5 A.U. and -130° C, after six months in Jovian orbit. 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Solar power far from the Sun.

Capability Description: Provide electrical power for exo-planetary missions (e.g., Jovian).

Capability State of the Art: Silicon Hi-ETA cells.

Parameter, Value:

Power: 7.1 kW beginning-of-life (BOL) at 1 A.U., 400 W at 5.25 A.U.; -130° C

Capability Performance Goal: High conversion efficiency at low temperature, long-duration, deep-space radiation tolerance.

Parameter, Value:

Array efficiency of 30% at 5 A.U. and -130 °C after six months in Jovian orbit.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enabling	--	2023	2020	2 years
Planetary Flagship: Europa	Enabling	--	2022*	2019	2 years
New Frontiers: lo Observer	Enabling	--	2029	2021	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

3.1 Power Generation
3.1.3 Solar

3.1.3.8 High-Temperature, Radiation-Tolerant Photovoltaic Blankets

TECHNOLOGY

Technology Description: High-temperature, radiation-tolerant photovoltaic cells, interconnects, and coverglasses integrated into solar array substrates.

Technology Challenge: Long life under intense radiation and at high temperature.

Technology State of the Art: No cells are being developed for high temperature operation.

Parameter, Value: Not applicable.

TRL: None

Technology Performance Goal: High conversion efficiency at high-temperature, long-duration, deep-space radiation tolerance.

Parameter, Value: Array efficiency of 30% at 0.35 A.U. and 250° C, after one year.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Solar power near the Sun.

Capability Description: Provide electrical power for near-Sun missions.

Capability State of the Art: Reflectors are used to deflect heat, lowering the efficiency of the array.

Parameter, Value: Not applicable.

Capability Performance Goal: High conversion efficiency at high-temperature, long-duration, deep-space radiation tolerance.

Parameter, Value: Array efficiency of 30% at 0.35 A.U. and 250° C, after one year.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Explorer Class: Explorer Missions	Enabling	--	2023	2020	2 years

3.1 Power Generation
3.1.3 Solar

3.1.3.9 Acid-Resistant, High-Temperature, Radiation-Tolerant Photovoltaic Blankets

TECHNOLOGY

Technology Description: Acid-resistant photovoltaic (PV) cells, interconnects, and coverglasses integrated into solar array substrates.

Technology Challenge: Long life under acid attack, intense radiation, and at high temperature.

Technology State of the Art: Single crystal rhombohedral silicon germanium (SiGe) growth with quantum well epitaxy demonstrated.

Parameter, Value:
Not applicable.

TRL 1

Technology Performance Goal: Low photovoltaic performance degradation in high Venus altitude for one year.

Parameter, Value:
PV efficiency: > 40%;
Life: > 1 year in high Venus altitude

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Solar power generation in high Venus altitude.

Capability Description: Provide electrical power for propulsion and spacecraft systems for high-altitude Venus missions.

Capability State of the Art: Does not exist.

Parameter, Value:
Not applicable.

Capability Performance Goal: Survivability in the Venus atmosphere.

Parameter, Value:
PV efficiency: > 40%;
Life: > 1 year at high Venus altitude

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years

3.1 Power Generation
3.1.3 Solar

3.1.3.10 Ultra-High-Efficiency Photovoltaic Blankets

TECHNOLOGY

Technology Description: High-efficiency photovoltaic (PV) blankets integrated into solar array substrates.

Technology Challenge: Ultra-high conversion efficiency in required environments; quantum dot photovoltaics.

Technology State of the Art: Carbon nanotube conductive coatings on III-V cells.

Parameter, Value: Efficiency: 38%

TRL 3

Technology Performance Goal: Efficiency > 50% at 1 A.U.

Parameter, Value: Efficiency: > 50% at 1 A.U.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Light-trapping and/or harvesting Nanostructures for Enhanced PV: TA 10.2.2

CAPABILITY

Needed Capability: Solar arrays with reduced mass and stowed volume.

Capability Description: 10’s kW (at 1 A.U.) class solar arrays to provide power for spacecraft systems on the Martian or lunar surface.

Capability State of the Art: Does not exist.

Parameter, Value: Not applicable.

Capability Performance Goal: Ultra-high conversion efficiency.

Parameter, Value: Efficiency: > 50% at 1 A.U.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years
Living with a Star: Geospace Dynamics Constellation (GDC)	Enhancing	--	2030	2019	2 years

3.1 Power Generation
3.1.3 Solar

3.1.3.11 Solar Concentrator Systems

TECHNOLOGY

Technology Description: Reflectors and lenses to concentrate solar radiation on high-efficiency photovoltaic (PV) cells or heat collection elements.

Technology Challenge: Ultra-lightweight lens and reflector material.

Technology State of the Art: Pop-up reflecting and refracting elements.

Parameter, Value:
Concentration: > 2x

TRL: 5

Technology Performance Goal: Concentration of solar radiation.

Parameter, Value:
Concentration: up to 10x

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Solar concentrator systems integrated into large, flexible blanket solar arrays.

Capability Description: Increase overall blanket specific power by increasing solar intensity on PV cells.

Capability State of the Art: Reflectors.

Parameter, Value:
Concentration: 2x

Capability Performance Goal: Increased solar collection to reduce the number of required photovoltaic cells to reduce the cost of very large solar arrays.

Parameter, Value:
Concentration: up to 10x

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years

3.1 Power Generation
3.1.3 Solar

3.1.3.12 Full-Spectrum Hybrid Solar-Thermal Systems

TECHNOLOGY

Technology Description: Hybrid solar-thermal systems to utilize the full-solar-spectrum in high-efficiency, high-energy systems for both electric power and dispatchable heat.

Technology Challenge: System integration of high-efficiency (> 30%), high-temperature (> 350° C) solar photovoltaic (PV) cells, high concentrator systems (concentration ratio > 100), and high-temperature thermodynamic cycle power systems to capture and convert energy at all solar spectrum wavelengths.

Technology State of the Art: System is at Technology Readiness Level (TRL) 1, PV solar cells at TRL 2, high concentration ratio systems at > TRL 8 on Earth (not in space), most thermodynamic cycle power systems at > TRL 7, and desired thermoacoustic systems at TRL 3. Full system still to be demonstrated at TRL 2.

Parameter, Value:

Efficiency: > 44%;

Specific power: > 10 W/kg on Earth;

Cost: $0.31 per W on Earth;

Power: 12 kW on Earth;

Volume efficiency: ~12 kW/m^3 without solar concentrator

TRL

1

Technology Performance Goal: Develop a full-spectrum solar-thermal system for potential powering and heating terrestrial systems and space habitats; need refractive and diffractive optics, and dichromic mirrors.

Parameter, Value:

System efficiency: > 44%;

Specific power: > 30 W/kg in space;

Cost: < $1 per W in space;

Power: 25-150 kW;

Stowed volume efficiency: > 30 kW/m^3;

Degradation rate: < 2% per year

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Photovoltaic element of 3.1.3.9 High-Temperature, Radiation-Tolerant Photovoltaic Blanket

CAPABILITY

Needed Capability: Utilize the energy in the full solar spectrum in highly efficient, high specific power systems that can provide robust, extendable missions in lunar and Mars environments.

Capability Description: Develop highly-integrated hybrid photovoltaic-thermodynamic cycle systems that capture the solar energy across the entire solar wavelength spectrum and convert to useful power generation in lightweight, compact systems. High-temperature solar photovoltaic cells (~350° C and higher).

Capability State of the Art: Does not exist.

Parameter, Value:

Not applicable.

Capability Performance Goal: Develop a full-spectrum solar-thermal system for potential powering of lunar and Mars human habitat. Develop refractive and diffractive optics and dichroic mirrors. Inflatable mirrors, parabolic dishes, and adaptive optics.

Parameter, Value:

System efficiency: > 44%;

Specific power: > 30 W/kg in space;

Solar PV cells: demonstrated at ≥350° C;

Concentration ratio: > 100 in space;

Cost: < $1 per W in space;

Power: 25-150kW;

Volume efficiency: > 30 kW/m^3;

Degradation rate: < 2% per year

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Missions (DRA 5.0)	Enhancing	2033	--	2027	4 years

3.1 Power Generation
3.1.4 Radioisotope

3.1.4.1 Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG-100)

TECHNOLOGY

Technology Description: Radioisotope thermoelectric generator (100 W) with general purpose heat source (GPHS) and high-efficiency thermoelectric converters (η ~10%).

Technology Challenge: Technology maturation, manufacturing, system development, and life demonstration.

Technology State of the Art: High efficiency Skutterudite (SKD) thermoelectric (TE) materials and high efficiency SKD couples with ZT = ~0.9. Life testing of couples (10,000 hours completed to date).

Parameter, Value:	TRL
Couple efficiency: 10% beginning of life (BOL)	3

Technology Performance Goal: 100 W class radioisotope thermoelectric generators (RTG) with high efficiency, high reliability long life, operational capability in deep space and planetary environments, and capable of providing with high quality waste heat.

Parameter, Value:	TRL
Power: 160 W_e; Efficiency: > 8%; Specific power: > 3.6 W_e/kg; Life: 17 years; Power degradation rate: < 2.5% per year; Provisions for effective use of waste heat; Flexibility in heat acquistion temperature up to 470 K	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: High ZT Thermoelectrics: TA 10.2.2

CAPABILITY

Needed Capability: 100-watt class radioisotope power system to power long-life deep-space and planetary surface missions.

Capability Description: 100 W class radioisotope power system that employs a GPHS and a static or dynamic power conversion system.

Capability State of the Art: Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) capable of operation in planetary and deep space environments.

Parameter, Value:

Power: 120 W_e;
Specific power: 2.8 W_e/kg;
Efficiency: 6.1% BOL;
Life: 17 years;
Power degradation rate: ~ 3.8% per year

Capability Performance Goal: 100 W class radioisotope power system with high efficiency, high reliability, long life, and operational capability in deep-space and planetary environments.

Parameter, Value:

Power: 120-160 W_e;
Specific power: ~ 4 W/kg;
Efficiency: 2 x VS MMRTG;
Life: 17 years;
Power degradation rate: < 2.5% per year

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years
New Frontiers: lo Observer	Enhancing	--	2029	2021	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

3.1 Power Generation
3.1.4 Radioisotope

3.1.4.2 Advanced Stirling Radioisotope Generator (ASRG-100)

TECHNOLOGY

Technology Description: Radioisotope power system (100 W) with general purpose heat source (GPHS) and high-efficiency Stirling engine converters (η ~30%).

Technology Challenge: Life and reliability.

Technology State of the Art: High-efficiency Stirling engines performance capabilities demonstrated (30% efficiency). Lab test article that is 100 W class electrically-heated advanced Stirling radioisotope generator (ASRG). Beginning-of-life (BOL) performance capabilities demonstrated. Completed 2 years of life testing at the system level.

Parameter, Value:
Power: 130-140 W;
Efficiency: ~30%;
Power degradation rate: ~1.2% per year

TRL 5

Technology Performance Goal: 100 W class radioisotope power system with high efficiency, high reliability, long life, and operational capability in deep-space and planetary environments.

Parameter, Value:
Power: 130-140 W_e;
Efficiency: ~30%;
Specific power: ~4 W_e/kg;
Life: 17 years;
Power degradation rate: ~1.2% per year

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: 100-watt class radioisotope power system to power long life, deep-space and planetary surface missions.

Capability Description: 100 W class radioisotope power system that employs a GPHS and a static or dynamic power conversion system.

Capability State of the Art: Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) capable of operation in planetary and deep-space environments.

Parameter, Value:
Power: 120 W_e;
Specific power: 2.8 W_e/kg;
Efficiency: 6.1% BOL;
Life: 17 years;
Power degradation rate: ~ 3.8% per year

Capability Performance Goal: 100 W class radioisotope power system with high efficiency, high reliability, long life, and operational capability in deep-space and planetary environments.

Parameter, Value:
Power: 120-160 W_e;
Specific power: ~4 W_e/kg
Efficiency: 2-5 x vs. MMRTG;
Life: 17 years;
Power degradation rate: < 2.5% per year

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years
New Frontiers: Io Observer	Enhancing	--	2029	2021	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

3.1 Power Generation
3.1.4 Radioisotope

3.1.4.3 High-Power Advanced Radioisotope Thermoelectric Generator (ARTG-500)

TECHNOLOGY

Technology Description: Radioisotope thermoelectric (TE) generator (500 W) with general purpose heat source (GPHS) and high-power, high-efficiency thermoelectric converters (η ~15%).

Technology Challenge: High-efficiency and long-life thermoelectric couples with lower power degradation rate; couples capable of integration with GPHS radioisotope thermoelectric generator (RTG)-like system platform.

Technology State of the Art: Developed higher-efficiency, higher-temperature TE materials (ZT_ave ~1.2). Segmented couples beginning-of-life (BOL) performance demonstrated (15%).

Parameter, Value:	TRL
Couple efficiency: 15% BOL	2

Technology Performance Goal: 500 W class RTG with high efficiency, high reliability, and long life capability for deep-space missions with high-quality waste heat.

Parameter, Value:	TRL
Power: 500 W_e; System efficiency: ~ 12%; System specific power: > 8 W_e/kg; System life: > 17 years; Power degradation rate: < 2.0% per year; Provisions for effective use of waste heat; Flexibility in heat acquistion temperature up to 470 K	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: High ZT Thermoelectrics: TA 10.2.2

CAPABILITY

Needed Capability: 500-watt class radioisotope power system to power long-life, deep-space science missions.

Capability Description: 500 W class radioisotope power system that employs a GPHS and a static or dynamic power conversion system.

Capability State of the Art: GPHS-RTG (290 W) capable of operating in deep-space vacuum environment; production capability has been discontinued and is not available anymore.

Parameter, Value:

Power: 250-290 W_e;
Specific power: 5.1 W/kg;
Efficiency: 6.3%;
Life: > 17 years;
Power degradation rate: ~ 1.6% per year

Capability Performance Goal: 500 W class radioisotope power system with high efficiency, high reliability, and long life capability for deep-space missions.

Parameter, Value:

Power: 400-600 W_e;
Efficiency: 2-5x vs. GPHS RTG;
Specific power: > 8 W_e/kg;
Life: > 17 years;
Power degradation rate: < 1.6% per year

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years

3.1 Power Generation
3.1.4 Radioisotope

3.1.4.4 High Power Stirling Radioisotope Generator (ASRG-500)

TECHNOLOGY

Technology Description: Radioisotope power system (500 W) with general purpose heat source (GPHS) and high-efficiency and high-power Stirling engine converters (η ~30%).

Technology Challenge: New Stirling radioisotope generator (SRG) development and/or integration of multi-engines generators; life and reliability; and system interfaces.

Technology State of the Art: High-efficiency Stirling engines performance capabilities demonstrated (30% efficiency).

Parameter, Value:

Power: 130-140 W;

Efficiency: ~ 30%

TRL 3

Technology Performance Goal: 500 W class RTG with high efficiency, high reliability, and long life capability for deep-space missions with high-quality waste heat.

Parameter, Value:

Power: 500 W_e;

Efficiency: > 30%;

Specific power: > 8 W_e/kg;

Life: 17 years;

Power degradation rate: < 1.2% per year

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: 500-watt class radioisotope power system to power long-life, deep-space science missions.

Capability Description: 500 W class radioisotope power system that employs a GPHS and a static or dynamic power conversion system.

Capability State of the Art: GPHS-radioisotope thermoelectric generator (RTG) (290 W) capable of operating in deep-space vacuum environment; production capability has been discontinued and is not available anymore.

Parameter, Value:

Power: 250-290 W_e;

Specific power: 5.1 W_e/kg;

Efficiency: 6.3%;

Life: > 17 years;

Power degradation rate: ~ 1.6% per year

Capability Performance Goal: 500 W class radioisotope power system with high efficiency, high reliability, and long life that can operate in deep-space and planetary environments.

Parameter, Value:

Power: 400-600 W_e;

Efficiency: 2-5x vs. GPHS RTG;

Specific power: > 8 W_e/kg;

Life: > 17 years;

Power degradation rate: < 1.6 % per year

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years

3.1 Power Generation
3.1.4 Radioisotope

3.1.4.5 mW-Class Radioisotope Thermoelectric Generators (mW RTG)

TECHNOLOGY

Technology Description: mW radioisotope thermoelectric generator that employs radioisotope heater unit (RHU) and high-efficiency thermoelectric converters.

Technology Challenge: System design and development, long life, and lower power degradation rates.

Technology State of the Art: Other government agencies have conceptual designs for mW-class, RHU-based radioisotope generators employing state of the art thermoelectric converters. Development of thermoelectic couples with advanced materials is in progress.

Parameter, Value:

Couple efficiency: 10% beginning-of-life (BOL)

TRL: 3

Technology Performance Goal: mW-class RTG with high efficiency, high reliability, and long life capability for planetary sensor networks.

Parameter, Value:

Efficiency: > 10%;

Lifetime: > 17 years

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: High ZT Thermoelectrics: TA 10.2.2

CAPABILITY

Needed Capability: mW-class radioisotope power system to power planetary sensor networks.

Capability Description: Radioisotope power system that employs a RHU and a thermoelectric power conversion system.

Capability State of the Art: Space-qualified mW radioisotope power system not available.

Parameter, Value:

Not applicable.

Capability Performance Goal: mW-class radioisotope power system with high efficiency, high reliability, and long life capability for planetary sensor networks.

Parameter, Value:

Power: 60-150 mW;

Efficiency; > 6%;

Lifetime: > 17 years

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years

3.1 Power Generation
3.1.4 Radioisotope

3.1.4.6 Alphavoltaic Atomic Battery

TECHNOLOGY

Technology Description: Radioisotope power system that contains a radioadioactive isotope (such as plutonium-238 (^{238}Pu) or another alpha-emitter) and a semiconductor device that converts alpha radiation directly into electricity.

Technology Challenge: Radiation-tolerant semiconductor materials, long-life alpha voltaic converters, high conversion efficiency, and system design.

Technology State of the Art: Proof of concept alpha voltaic converters have been tested.

Parameter, Value:

Not applicable.

TRL: 1

Technology Performance Goal: Radioisotope power system with high specfic power, high efficiency, long life capability, and can operate in deep-space and planetary environments.

Parameter, Value:

Specific power: > 12 W_e/kg;

Efficiency: > 50%;

Power: 100 W_e to 1 kW_e;

Isotope: ^{238}Pu

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High specific power radioisotope power system to power long-life, deep-space, and planetary surface missions.

Capability Description: Science and human exploration missions would be greatly enhanced by radioisotope power systems offering higher specific power with ^{238}Pu or other alpha-emitter radioisotopes.

Capability State of the Art: Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) capable of operation in planetary and deep-space environments.

Parameter, Value:

Power: 120 W_e;

Specific power: 2.8 W_e/kg;

Efficiency: 6.1%;

Life: 17 years;

Power degradation rate: ~ 3.8% per year

Capability Performance Goal: Radioisotope power system with high specific power, high efficiency, and long life capability that can operate in deep-space and planetary environments.

Parameter, Value:

Specific power: > 12 W_e/kg;

Efficiency: > 50%;

Power: 100 W_e to 1 kW_e;

Isotope: ^{238}Pu

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Push	Enhancing	--	--	--	6 years

3.1 Power Generation
3.1.5 Fission

3.1.5.1 1-4 kW_e Thermoelectric Fission Power System

TECHNOLOGY

Technology Description: 1 to 10 kW_e fission power systems scalable from a common fission core for outer planetary and electric propulsion missions. System uses thermoelectric power conversion.

Technology Challenge: The primary challenge is integrating the required technologies into an affordable system with acceptable performance. Technical challenges include: high-efficiency thermoelectrics, long life, high reliability, system interfaces, and integration.

Technology State of the Art: Low Technology Readiness Level (TRL) small reactor power system designs and demonstrate conceptual feasibility. Some of the major accomplishments to date include: fuel (uranium molybdenum (U-Mo)) tested, and heat pipes tested.

Parameter, Value:

Not available.

TRL: 3

Technology Performance Goal: Common reactor (core/reflector/shield/control) must have adequate specific power at 1 kW_e and have lifetime and reactivity sufficient to support 4 kW_e (per unit) surface power with high-quality waste heat. The goal is to provide an energy-rich environment anywhere in the solar system with adequate specific power.

Parameter, Value:

Power: 1-10 kW_e;

Efficiency: > 8%;

Specific power: > 3 W_e/kg at 4 kW_e;

Life: > 17 years;

Power degradation rate: < 2.5% per year;

10 to 45 kW of waste heat at 470 K

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: High ZT Thermoelectrics: TA 10.2.2

CAPABILITY

Needed Capability: Kilopower fission power system.

Capability Description: Provide 1-4 kW of power using a safe, affordable, reliable, and long-life fission power system for planetary surface missions.

Capability State of the Art: Fission reactor power systems (SNAP series) using thermoelectric conveters were developed in the early 1960s. SNAP-10A reactor power system was used to power a low-Earth orbit (LEO) satellite.

Parameter, Value:

System power: 500 W;

System effciency: 1.6%;

Specific power: < 1 W_e/kg

Capability Performance Goal: 1-10 kW_e fission power at higher specific power.

Parameter, Value:

Power: 1-10 kW_e;

Efficiency: > 8%;

Specific power: > 3 W_e/kg at 4 kW_e;

Life: > 17 Years;

Power degradation rate: < 2.5% per year;

10 to 45 kW of waste heat at 470 K

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	4 years
Planetary Flagship: Europa	Enabling	--	2022*	2019	4 years
New Frontiers: Io Observer	Enabling	--	2029	2021	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

3.1 Power Generation
3.1.5 Fission

3.1.5.2 1-10 kW_e Stirling Fission Power System

TECHNOLOGY

Technology Description: 1 to 10 kW_e fission power systems scalable from a common fission core for outer planetary and electric propulsion missions. Power conversion system options include Stirling and Brayton engines.

Technology Challenge: The primary challenge is integrating the required technologies into an affordable system with acceptable performance. Technical challenges include: high-efficiency Stirling engines, long life, high reliability, system interfaces, and integration.

Technology State of the Art: Low Technology Readiness Level (TRL) small reactor power system designs. Some of the major accomplishments to date include: fuel (U-Mo) tested, and heat pipes tested.

Parameter, Value:

Not available.

TRL: 3

Technology Performance Goal: Common reactor (core/reflector/shield/control) must have adequate specific power at 1 kW_e and have lifetime and reactivity sufficient to support 10 kW_e (per unit) surface power. The goal is to provide an energy-rich environment anywhere in the solar system with adequate specific power.

Parameter, Value:

Power: 1-10 kW_e;

Efficiency: > 20%;

Specific power: > 5 W_e/kg at 10 kW_e;

Life: 17 years;

Power degradation rate: < 1% per year;

4 to 40 kW of waste heat at 420 K

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Kilopower fission power system.

Capability Description: Provide 1-10 kW_e of power using a safe, affordable, reliable, long-life fission power system for planetary surface missions.

Capability State of the Art: Fission reactor power systems (SNAP series) using thermoelectric conveters were developed in the early 1960s. SNAP-10A reactor power system was used to power a low-Earth orbit (LEO) satellite.

Parameter, Value:

System power: 500 W;

System effciency: 1.6%;

Specific power: < 1 W_e/kg

Capability Performance Goal: 1-10 kW_e fission power at higher specific power.

Parameter, Value:

Power: 1-10 kW_e;

Efficiency: > 20%;

Specific power: > 5 W_e/kg at 10 kW_e;

Life: 17 years;

Power degradation rate: < 1% per year;

4 to 40 kW of waste heat at 420 K

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	4 years
Planetary Flagship: Europa	Enabling	--	2022*	2019	4 years
New Frontiers: Io Observer	Enabling	--	2029	2021	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

3.1 Power Generation
3.1.5 Fission

3.1.5.3 10-100 kW_e Fission Power System with Stirling Conversion

TECHNOLOGY

Technology Description: 1 to 10 kW_e fission power systems scalable from a common fission core for outer planetary and electric propulsion missions. System uses thermoelectric power conversion.

Technology Challenge: Life and reliability.

Technology State of the Art	Technology Performance Goal
Technology State of the Art: Uranium dioxide (UO_2) fuel has extensive operating history in relevant environment (nuclear reactor) but has not been operated for long durations (> 10 years) in the exact geometry and temperatures of this application. Other technologies are similarly qualified, but the integrated system is not space qualified.	**Technology Performance Goal:** System must have adequate life at 10-100 kW_e.
Parameter, Value: Not available. **TRL** 4	**Parameter, Value:** Conversion topping temperature: < 900 K; Maximum burnup: 1%; Operating life: > 8 years **TRL** 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: 10-100 kW_e space fission power system.

Capability Description: Provide 10-100 kW_e of power to support both human and robotic missions in deep space and on planetary surfaces.

Capability State of the Art	Capability Performance Goal
Capability State of the Art: None available.	**Capability Performance Goal:** System must have adequate life at 10-100 kW_e.
Parameter, Value: None available.	**Parameter, Value:** Conversion topping temperature: < 900 K; Maximum burn-up: 1%; Operating life: > 8 years

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	8 years

3.1 Power Generation
3.1.5 Fission

3.1.5.4 10-100 kW_e Fission Power System with Solid State Conversion

TECHNOLOGY

Technology Description: 10-100 kW_e fission power system with solid state energy conversion capable of providing full power independent of available sunlight.

Technology Challenge: The primary challenge is integrating the required technologies into an affordable system with acceptable performance. Technical challenges include: high-efficiency thermoelectrics, long life, high reliability, system interfaces, and integration.

Technology State of the Art: Uranium dioxide (UO_2) fuel has extensive operating history in relevant environment (nuclear reactor) but has not been operated for long durations (> 10 years) in the exact geometry and temperatures of this application. Other technologies are similarly qualified, but the integrated system is not space qualified.

Parameter, Value:

Not available.

TRL

4

Technology Performance Goal: 10-100 kW_e fission power at higher specific power with adequate lifetime.

Parameter, Value:

Power: 10-100 kW_e;

Specific power: > 5 W_e/kg;

Operating life: > 8 years;

Maximum burn-up: 1%

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Fluid boiling/evaporation and condensation phase change behavior in partial or microgravity.

CAPABILITY

Needed Capability: 10-100 kW_e space fission power system.

Capability Description: Provide 10-100 kW_e of power to support both human and robotic missions in deep space and on planetary surfaces.

Capability State of the Art: Fission reactor power systems (SNAP series) using thermoelectric converters were developed in the early 1960s. The SNAP-10A reactor power system was used to power a low-Earth orbit (LEO) satellite.

Parameter, Value:

System power: 500 W;

System efficiency: 1.6%;

Specific power: < 1 W_e/kg

Capability Performance Goal: 10-100 kW_e fission power at higher specific power with adequate lifetime.

Parameter, Value:

Power: 10-100 kW_e;

Specific power: > 5 W_e/kg;

Operating life: > 8 years;

Maximum burn-up: 1%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	8 years

3.1 Power Generation
3.1.5 Fission

3.1.5.5 1-10 MW_e Space Fission Power System

TECHNOLOGY

Technology Description: 1-10 MW_e space fission power system capable of providing abundant energy anywhere in the solar system. Primary use would be nuclear electric propulsion to decrease launch mass requirements or mission duration for human missions to Mars.

Technology Challenge: High-temperature fuel certification and minimizing specific mass of integrated system.

Technology State of the Art: Cermet fuels (typically tungsten (W)/uranium dioxide (UO_2) or molybdenum (Mo)/uranium nitride (UN)) have been previously tested and show good potential for meeting performance requirements. The fuels could also be directly applicable to nuclear thermal propulsion. Other fuel forms may also be viable, but are less developed for these particular requirements.

Parameter, Value:

W/UO_2 cermets have been tested to 1,900 K at 1.6 a/o burnup, but are not fully certified for some mission applications.

TRL: 2

Technology Performance Goal: Nuclear fuel will be one key technology. The fuel should be capable of operating at > 1,500 K for a minimum of 2 years and to a total burnup > 5%. If possible, dual-use fuels should be investigated, such as fuel forms potentially applicable to both high-power reactors and nuclear thermal propulsion. High-temperature dynamic power conversion subsystems and high-temperature, low-mass radiators must also be developed.

Parameter, Value:

Specific mass: < 15 kg/kW_e at high power;

Cycle peak temperature: ~ 1,500 K;

Maximum burnup: > 5%;

Operating life: > 2 years

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Megawatt TCS Components: TA 14.2.3

CAPABILITY

Needed Capability: 1-10 MW_e space fission power suitable for advanced nuclear electric propulsion.

Capability Description: Provides abundant energy anywhere in solar system. Primary use would be nuclear electric propulsion to decrease launch mass requirements or mission duration for human missions to Mars.

Capability State of the Art: None available.

Parameter, Value:

None available.

Capability Performance Goal: System must have a low specific mass and adequate life at high power.

Parameter, Value:

System specific mass: < 15 kg/kW_e at high power;

Cycle peak temperature: ~ 1,500 K;

Maximum burnup: > 5%;

Lifetime: > 2 years

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: Push	Enhancing	--	--	--	10 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years

3.1 Power Generation
3.1.5 Fission

3.1.5.6 > 10 MW_e Space Fission Power System

TECHNOLOGY

Technology Description: Low-specific-mass space fission power systems for supporting fast-transit human Mars missions by providing power for nuclear electric propulsion systems.

Technology Challenge: Developing and coupling high-temperature reactor with high-temperature power conversion subsystem.

Technology State of the Art: W/UO_2 cermet fuel has been previously tested and shows some potential for meeting performance requirements. Limited research has been performed on uranium tetrafloride systems, which show significant potential if successfully coupled to magnetohydrodynamics or thermionic power conversion.

Parameter, Value:

Tungsten/uranium dioxide (W/UO_2) cermets have been tested to 1,900 K at 1.6 a/o burnup, but are not fully certified for some mission applications. Thermionic conversion elements have shown in tests conversion efficiency up to 15%.

TRL: 2

Technology Performance Goal: Lower-power system specific mass for mission architectures with reduced launch mass or mission duration.

Parameter, Value:

Specific mass: < 5 kg/kW_e;
Power: > 10 MW_e;
Conversion cycle peak temperature: > 2,000 K;
Maximum burnup: > 5%;
Operating life: > 2 years

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Megawatt TCS Components TA 14.2.3; Thermionic Power Cells TA 10.2.1

CAPABILITY

Needed Capability: Fast-transit human Mars missions.

Capability Description: Ability to perform rapid Earth-Mars transits.

Capability State of the Art: Not available.

Parameter, Value:

Not available.

Capability Performance Goal: > 10 MW_e space fission power system capable of providing abundant energy anywhere in solar system. Primary use would be nuclear electric propulsion to decrease launch mass requirements or mission duration for human missions to Mars or beyond.

Parameter, Value:

Specific mass: < 5 kg/kW_e;
Power: > 10 MW_e;
Conversion cycle peak temperature: > 2,000 K;
Maximum burnup: > 5%;
Operating life: > 2 years

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: Push	Enhancing	--	--	--	10 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

3.1 Power Generation
3.1.6 Fusion

3.1.6.1 Aneutronic Fusion In-Space Power

TECHNOLOGY

Technology Description: Non-Maxwellian plasma confinement of p-^{11}B fusion plasma with traveling-wave direct energy conversion.

Technology Challenge: Challenges include confinement of plasma sufficient to produce net power with Q > 4 and direct energy conversion of fusion product beams of efficiency > 70%.

Technology State of the Art: Experimental data indicates several potential confinements may be scalable to a Q > 1 reactor and test programs are underway. Traveling-wave direct conversion systems have been analytically verified and test validation is underway.

Parameter, Value:	TRL
Not available.	1

Technology Performance Goal: Aneutronic fusion power for in-space propulsion with no activated waste or neutron shielding.

Parameter, Value:	TRL
Specific mass: < 3 kg/kW_e	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Megawatt TCS Components: TA 14.2.3

CAPABILITY

Needed Capability: In-space nuclear power at ultra-low specific mass.

Capability Description: Provides power and propulsion in space to enable round-trip human missions to the Mars surface of less than one year duration.

Capability State of the Art: None available.

Parameter, Value:
Not available.

Capability Performance Goal: In-space nuclear power at ultra-low specific mass with no neutron emissions or activated waste.

Parameter, Value:
System specific mass: < 3 kg/kW_e

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: Push	Enhancing	--	--	--	10 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

3.2 Energy Storage
3.2.1 Batteries

3.2.1.1 High-Specific-Energy, Human-Rated Lithium (Li) Secondary Batteries

TECHNOLOGY

Technology Description: Lithium (Li) secondary batteries employing high specific-capacity electrodes and low-flammability electrolyte.

Technology Challenge: Development of battery components, scale up of these materials, and integration into functioning high-performance and safe cells, higher rates, long cycle life, long calendar life, and improved safety.

Technology State of the Art: Secondary Li-sulfur batteries are being developed for terrestrial applications. These batteries have limited life capabilities and safety issues.

Parameter, Value:

Cell level performance:

Specific energy: 300 Wh/kg;

Cycle life: < 100 cycles (at 100% depth of discharge (DOD))

TRL 3

Technology Performance Goal: High specific energy secondary batteries with low mass, low volume, and improved safety.

Parameter, Value:

Specific energy: > 300 Wh/kg;

Energy density: > 500 Wh/l;

Cycle life: > 200 (at 90% DOD)

Calendar life: > 5 years;

Discharge rate: > C/10;

Tolerant to electrical and mechanical abuse without fire or thermal runaway.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Secondary batteries for long-duration extravehicular activity (EVA).

Capability Description: Secondary batteries with high specific energy and improved safety.

Capability State of the Art: Secondary Li-Ion batteries.

Parameter, Value:

Specific energy: 80-100 Wh/kg;

Energy density: 150-200 Wh/l;

Cycle life: < 500 (at 100% DOD);

Calendar life: > 5 years;

Operating temperature: 0-25° C

Capability Performance Goal: Safe secondary batteries with very low mass, volume, and improved safety.

Parameter, Value:

Specific energy: > 300 Wh/kg;

Energy density: > 500 Wh/l;

Cycle life: > 200 (at 90% DOD);

Calendar life: > 5 years;

Discharge rate: > C/10;

Operating temperature: 0-40° C;

Battery voltage: 20-28 V;

Tolerant to electrical and mechanical abuse without fire or thermal runaway.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	2 years

3.2 Energy Storage
3.2.1 Batteries

3.2.1.2 Long-Life Lithium (Li)-Ion Secondary Batteries

TECHNOLOGY

Technology Description: Long-cycle-life lithium (Li)-Ion batteries employing high-specific-capacity electrode materials and stable electrolytes.

Technology Challenge: Developing very stable electrolytes and high-specific-energy electrode materials with intrinsic reversibility, mass-efficient and safe cell designs, and novel charge management methods.

Technology State of the Art: Prototype C-LiNCA cells with flame retardant electrolytes have been developed and cycle life testing is in progress.

Parameter, Value:	TRL
Cell level performance: Specific energy: 200 Wh/kg; Energy density: 400 Wh/l; Cycle life: 300 (at 100% DOD); Operating temperature: 0-40° C	3

Technology Performance Goal: Long-life, rechargeable Li-ion batteries with low mass, low volume, long calendar life, and improved safety.

Parameter, Value:	TRL
Specific energy: 200-250 Wh/kg; Energy density: 400-500 Wh/l; Cycle life: > 50,000 (at 30% DOD); Calendar life: > 10 years; Discharge rate: > C/5; Operating temperature: 0-25° C; Battery voltage: 28 V; Tolerant to electrical and mechanical abuse without fire or thermal runaway	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Nanostructured Electrodes for Li-Ion Batteries: TA 10.2.2

CAPABILITY

Needed Capability: Long-cycle-life secondary batteries with high specific energy.

Capability Description: Provide long-life secondary batteries for Earth or planetary orbiters and flybys.

Capability State of the Art: Secondary Li-Ion batteries.

Parameter, Value:

Specific energy: 80-100 Wh/kg;

Energy density: 150-200 Wh/l;

Cycle life: < 30,000 (at 30% DOD);

Calendar life: > 5 years;

Operating temperature: 0-25° C

Capability Performance Goal: Secondary batteries with low mass, low volume, very long cycle life, long calendar life, and improved safety.

Parameter, Value:

Specific energy: 200-250 Wh/kg;

Energy density: 400-500 Wh/l;

Cycle life: > 50,000 (at 30% DOD);

Calendar life: > 10 years;

Discarge rate: > C/5;

Operating temperature: 0-25° C;

Battery voltage: 28 V;

Tolerant to electrical and mechanical abuse without fire or thermal runaway

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Earth Systematic Missions: Gravity Recovery and Climate Experiment Follow On (GRACE-FO)	Enhancing	--	2017	2015	2 years

3.2 Energy Storage
3.2.1 Batteries

3.2.1.3 Very Low-Temperature Secondary Lithium (Li)-Ion Batteries

TECHNOLOGY

Technology Description: Low-temperature lithium (Li)-Ion batteries employing electrode materials and electrolytes with improved low-temperature performance (-60° C).

Technology Challenge: Development of low-temperature, non-aqueous electrolytes, and high-specific-energy electrode materials with intrinsic reversibility and mass-efficient cell designs.

Technology State of the Art: Prototype C-LiNCA cylindrical cells have been developed and cycle life testing is in progress.

Parameter, Value:
Cell level performance:
Specific energy: 200 Wh/kg;
Energy density: 400 Wh/l;
Cycle life: 300 (at 100% DOD);
70% capacity retention at -30° C

TRL
3

Technology Performance Goal: Low-temperature secondary Li-Ion batteries with low mass, low volume, medium-long cycle life, and long calendar life.

Parameter, Value:
Specific energy: 200-250 Wh/kg;
Energy density: 400-500 Wh/l;
Cycle life: > 2,000 (at 50% DOD);
Calendar life: > 10 years;
80% capacity retention at -60° C

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Nanostructured Electrodes for Li-Ion Batteries TA 10.2.2

CAPABILITY

Needed Capability: Low-temperature secondary batteries with high specific energy.

Capability Description: Provide low-temperature secondary batteries for robotic and human lunar and Mars lander and rovers.

Capability State of the Art: Secondary Li-ion batteries.

Parameter, Value:
Specific energy: 80-120 Wh/kg;
Energy density: 200-300 W/l;
Cycle life: > 1,000;
Calendar life: 10 years;
Operating temperature: -20 to 40° C

Capability Performance Goal: Secondary batteries with low mass, low volume, medium-long cycle life, long calendar life, and capable of operating at -60° C.

Parameter, Value:
Specific energy: 200-250 Wh/kg;
Energy density: 400-500 W/l;
Cycle life: > 2,000 (at 50% DOD);
Calendar life: > 10 years;
Operating temperature: -60 to 40° C;
Battery voltage: 30 to 120 V

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years

3.2 Energy Storage
3.2.1 Batteries

3.2.1.4 High-Temperature Secondary Batteries

TECHNOLOGY

Technology Description: High-temperature lithium (Li) rechargeable batteries employing electrode materials and electrolytes with high temperature performance capability (200-450° C).

Technology Challenge: Development of high-temperature electrode materials with intrinsic reversibility, high-temperature electrolytes, mass-efficient cell designs, and novel thermal management methods.

Technology State of the Art: High-temperature Na/S, Na-MCl_2 batteries are under development for terrestrial load-leveling applications. Li-FeS_2 batteries were developed in the 1980s.

Parameter, Value:
Cell level performance:
Specific energy: 100 Wh/kg;
Energy density: 200- 250 Wh/l;
Cycle life: 500-1,000 (at 100% DOD);
Operating temperature: 300-400° C

TRL
3

Technology Performance Goal: High-temperature Li battery for one month of operation in Venus surface environments.

Parameter, Value:
Specific energy: > 150 Wh/kg;
Cycle life: > 500;
Environment: 200-450° C and acidic atmosphere;
Calendar life: 5 year

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Nanostructured Electrodes for Li-Ion Batteries: TA 10.2.2

CAPABILITY

Needed Capability: High-temperature secondary batteries with high specific energy.

Capability Description: Provide high-temperature secondary batteries for inner planetary atmospheric and surface missions.

Capability State of the Art: Secondary high-temperature Na-S and Na-MCl_2 batteries for terrestrial applications only.

Parameter, Value:
Specific energy: 80-100 Wh/kg;
Energy density: 80-100 Wh/l;
Operating temperature: 350° C;
Cycle life: > 500

Capability Performance Goal: Secondary high-temperature battery for one month of operation in Venus surface environment.

Parameter, Value:
Specific energy: > 150 Wh/kg;
Cycle life: > 500;
Environment: 200-450° C and acidic atmosphere;
Calendar life: > 3 years

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years

3.2 Energy Storage
3.2.1 Batteries

3.2.1.5 Ultra-Low-Temperature Primary Batteries

TECHNOLOGY

Technology Description: Low-temperature lithium (Li) primary batteries employing electrode materials and electrolytes with ultra-low-temperature performance capability (-150 °C).

Technology Challenge: Development of ultra-low-temperature, non-aqueous electrolytes, high-specific-energy cathode materials, and novel thermal management methods that can provide safe operation at high specific energies.

Technology State of the Art: Inorganic sulfur battery materials concepts.

Parameter, Value:
Not applicable.

TRL
1

Technology Performance Goal: Primary Li batteries with low mass and volume, and capable of operating safely at ultra-low temperatures.

Parameter, Value:
Specific energy: > 200 Wh/kg;
Energy density: > 300 Wh/l;
Operating temperature: -150° C;
Calendar life: 5 years

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Nanostructured Electrodes for Li-Ion Batteries: TA 10.2.2

CAPABILITY

Needed Capability: Ultra-low-temperature primary batteries with high specific energy.

Capability Description: Provide low-temperature primary batteries for outer planetary landers and probes.

Capability State of the Art: Primary Li-$SOCl_2$/Li-SO_2 batteries with thermal management.

Parameter, Value:
Specific energy: 200-250 Wh/kg;
Energy density: 300-400 Wh/l;
Operating temperature: -40 to 30° C;
Calendar life: 7 years

Capability Performance Goal: Primary batteries with low mass and volume, and capable of operating safely at ultra-low temperatures.

Parameter, Value:
Specific energy: > 200 Wh/kg;
Energy density: > 300 Wh/l;
Operating temperature: -150° C;
Calendar life: 5 years

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years

3.2 Energy Storage
3.2.1 Batteries

3.2.1.6 High-Temperature Primary Batteries

TECHNOLOGY

Technology Description: High-temperature lithium (Li) primary batteries employing electrode materials and electrolytes with high-temperature performance capability (200-450° C).

Technology Challenge: Development of high-temperature electrode materials and electrolytes, safe operation at high specific energies, as well as mass-efficient cell designs and novel thermal management methods.

Technology State of the Art: Li-FeS_2 thermal batteries have been developed for other U.S. government agencies.

Parameter, Value:

Specific energy: 35 Wh/kg;

Operating temperature: 300° C

TRL 3

Technology Performance Goal: Primary Li batteries with low mass and volume, and capable of operating at high temperature.

Parameter, Value:

Specific energy: > 200 Wh/kg; Environment: 200-450° C and acidic atmosphere;

Calendar life: 5 years

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Nanostructured Electrodes for Li-Ion Batteries: TA 10.2.2

CAPABILITY

Needed Capability: High-specific-energy and high-temperature primary batteries.

Capability Description: Provide primary batteries for inner planetary landers and probes.

Capability State of the Art: Primary Li-$SOCl_2$ batteries with thermal management.

Parameter, Value:

Specific energy: 200-250 Wh/kg;

Energy density: 300-400 Wh/l;

Operating temperature: 40° C;

Calendar life: 5 years

Capability Performance Goal: Primary high-temperature battery for one month of operation in Venus surface environment.

Parameter, Value:

Specific energy: > 200 Wh/kg;

Environment: 200-450° C and acidic atmosphere;

Calendar life: > 3 years

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years

3.2 Energy Storage
3.2.1 Batteries

3.2.1.7 Battery Physics-Based Models

TECHNOLOGY

Technology Description: Physics-based models that incorporate detailed component geometry and materials to predict the behavior of advanced battery designs under changing environmental conditions.

Technology Challenge: Modeling the microstructure and electrochemical interaction of high-energy battery components.

Technology State of the Art: Models of limited capability are being implemented for electric vehicle applications.

Parameter, Value:

Cell-specific energy and lifetime prediction differs by > 100%.

TRL: 2

Technology Performance Goal: Cell-specific energy and lifetime prediction to within 10% of measured value.

Parameter, Value:

Cell-specific energy and lifetime prediction to within 10% of measured value.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Battery development models.

Capability Description: Predict the performance and guide the development of new battery materials and cell concepts.

Capability State of the Art: Empirical and highly simplified models.

Parameter, Value:

Cell-specific energy and lifetime prediction differs by > 100%.

Capability Performance Goal: Cell-specific energy and lifetime prediction to within 10% of measured value.

Parameter, Value:

Cell-specific energy and lifetime prediction to within 10%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	2 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	2 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years

3.2 Energy Storage
3.2.1 Batteries

3.2.1.8 Extended Shelf-Life Batteries

TECHNOLOGY

Technology Description: High-reliability batteries (or easily assembled battery components) with shelf life in excess of 15 years.

Technology Challenge: High reliability, safety, and output, at relatively low mass, all with a long shelf life.

Technology State of the Art: Single-use commercial batteries advertise shelf lives up to 10 years, but rechargeable batteries typically have poor shelf life.

Parameter, Value:
Shelf life: 5 years

TRL
9

Technology Performance Goal: Batteries must have a long shelf and service life, be highly reliable, safe in close proximity to crew, and store energy at as low a mass as possible (every kilogram of battery mass takes at least 7 kilograms of propellant to ascend off the surface of Mars).

Parameter, Value:
Shelf life: 15 years

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Long shelf-life secondary batteries.

Capability Description: Any battery used for the human exploration of Mars must be able to perform after remaining quiescent for many years.

Capability State of the Art: Single-use commercial batteries advertise shelf lives up to 10 years, but rechargeable batteries typically have poor shelf life.

Parameter, Value:
Secondary battery shelf life: 5 years

Capability Performance Goal: Batteries used in a Mars Ascent Vehicle application will be acceptance tested on Earth, sit quiescent for at least 5.5 years before being re-activated for checkout tests about a week before powering the vehicle used for crew return. Batteries must have a long shelf and service life, be highly reliable, be safe in close proximity to crew, and store energy at as low a mass as possible (every kilogram of battery mass takes at least 7 kilograms of propellant to ascend off the surface of Mars).

Parameter, Value:
Secondary battery shelf life: 15 years

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

3.2 Energy Storage
3.2.2 Flywheels

3.2.2.1 Large Energy Storage Flywheels

TECHNOLOGY

Technology Description: Mechanical energy storage system using high-speed, magnetically-suspended composite wheels and a motor generator to charge and discharge.

Technology Challenge: High-strength fibers for high-energy-density, magnetic materials for frictionless bearings. Integration and qualification of terrestrial flywheel technology for NASA missions.

Technology State of the Art: 100 kW, 25 kW/hour carbon fiber magnetically-suspended flywheels are currently deployed terrestrially in arrays up to 40 MW each. Flywheels have not been developed beyond Technology Readiness Level (TRL) 4 for NASA applications and have limited NASA safety certification.

Parameter, Value:

Specific energy: 50 Wh/kg;

Magnetic bearing loss: 1-2 W per bearing;

High strength fibers: 100,000 psi

Life without service: 15 years and 90,000 cycles

TRL

4

Technology Performance Goal: Improved fiber and magnetic bearing technology to increase energy density and reduce losses.

Parameter, Value:

Specific energy: > 200+ Wh/kg; Temperature: -150° C to +150° C;

Life without service: 20 years and > 150,000 cycles;

Charge/discharge rate: 1 C;

Magnetic bearing loss: 0.01 W per bearing;

High strength fibers,:400,000 psi

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Long-duration, high-power energy storage unaffected by pre-launch storage, wide temperature variations, or long periods of complete discharge standby.

Capability Description: Provide MWh-class energy storage for surface applications.

Capability State of the Art: Flywheels have not yet been flown in space, so batteries that have flown are the proper comparison.

Parameter, Value:

Specific energy: 80-100 Wh/kg;

Operating temperature: 0-25° C;

Cycle life: < 30,000 (at 30% DOD);

Charge/discharge rate: C/10

Capability Performance Goal: Long cycle life, high discharge rate in planetary environment with performance that is not impacted by mission delays or long fully-discharged standby periods.

Parameter, Value:

Specific energy: > 200 Wh/kg;

Temperature: -150° C to +150° C;

Life without service: 20 years and > 150,000 cycles;

Storage life or fully discharged standby life: 5 years;

Charge/discharge Rate: 1 C;

Magnetic bearing loss: 0.01 W per bearing

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years

3.2 Energy Storage
3.2.2 Flywheels

3.2.2.2 High Specific Energy, High Temperature Flywheels

TECHNOLOGY

Technology Description: Mechanical energy storage system using magnetically-suspended carbon nantotube fiber or graphene wheels and a motor generator to charge and discharge.

Technology Challenge: High-strength fibers for high-energy-density, high-temperature epoxy, high-temperature magnetic materials for low-loss, frictionless bearings.

Technology State of the Art: Carbon fiber flywheels have the potential to reach ~200 Wh/kg.

Parameter, Value:	TRL
Carbon fiber limits in flywheel application: ~6 GPa, 150° C	2

Technology Performance Goal: Develop materials for flywheel rotors to dramatically increase specific energy and operating temperature.

Parameter, Value:	TRL
Carbon nanotube or graphine in flywheel application: > 100 GPa, 500° C	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Nanotube flywheels: TA 10.2.2

CAPABILITY

Needed Capability: Energy storage with high specific energy and high operating temperature.

Capability Description: Provide kWh-class energy storage for high-temperature applications.

Capability State of the Art: Flywheels have not yet been flown in space, so batteries that have flown are the proper comparison.

Parameter, Value:

Specific energy: 80-100 Wh/kg;

Operating temperature: 0-25° C;

Cycle life: < 30,000 (at 30% DOD);

Charge/discharge rate: C/10

Capability Performance Goal: Extremely high energy storage capacity with long cycle life and high discharge rate in planetary environment.

Parameter, Value:

Specific energy: > 1,000 Wh/kg;

Operating temperature: +500° C;

Life: 20 years and > 150,000 cycles;

Charge/discharge rate: 1 C

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Push	Enhancing	--	--	--	5 years

3.2 Energy Storage
3.2.2 Flywheels

3.2.2.3 Energy Storage Flywheels for Low-Temperature Applications

TECHNOLOGY

Technology Description: Mechanical energy storage system using high-speed magnetically-suspended composite wheels and a motor generator to charge and discharge.

Technology Challenge: Extremely low loss magnetic suspension that works at cryogenic temperatures.

Technology State of the Art: No low-temperature flywheels currently are in operation. However, high-performance cryogenic bearings have been demonstrated.

Parameter, Value:	TRL
Cryogenic magnetic bearings operating temperature: < -250° C	4

Technology Performance Goal: Flywheel materials characterized at cryogenic temperatures, and magnetic suspension technology demonstrated at cryogenic temperatures in a flywheel system.

Parameter, Value:	TRL
Specific energy: > 200 Wh/kg; Temperature: -250° C to +150° C; Cycle life: > 150,000 cycles; Standby losses: < 1 W; Charge/discharge rate: 1 C	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low-temperature, high-power energy storage.

Capability Description: Provide kWh-class energy storage for low-temperature applications.

Capability State of the Art: Flywheels have not yet been flown in space, so batteries that have flown are the proper comparison.

Parameter, Value:

Specific energy: 80-100 Wh/kg;
Operating temperature: 0-25° C;
Cycle life: < 30,000 (at 30% depth of discharge (DOD));
Charge/discharge rate: C/10

Capability Performance Goal: Long cycle life, high discharge rate in planetary environment.

Parameter, Value:

Specific energy: > 200 Wh/kg;
Temperature: -250° C to +150° C:
Cycle life: > 150,000 cycles;
Charge/discharge rate: 1 C

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Push	Enhancing	--	--	--	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years

3.2 Energy Storage
3.2.3 Regenerative Fuel Cells

3.2.3.1 Hydrogen (H_2)/Oxygen (O_2)-Based Regenerative Fuel Cell

TECHNOLOGY

Technology Description: Regenerative fuel cells (RFCs) produce power and water from energy stored as oxygen and hydrogen and store energy by drawing power to electrolyze stored water into hydrogen and oxygen.

Technology Challenge: Small-scale systems (100 W) must be scaled up and integrated.

Technology State of the Art: Commercial RFC systems rely on gravity water removal and are air-based. NASA has developed NFT proton exchange membrane fuel cell (PEMFC) and is developing 100 W static feed electrolyzer; integrated system not yet developed.

Parameter, Value:
Not applicable.

TRL
2

Technology Performance Goal: Develop 3 kW PEM RFC for Mars surface use.

Parameter, Value:
Specific power/energy: > 50 w/kg;
Efficiency: > 64%;
Life: > 10,000 hours

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High specific energy.

Capability Description: Store energy and provide long-duration power where hydrogen and oxygen are readily available and on/off cycling is expected.

Capability State of the Art: PEM electrolyzers are in use on the International Space Station (ISS) and have been used in past Apollo missions. Regenerative fuel cells have never been built for space applications.

Parameter, Value:
Specific power/energy: 50 W/kg;
Efficiency: 64%;
Lifetime: 1,000 hours

Capability Performance Goal: High-reliability, long-life energy conversion power generation device.

Parameter, Value:
Specific power/energy: > 50 W/kg;
Efficiency: > 64%;
Life: > 10,000 hours

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	2 years

3.2 Energy Storage
3.2.3 Regenerative Fuel Cells

3.2.3.2 Methane (CH_4)/Carbon Dioxide (CO_2)-Based Regenerative Fuel Cell

TECHNOLOGY

Technology Description: Regenerative fuel cells (RFCs) produce power, water, and carbon dioxide from energy stored as methane, oxygen, and water. The carbon dioxide can be exhausted into the Martian atmosphere. These units then store energy by drawing power to electrolyze water into hydrogen and oxygen and drawing hydrogen and power to convert atmospheric carbon dioxide into methane.

Technology Challenge: Sulfur and coke-resistant anodes must be developed and life tested, system-level architecture consistent with 2,000 psi reactant storage must be developed.

Technology State of the Art: Solid oxide fuel cells (SOFCs) are manufactured for terrestrial use today using reformed natural gas or pure hydrogen and air as the fuels. SOFC RFCs have not been demonstrated.

Parameter, Value:

Not applicable.

TRL: 2

Technology Performance Goal: Develop 3 kW SOFC modules that can be used for power generation and fuel regeneration on Mars surface.

Parameter, Value:

Specific power (stack level): 250-500 W/kg;

Specific power (system level): 50-100 W/kg;

Efficiency (stack level): 70-80%; Efficiency (system level): 40-50%; Lifetime of fuel cell and electrolyzer stacks: > 10,000 hours

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Nanoporous SOFC electrodes: TA 10.2.1

CAPABILITY

Needed Capability: High specific energy.

Capability Description: Store energy and provide long-duration power where methane scavenging from fuel supply is a possibility and fuel regeneration is a possibility from carbon dioxide.

Capability State of the Art: SOFC has been used terrestrially but has never been space qualified. Solid oxide regenerative fuel cells do not exist.

Parameter, Value:

Not applicable.

Capability Performance Goal: High-reliability, long-life energy conversion power generation device, with ability to use harvested CH_4 for fuel or CH_4 generated from CO_2.

Parameter, Value:

Specific power (stack level): 250-500 W/kg;

Specific power (system level): 50-100 W/kg;

Efficiency (stack level): 70-80%;

Efficiency (system level): 40-50%;

Lifetime of fuel cell and electrolyzer stacks: > 10,000 hours

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

3.2 Energy Storage
3.2.4 Capacitors

3.2.4.1 High Specific Energy and Power, Wide Temperature Supercapacitors

TECHNOLOGY

Technology Description: Supercapacitors with high specific energy and power over wide operating temperatures, for pulse power applications.

Technology Challenge: Improving the specific energy of supercapacitors, while retaining or improving specific power at low temperatures. Current technologies feature relatively low specific energy, which limits applicability.

Technology State of the Art: Li-ion capacitors, pseudocapacitors, and asymmetric capacitors

Parameter, Value:
Specific energy: 25 Wh/kg;
Specific power: 1,000-10,000 W/kg;
Operating limit: -20° C to +30° C

TRL
3

Technology Performance Goal: Improved specific energy at low temperature, while retaining specific power.

Parameter, Value:
Specific energy: 50-100 Wh/kg;
Specific power: 10,000 W/kg;
Operating limit: -60° C to +30° C

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Provide pulse power capability at low temperatures for spacecraft and avionics operating at low temperatures; supercapacitors can be hybridized with batteries or used for standalone energy storage. Used for high power loads, such as communications, radar, actuation, thrusters, etc.

Capability Description: Double-layer capacitors.

Capability State of the Art: Double-layer capacitors with thermal management.

Parameter, Value:
Specific energy: 5 Wh/kg;
Specific power: 10,000 W/kg;
Operating limit: -40° C to +85° C

Capability Performance Goal: Improved specific energy capacitors at low temperature, while retaining specific power.

Parameter, Value:
Specific energy: 50-100 Wh/kg;
Specific power: 10,000 W/kg;
Operating temperature: -60° C to +85° C

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years

3.3 Power Management and Distribution
3.3.1 Fault Detection, Isolation, and Recovery

3.3.1.1 Autonomous Fault Detection and Isolation for Complex Power Systems

TECHNOLOGY

Technology Description: Autonomous fault detection amounts to detecting the presence of anomalous system behaviors. Fault isolation involves the identification of likely fault candidates that would explain anomalous system behaviors.

Technology Challenge: Spacecraft may have thousands of unique electrical components that can fail. Fault detection and isolation algorithms must be sensitive enough to detect faults early (before catastrophic failures occur), but must also be robust enough to avoid raising too many false alarms.

Technology State of the Art: Fault detection and isolation is currently done primarily with hard coded thresholds. New techniques, which use data driven and model-based analytical techniques to detect anomalous system behavior and isolate probable causes, have been demonstrated in some prototype systems.

Parameter, Value:
> 10% false positive anomaly detection;
< 2% false negative anomaly detection;
Human-in-the-loop needed for fault identification:
< 5% false positive fault identification;
< 10% false negative fault identification

TRL
5

Technology Performance Goal: Technology Readiness Level (TRL) maturation of fault detection and isolation system prototypes for spacecraft power systems. Demonstration on spacecraft power systems.

Parameter, Value:
< 10% false positive anomaly detection;
< 2% false negative anomaly detection;
No human-in-the-loop needed for fault identification:
< 5% false positive fault identification;
< 10% false negative fault identification

TRL
7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reduction in false alarms generated by conservative, hard-coded fault detection thresholds. Reduction in human-in-the-loop actions needed for fault identification.

Capability Description: A reduction in false alarms without an increase in missed fault detection can be accomplished by switching from hard-coded fault detection thresholds to new model-based analytical techniques that will detect anomalous system behavior and isolate probable causes. This also improves confidence in root cause identification and reduces the need for human-in-the-loop analysis.

Capability State of the Art: New techniques have been demonstrated in some prototype systems in laboratory-like settings.

Parameter, Value:
For threshold-based approaches:
> 10% false positive anomaly detection;
< 2% false negative anomaly detection;
Human-in-the-loop needed for fault identification:
< 5% false positive fault identification;
< 10% false negative fault identification

Capability Performance Goal: Demonstration of autonomous fault detection and isolation on spacecraft. Demonstration of the improvement in human-in-the-loop resources needed to check false alarms and make correct maintenance and operations decisions after fault detection.

Parameter, Value:
Small to medium scale spacecraft systems:
< 10% false positive anomaly detection;
< 2% false negative anomaly detection;
No human-in-the-loop needed for fault identification:
< 5% false positive fault identification;
< 10% false negative fault identification

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	2 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years

3.3 Power Management and Distribution
3.3.1 Fault Detection, Isolation, and Recovery

3.3.1.2 Remaining Useful Life Prediction After Fault Detection

TECHNOLOGY

Technology Description: Estimation of the remaining useful operating time of power system components after fault detection.t

Technology Challenge: Spacecraft may have fault cases that still allow for the spacecraft to function. The question to be answered is then: how long can operations be sustained with the degraded system?

Technology State of the Art: Remaining useful life prediction is currently performed in practice mainly using rough calculations of mean component lifetime. Supplementing fault identification and state-of-health estimates with fault growth modeling has been demonstrated for selected power system components, such as wiring, batteries, and motors.

Parameter, Value: Low confidence, reliability-based time-to-failure estimates.

TRL: 4

Technology Performance Goal: Incorporation of fault identification and online state-of-health estimates with fault growth modeling to enable estimation of remaining useful life. Fault growth models can only be developed for some of the critical components in the power system. The initial performance goal is to focus on the prognostics of 2 to 3 critical fault modes.

Parameter, Value: Remaining useful life estimation to supplement fault identification and state-of-health estimation for 2 to 3 critical fault modes in a spacecraft power system.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Estimation of remaining useful operating time assessments are needed to plan system operations and maintenance.

Capability Description: With the online remaining useful life estimates system, operations can be made more efficient and system safety can be improved by replacing critical parts just before they reach end of life.

Capability State of the Art: The state of practice for estimating remaining useful life offers very little quantitative data. Maintenance designers are then forced to rely on conservative maintenance policies or accept the risk of sudden failure.

Parameter, Value: No trustworthy, quantitative prognostic estimates for critical power system fault modes exist.

Capability Performance Goal: Demonstration of quantitative remaining useful life estimates based on online fault identification and online component state-of-health estimates. Demonstration of the usefulness of remaining useful life estimates to improve the efficiency and safety of maintenance policies.

Parameter, Value: Remaining useful life estimation to supplement fault identification and state-of-health estimation for 2 to 3 critical fault modes in a spacecraft power system.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	2 years

3.3 Power Management and Distribution
3.3.2 Management and Control

3.3.2.1 Hierarchical Control of a Power System

TECHNOLOGY

Technology Description: Autonomous management of power generation and energy storage, power distribution, and detected faults.

Technology Challenge: Challenges include algorithm development, verification and validation, interfaces with the overall vehicle mission manager, standards and specifications, and development of modular hardware.

Technology State of the Art: Current technology relies on the ground operation to perform most management tasks for power. Any automatic operation is scripted. Small, functional demonstrations have been conducted for the management of energy, distribution, and faults. Some tools exist to aid flight controllers and mission planners with this activity.

Parameter, Value:

Power system control is entirely manual (either ground or flight crew), except for the application of automatic load shed tables for contingencies on orbit (e.g., International Space Station (ISS)).

TRL 3

Technology Performance Goal: Energy management, power distribution management, and fault management should be performed with no human intervention for extended periods of time.

Parameter, Value:

Energy management autonomous operation: > 2 hours;

Power system distribution network management: > 2 hours;

Fault identification and coverage: > 95% for 2 hours

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Intelligent power management and autonomy.

Capability Description: Management and control of the overall power system, including the management of the power generation and energy storage system, the management of the distribution network, and load schedule evaluation. The management and control of the power system described above is performed in autonomous fashion without control by the ground. The system provides monitoring and advice to the astronauts, onboard automated mission manager, and mission control for the operation, management, saving, and fault recovery of the power system.

Capability State of the Art: Current technology relies on the ground operation to perform most of the management tasks for power. Any automatic operation is scripted.

Parameter, Value:

Power system control is entirely manual (either ground or flight crew), except for the application of automatic load shed tables for contingencies on-orbit (e.g., ISS).

Capability Performance Goal: Provide autonomous control of the power system during normal, emergency, and fault recovery operations with support required from the ground and the crew only by exception.

Parameter, Value:

Maintain positive power margins and operational control, safe vehicle equipment and crew during off-nominal operations with minimal human intervention.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	2 years

3.3 Power Management and Distribution
3.3.2 Management and Control

3.3.2.2 Advanced Power Sensors

TECHNOLOGY

Technology Description: Development of non-invasive voltage and current sensors linked with standards-based wireless data links to provide a data-rich environment for power system control and health monitoring.

Technology Challenge: High accuracy and linear operation over wide temperature range.

Technology State of the Art: Current voltage and current sensors must use invasive techniques to achieve required accuracy and bandwidth and generally do not use wireless technology.

Parameter, Value:

Sensor update time: > 1 second;

Hard wired connections;

Invasive sensing

TRL

3

Technology Performance Goal: Provide the ability to run the power system closer to its performance limits with wireless non-invasive sensor technology, thereby reducing mass and increasing reliability.

Parameter, Value:

Sensor update time: < 0.1 second;

Number of sensors points: 10x baseline;

Mass reduction: by 20% via wireless communication;

Sensing methodology: non-invasive

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Increased observability of the power system.

Capability Description: Monitors the power system without disturbing it using a high-data-rate sensor network.

Capability State of the Art: Current voltage and current sensors must use invasive techniques to achieve required accuracy and bandwidth and generally do not use wireless technology.

Parameter, Value:

Sensor update time: > 1 second;

Number of sensors points: baseline;

Cable mass: baseline

Capability Performance Goal: Develop wireless sensors that can use non-invasive techniques along with wireless interconnects to provide a data-rich environment for control.

Parameter, Value:

Sensor update time: < 0.1 second;

Number of sensors points: 10x baseline;

Mass reduction: 20% via wireless communication;

Non-invasive sensors

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	2 years

3.3 Power Management and Distribution
3.3.2 Management and Control

3.3.2.3 Multi-Processor Real-Time Power Simulation

TECHNOLOGY

Technology Description: Networked processors that run distributed, high-fidelity models of power components in real-time systems that provide an input and output environment to evaluate and verify advanced control performance.

Technology Challenge: Development and decomposition of power system models that can be executed in real time on a network of processors.

Technology State of the Art: Current technology relies on general-purpose processors networked with specialized software and standard networks to achieve soft real-time capability.

Parameter, Value:

Current system use: < 12 processors

TRL: 3

Technology Performance Goal: Specialized processors that use dedicated interconnects to achieve high-speed execution of high-fidelity models.

Parameter, Value:

Model update: < 10 msec;

Number of power elements: 50

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Model-based Fault Management Architectures: TA 11.2.2

CAPABILITY

Needed Capability: Real-time power system simulation.

Capability Description: Develop and verify advanced power control systems using high-fidelity simulations.

Capability State of the Art: Current technology permits the use of multiprocessor models, but they can be executed on a limited number of processors with limited fidelity of the model.

Parameter, Value:

Model update time: 100 msec;

Number of power elements: 10

Capability Performance Goal: The current update time needs to be improved to ensure that the proper system dynamics are preserved.

Parameter, Value:

Model update: < 10 msec;

Number of power elements: 50

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	2 years

3.3 Power Management and Distribution
3.3.3 Distribution and Transmission

3.3.3.1 High-Conductivity Carbon Nanotube Wire

TECHNOLOGY

Technology Description: Ultra-low loss (low resistance) wiring that utilizes woven carbon nanotube fiber.

Technology Challenge: Fabrication of low-defect, long-length, highly conductive fiber and low-ohmic-loss, high-mechanical-strength interweave technique.

Technology State of the Art: State of the art is less than the performance of copper wire due to insufficient nanotube fiber length and continuity. A very low-current application, such as signal wire, is acceptable for flight now.

Parameter, Value:
Mass resistivity: ~100 x 10^{-5} W-kg/m^2

TRL: 3

Technology Performance Goal: Produce long high-quality nanotube fiber to be woven into wire that has a high continuity of conductance and strength performance.

Parameter, Value:
Mass resistivity: 0.7 x 10^{-5} W-kg/m^2

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lightweight power distribution wiring.

Capability Description: Distribute power using ultra-high-conductivity cabling to reduce mass and resistivity.

Capability State of the Art: Copper wiring; baseline cable mass (copper with silver plate) for signal wiring.

Parameter, Value:
Mass resistivity: 15 x 10^{-5} W-kg/m^2

Capability Performance Goal: Need lower resistance than copper while keeping equivalent or better tensile strength, turn radius, temperature rating, performance of material over time, and maintaining acceptable making of connections and splicing.

Parameter, Value:
Mass resistivity: 0.7 x 10^{-5} W-kg/m^2

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years

3.3 Power Management and Distribution
3.3.3 Distribution and Transmission

3.3.3.2 Aluminum Wiring and Connectors

TECHNOLOGY

Technology Description: Low-mass wiring.

Technology Challenge: Fabrication of wiring and connectors with adequate bend radius, cold flow resistance, and ability to withstand launch vibration.

Technology State of the Art: Aluminum wiring has flown in commercial aircraft.

Parameter, Value:
Mass resistivity: 7 x 10^{-5} W-kg/m^2

TRL 5

Technology Performance Goal: Produce aluminum wiring and connectors with adequate life that are capable of withstanding spacecraft environmental specifications.

Parameter, Value:
Mass resistivity: 7 x 10^{-5} W-kg/m^2

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lightweight power distribution wiring.

Capability Description: Distribute power using high-conductivity cabling to reduce mass and resistivity.

Capability State of the Art: Copper (Cu) wiring.

Parameter, Value:
Mass resistivity: 15 x 10^{-5} W-kg/m^2

Capability Performance Goal: Lower-mass wiring than Cu for equivalent current capability.

Parameter, Value:
Mass resistivity: 7 x 10^{-5} W-kg/m^2

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	1 year
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	1 year
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	1 year
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	1 year
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	1 year
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	1 year
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	1 year

3.3 Power Management and Distribution
3.3.3 Distribution and Transmission

3.3.3.3 Modular High- and Low-Power Switchgear

TECHNOLOGY

Technology Description: Modular switch using a combination of intelligent semiconductors, flexible mechanical components, and standard thermal interfaces to enable reusability; basic switching element can be reconfigured for multiple applications—both high power and low power. Interface and performance standards are enforced to provide maximum commonality and eliminate proprietary interfaces.

Technology Challenge: Development of mechanical, thermal, and electrical specifications and standards that can be used across multiple platforms.

Technology State of the Art: There are no power orbital replacement units (ORUs) in production that can be used in multiple platforms.

Parameter, Value:
None available.

TRL 3

Technology Performance Goal: Development of modular switching components that can be used for multiple missions and reduce development costs, logistics cost, and logistics weight.

Parameter, Value:
Not applicable.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Modular high- and low-power switchgear.

Capability Description: Reduction of logistics by incorporating interchangeable parts in constructing the power distribution system.

Capability State of the Art: There are no power ORUs in production that can be used in multiple platforms.

Parameter, Value:
Development cost: baseline;
Logistics cost: baseline;
Logistics mass: baseline;
MTBF: > 157,000 hours

Capability Performance Goal: Development of basic power building blocks that can be used for multiple applications in the power distribution system.

Parameter, Value:
Development cost: 50% baseline;
Logistics cost: 50% baseline;
Logistics mass: 25% baseline;
MTBF: > 630,000 hours

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	2 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	2 years

3.3 Power Management and Distribution
3.3.3 Distribution and Transmission

3.3.3.4 High-Voltage Power Distribution, High-Voltage Semiconductors, Passive Components

TECHNOLOGY

Technology Description: Develop new power distribution components to enable reliable operation in a high-voltage environment.

Technology Challenge: High-voltage power switches.

Technology State of the Art: State of the art is limited to 180 volts due to semiconductor limitations.

Parameter, Value:
De-rated semiconductor operating voltage: 180 V;
Passive component derated voltage: ~ 180 V

TRL 3

Technology Performance Goal: Distribute power at increased voltage to lower over power system mass.

Parameter, Value:
De-rated semiconductor operating voltage: > 300 V;
Passive component derated voltage: > 500 V

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Extreme Environment Electronics: TA 10.4.2

CAPABILITY

Needed Capability: Low-mass, high-power distribution.

Capability Description: Distribute 500+ kW of electric power with no increase in mass or loss over present systems.

Capability State of the Art: SOA for present systems is the International Space Station (ISS) power distribution operating at 180 V.

Parameter, Value:
De-rated semiconductor operating voltage: 180 V

Capability Performance Goal: Distribute power at increased voltage to lower overall power system mass.

Parameter, Value:
Distribution system: 50% of baseline

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	2 years

3.3 Power Management and Distribution
3.3.3 Distribution and Transmission

3.3.3.5 High-Temperature Semiconductors, Passive Components, and Interconnects

TECHNOLOGY

Technology Description: Develop new high-temperature semiconductor switches, switch driver diodes, high-temperature capacitors, and magnetic wire and interconnection techniques to permit the high-temperature operation of switchgear and permit reduction in the heat rejection system.

Technology Challenge: Certification of high-temperature control electronics.

Technology State of the Art: State of the art requires a large heat rejection system to maintain the relatively low operating temperature of high-power applications.

Parameter, Value:

Power semiconductor junctions: 100° C;
Control electronics: 100° C;
Passive components: 100° C; Interconnections: 260° C

TRL 3

Technology Performance Goal: Power distribution components and interconnects at high temperatures.

Parameter, Value:

Power semiconductor junctions: 300° C;
Control electronics: 300° C;
Passive components: 300° C; Interconnections: 325° C

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Extreme Environment Electronics: TA 10.4.2

CAPABILITY

Needed Capability: Reduction of thermal cooling mass through the use of high-grade heat.

Capability Description: Increase the operating temperature for high-power applications in order to reduce the mass of heat rejection systems.

Capability State of the Art: Currently, the International Space Station (ISS) requires a large heat rejection system to maintain the relatively low operating temperature of high-power applications.

Parameter, Value:

Power semiconductor junctions: 100° C;
Control electronics: 100° C;
Passive components: 100° C;
Interconnections: 260° C

Capability Performance Goal: Reduction of spacecraft radiator mass through higher operating temperature of electronics.

Parameter, Value:

Power semiconductor junctions: 300° C;
Control electronics: 300° C;
Passive components: 300° C;
Interconnections: 325° C

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	2 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	2 years

3.3 Power Management and Distribution
3.3.3 Distribution and Transmission

3.3.3.6 Extreme Radiation-Hardened Power Distribution

TECHNOLOGY

Technology Description: Develop new power semiconductors and drivers to enable radiation-hard power distribution system.

Technology Challenge: Design and fabrication of solid-state junction to tolerant high total ionizing dose and single event effects.

Technology State of the Art: Parts that have low total ionizing doe (TID) tolerance and low MeV tolerance.

Parameter, Value: Current semiconductor and drivers uses 100 krad TID and single event effects (SEE), 30 MeV.

TRL 3

Technology Performance Goal: Operation or semiconductors and diodes in high radiation environment.

Parameter, Value:
Survival in > 300 krad at low dose rate, SEE > 75 MeV.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Extreme Environment Electronics: TA 10.4.2

CAPABILITY

Needed Capability: Distribution of high power in high-radiation environments.

Capability Description: Distribute 100+ kW of electric power for high-radiation environments with no increase in mass or loss over present systems.

Capability State of the Art: Develop semiconductor switches, drivers, and diodes to survive high-radiation environments. These items require radiation hardening to reduce shielding mass.

Parameter, Value:
Distribution system certified for 20 krad TID and 35 MeV SEE.

Capability Performance Goal: Distribute high power 100+ kW within increased radiation environments and same system mass.

Parameter, Value:
System tolerates > 300 krad TID at low dose rate and SEE > 75 MeV.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enabling	--	2022*	2019	2 years
New Frontiers: Io Observer	Enabling	--	2029	2021	2 years
New Frontiers: Saturn Probe	Enabling	--	2024	2016	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

3.3 Power Management and Distribution
3.3.4 Wireless Power Transmission

3.3.4.1 Integrated Power Conversion for Wireless Power Transmission

TECHNOLOGY

Technology Description: Augment existing E or B field wireless charging to accommodate higher powers over longer throw distance.

Technology Challenge: Development of wireless power transmission components, such as high-efficiency millimeter wave receivers and transmitters, and self-resonant magnetic coupling coils.

Technology State of the Art: Wireless charging for personal electronics and inductive charging of electric vehicles (e.g., buses) and diesel-electric locomotives (2.5 kW capability).

Parameter, Value:

Power in tens of watts with aligned direct contact;

Current receiver efficiency is < 40%

TRL 3

Technology Performance Goal: For millimeter wavelength generators, the efficiency is adequate. However, the efficiency of the receiver needs to be improved.

Parameter, Value:

Power: > 3kW, (100 A charge rate for 32 V system);

Pad alignment forgiving with 1 inch throw distance;

Receiver efficiency: > 85%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Wireless battery charging.

Capability Description: In surface environments where debris and dust makes traditional electrical connectors a maintenance problem (particularly in cases when crew has reduced mobility), wireless charging is a necessary capability. This would also be true for drone refueling, vehicle/rover refueling, etc.

Capability State of the Art: Traditionally, electrical connectors used as wireless power charging methods are limited in distance and power level. Receiver efficiency at millimeter wave frequency is limited.

Parameter, Value:

Power in tens of watts with aligned direct contact;

Current wireless receiver efficiency: < 40%.

Capability Performance Goal: Ideally, drones and surface vehicles would be able to recharged in this manner. These would be higher power systems.

Parameter, Value:

Power: > 3 kW, (100 A charge rate for 32 V system);

Pad alignment forgiving with 1 inch throw distance;

Receiver efficiency: > 85%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	2 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	2 years

3.3 Power Management and Distribution
3.3.4 Wireless Power Transmission

3.3.4.2 Beaming Stations

TECHNOLOGY

Technology Description: Beaming stations are power sources that beam energy to small spacecraft for propulsion and/or power using lasers or microwaves. The technology can also be used for orbital debris removal with laser ablation. The stations can be ground based or space based. The beams can be continuous or pulse mode and provide more flux intensity than sunlight.

Technology Challenge: Challenges include sufficient power generation, storage, and distribution; beam generation system and beam control with adaptive optics; heat dissipation capacity; pointing and tracking subsystem; and atmospheric losses for ground-based stations.

Technology State of the Art: Current solid state diode pumped lasers have had exponential growth in capability over the last 15 years. Time-averaged power output for microwave sources has also increased.

Parameter, Value:

~105 kW laser beam with ~19% wall plug efficiency with a run time of minutes;

1 MW gyrotron oscillator off-the-shelf

TRL: 2

Technology Performance Goal: Operate the total output power requirement with a farm of laser modules or gyrotrons incoherently combined.

Parameter, Value:

Output beam power for LEO to GEO: space-based: -0.5MW, ground-based: ~78 MW;

For deep-space: space-based ~50 MW, ground-based: ~78 MW;

For launch: 240-350 MW laser or 600 MW millimeter microwave.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Small spacecraft weight and volume savings.

Capability Description: Beamed energy reduces spacecraft weight and size by operating as an off-board power source for spacecraft propulsion and/or power.

Capability State of the Art: Current spacecraft obtain propulsion and power from chemical combustion, solar electric, or radioisotopes.

Parameter, Value:

Upper stage mass fraction low-Earth orbit (LEO) to geosynchronous orbit (GEO): ~0.08

Capability Performance Goal: Increase payload mass fraction.

Parameter, Value:

Upper stage mass fraction LEO to GEO: ~0.43

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years
Earth Systemic Missions: Push	Enhancing	--	--	--	5 years
Discovery Class: Push	Enhancing	--	--	--	5 years
New Frontiers: Push	Enhancing	--	--	--	5 years

3.3 Power Management and Distribution
3.3.5 Conversion and Regulation

3.3.5.1 Very High-Voltage, High-Power Semiconductors

TECHNOLOGY

Technology Description: Semiconductor Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETS) and diodes that are high-voltage, high-temperature, radiation-hardened, and exhibit low switching and conduction loss.

Technology Challenge: Efficient operation at high voltage and high power without suffering single event radiation damage in the deep space environment.

Technology State of the Art: While terrestrial parts are available with blocking voltages in excess of 1,700 V, the radiation tolerance of these parts are lacking such that blocking voltage is reduced to ~100 V. Further, junction temperature is limited to 150° C.

Parameter, Value:

Power: ~10 kW (International Space Station (ISS) power channel 1 of 8);

Blocking voltage: ~180 V in ISS environment;

Temperature: 100° C:

Radiation tolerance: 20 krad total ionizing dose (TID) and 35 MeV single event effects (SEE)

TRL 3

Technology Performance Goal: For an 800 V thruster operating point, minimum semiconductor rating would be 1,200 V. Further, the goal would be to have junction temperatures allowable up to 300° C, which would enable the heat sinking system mass to be reduced and rejection efficiency to be improved. All of these would be in extreme environments and with the same conduction and switching loss levels or less.

Parameter, Value:

Power rating: >10 kW and scalable to 300 kW;

Blocking voltage: > 1,200 V; Temperature: 300° C;

Radiation tolerance: > 300 krad TID at low dose rate and SEE > 75 MeV

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Extreme Environment Electronics: TA 10.4.2

CAPABILITY

Needed Capability: High power conversion > 10 kW. Parts will also be needed for very high voltage (kV) power distribution.

Capability Description: Convert power for large electric propulsion applications and surface systems.

Capability State of the Art: No conversion at this power level currently exists in space applications, but if it were implemented it would be done with many parallel and series modules made from lower-rated semiconductor parts.

Parameter, Value:

Power: ~10 kW (ISS power channel 1 of 8);

Blocking voltage: ~180 V in ISS environment;

Temperature: 100° C;

Radiation tolerance: 20 krad TID and 35 MeV SEE

Capability Performance Goal: High-power conversion capability (> 10 kW) in a dense, highly efficient package that can operate in extreme environments, especially those with extreme radiation and temperatures. A converter that can run at high temperatures can reduce system thermal mass with smaller heat sinking.

Parameter, Value:

Power Rating: > 10 kW and scalable to 300 kW;

Blocking voltage: > 1,200 V;

Temperature: 300° C;

Radiation tolerance: > 300 krad TID at low dose rate and SEE > 75 MeV

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

3.3 Power Management and Distribution
3.3.5 Conversion and Regulation

3.3.5.2 High-Temperature, High-Voltage Capacitors

TECHNOLOGY

Technology Description: Low equivalent series resistance (ESR), high-voltage capacitors that can operate in the intended space environment are critical to successful converter design.

Technology Challenge: Efficient and durable operation at high voltage and high temperature in the radiation environment of deep space.

Technology State of the Art: In order to produce high-voltage conversion, in addition to power semiconductors rated at high voltages, passives are needed that are rated at voltages in excess of 200 V and space rated.

Parameter, Value:

Voltage: 200 V;

Capacitance: 1 mF;

Temperature: < 85° C;

Volume: > 1 cm^3

TRL 3

Technology Performance Goal: For an 800 V thruster operating point, the minimum capacitor rating required would be 1,500 V. Also required are capacitance values in the hundreds of mF at temperatures around 150-200° C, in order to allow reduction in heat rejection system mass and improvement efficiency. All of these must be available in extreme radiation environments and with the same size packaging as traditional capacitors.

Parameter, Value:

Voltage: > 1,500 V;

Capacitance: > 100 mF;

Temperature: > 300° C;

Volume: < 1 cm^3

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High (> 10 kW) power conversion.

Capability Description: Convert power for large electric propulsion applications and surface systems.

Capability State of the Art: No conversion at this power level currently exists in space applications, but if it were implemented, it would be done with many parallel and series modules made from lower-rated semiconductor parts.

Parameter, Value:

Power: ~10 kW (International Space Station (ISS) power channel 1 of 8)

Capability Performance Goal: High-power conversion capability (> 10 kW) in a dense, highly efficient package that can operate in extreme environments. A converter that can run at high temperatures can reduce system thermal mass with smaller heat sinking.

Parameter, Value:

Voltage: > 1,500 V;

Capacitance: > 100 mF;

Temperature: > 300° C;

Volume: < 1 cm^3

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

3.3 Power Management and Distribution
3.3.5 Conversion and Regulation

3.3.5.3 Modular Power Converters

TECHNOLOGY

Technology Description: Modular power processing technology that can use a combination of intelligent embedded controls, advanced semiconductors, flexible mechanical components, and "smart" standard thermal and electrical interfaces to enable reusability and highly-efficient power transfer.

Technology Challenge: High reliability power conversion with standard interfaces for operation in the extreme radiation and thermal environments of deep space.

Technology State of the Art: Controls: analog;
Thermal-mechanical interface: custom

Parameter, Value:
Not applicable.

TRL
3

Technology Performance Goal: Controls: digital;
Thermal-mechanical interface: "smart" standard

Parameter, Value:
500 W/kg at multi-kW value;
Efficiency: 96-98%

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Radiation-hard digital controls, advanced power semiconductors, and reconfigurable mechanical and thermal interfaces.

CAPABILITY

Needed Capability: Modular bi-directional converter that can be used for battery charge/discharge, as well as vehicle-to-vehicle interfaces that can be configured in series and parallel arrangements to provide additional power and N+1 redundancy.

Capability Description: Currently, each power processor is custom designed for its particular application.

Capability State of the Art: Power density: baseline;
Efficiency: baseline;
Application: specialized design tailored to specific purpose

Parameter, Value:
Power density 300 W/kg at multi-kilowatt level;
Efficiency: 92 to 93%

Capability Performance Goal: Increased power density; increased power processing efficiency; and reduced design, development, test, and evaluation (DDT&E) and logistics costs.
Enables high-voltage, high-power conversion and conditioning. Application includes a module that reconfigures.

Parameter, Value:
500 W/kg at multi-kilowatt level;
Efficiency: 96 to 98%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	2 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	2 years

3.3 Power Management and Distribution
3.3.5 Conversion and Regulation

3.3.5.4 Advanced Power Processing Units

TECHNOLOGY

Technology Description: Advanced power processing unit for a high-power electric propulsion system.

Technology Challenge: Development of high-voltage, high-current, radiation-hard power processing unit, which is highly efficient and less massive, while minimizing development risk and complexity.

Technology State of the Art: Conversion technology using convention silicon semiconductors on flight.

Parameter, Value:

Parameter, Value	TRL
Input voltage: 70-100 V; Output voltage: 150-400 V; Output power: ~ 5 kW; Efficiency: > 92%; Specific mass: 2.8 kg/kW; Volume per kW: 234 in3/kW; Operating temperature: 50° C	3

Technology Performance Goal: High-voltage, radiation-hard switching devices with high power and voltage, while processing power at higher efficiency and at with lower converter mass and volume.

Parameter, Value:

Parameter, Value	TRL
Input voltage; 250-400 V; Output voltage: 800-1,000 V; Output power: 10 kW scalable to 80 kW; Efficiency: > 97%; Specific mass: < 0.5 kg/kW; Volume per kW: < 50 in3/kW; Operating temperature: 100° C	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Advanced high voltage semiconductors that are radiation hard, innovative power processing topologies that provide high efficiency across a wide power and voltage spectrum, input series stacking control technologies.

CAPABILITY

Needed Capability: Power processing units for electric thruster in the 10 to 100 kW class that provide 96 to 98% efficiency and operate at high input voltage > 200 V and even higher output voltages > 800 V.

Capability Description: Current flight electric thrusters are in the 5 kW range; 7 kW systems have been demonstrated in the laboratory environment (Technology Readiness Level (TRL) 3). Technology needs to advance the state of the art to 10 to 100 kW in order to enable high power electric propulsion systems.

Capability State of the Art: Low output power with low voltage input.

Parameter, Value:

5 kW power at 140 V input

Capability Performance Goal: High power with high voltage input.

Parameter, Value:

10 to 100 kW inputs at > 250 V input

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enabling	2015	2018	2015	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	2 years