U.S. DEPARTMENT OF
**ENERGY**

# ENERGY FOR SPACE

## DEPARTMENT OF ENERGY'S STRATEGY TO ADVANCE AMERICAN SPACE LEADERSHIP

(FY 2021–FY 2031)

# Executive Summary

The United States is facing an increasingly diverse and competitive environment in the commercial and military exploitation of space. A growing number of nations are seeking to venture into space, and our adversaries are energetically pursuing commercial and military advantage in this domain. The current National Space Strategy, National Space Policy, and Space Policy Directives (SPDs) call for a reinvigorated, whole-of-nation approach to advance America's leadership in space-based science, technology, commerce, and security. U.S. priorities include returning American astronauts to the Moon for the long-term, followed by human exploration missions to Mars and beyond; ensuring an unfettered ability to operate in space by deterring, countering, and defeating space-oriented threats to U.S. security; and reforming regulatory frameworks and pursuing international cooperation to foster growth in space commerce. America's leadership in space will depend upon developing advanced, space-applicable technology, through our own U.S. efforts and in partnership with nations and international space agencies that share our values and interests.

Since the earliest days of space exploration, the Department of Energy (DOE) and its National Laboratories have been essential suppliers of the scientific research, knowledge, and technologies that have led to a sustained U.S. presence in space, to ever-longer space exploration missions, and to significant space achievements. The DOE innovation enterprise brings together a world-class community of scientists, engineers, and technologists with unique, cutting-edge research facilities, capable of solving U.S. space mission challenges and advancing U.S. scientific understanding of the universe.

Through this Energy for Space strategy, DOE will build on its support to U.S national space policies and programs, and contribute to advancing U.S. leadership in space exploration, security, and commerce via a more strategic approach to DOE's work with the space community. This strategy also demonstrates the connections between DOE's space-related contributions and DOE's pursuit of its own core missions in science, energy, security, and the environment.

## Vision

**The Department of Energy will be an essential source of the science, technology, and engineering solutions needed for advancing U.S. leadership in the space domain.**

## Strategic Goals

DOE will apply the Department's core competencies and emerging capabilities, including those of its 17 National Laboratories, to the needs of the U.S. space community through focused strategic goals:

- **Power the Exploration of Space.** DOE will develop space-capable energy technologies (both nuclear and non-nuclear) for U.S. space customers, explore energy management systems for their potential application to space missions, and advance innovative energy generation, collection, storage, distribution, employment, dissipation, and thermal management technologies for space systems.
- **Solve the Mysteries of Space.** DOE will harness the capabilities and expertise within its laboratory complex and across its broad community of researchers to make scientific discoveries for space and in space, advancing our fundamental understanding of the universe and the ways in which humans can live and work in it safely, securely, productively, and profitably.
- **Support the Secure and Peaceful Use of Space.** DOE, including the National Nuclear Security Administration (NNSA), will provide technical capabilities, systems, multi-purpose sensors, and satellite development/deployment support with application to national security as well as civil space programs.
- **Enable the Development of Space.** DOE will drive innovation in space science research and achieve breakthroughs in space-applicable technology for future U.S. space missions and grow U.S. space commerce.

## Principles

DOE's approach to these four strategic goals will be underpinned by three foundational principles:

- DOE's space-related activities will concurrently develop DOE's scientific and technically skilled workforce within DOE's primary mission areas; create opportunities to maintain and retain DOE's cadre of experienced scientists, engineers, and technicians; and promote educational achievement in Science, Technology, Engineering, and Mathematics (STEM) programs aimed at building DOE's next generation workforce.
- DOE's scientific facilities and infrastructure will benefit from the additional work provided by other agencies sponsoring space research, experiments, and technology development across the DOE enterprise.
- DOE's flexible Federally Funded Research and Development Center (FFRDC) contracting model, as well as strategic partnering with other Federal agencies, industry, and universities, will both support U.S. space initiatives as well as offer practical opportunities for DOE to improve the effectiveness and efficiency of contract administration and project management performance at the best value to the U.S. taxpayer.

## Implementation

The *Energy for Space* strategy was prepared through the internal DOE Space Coordinating Group and in consultation with external U.S. space leaders, stakeholders, and partners, including the National Space Council, National Security Council, National Aeronautics and Space Administration (NASA), the Department of Defense (DoD) and U.S. Space Force, and others. The implementation of this strategy will take place through a series of programmatic objectives and lines of action that DOE will pursue to support the requirements and needs of other U.S. space agencies and industry, consistent with DOE's strategic goals and principles. The anticipated supporting program actions are outlined in the appendices to this document.

# Table of Contents

# Acronyms and Abbreviations

| | |
|---|---|
| **AI** | Artificial Intelligence |
| **BNL** | Brookhaven National Laboratory |
| **CRADA** | Cooperative Research and Development Agreements |
| **CSP** | Concentrating Solar Power |
| **DAMIEN** | Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects |
| **DART** | Double Asteroid Redirection Test |
| **DC** | Direct Current |
| **DoD** | Department of Defense |
| **DOE** | Department of Energy |
| **DOE NE** | Department of Energy Office of Nuclear Energy |
| **DOE OE** | Department of Energy Office of Electricity |
| **FEMA** | Federal Emergency Management Agency |
| **FFRDC** | Federally Funded Research and Development Center |
| **GPS** | Global Positioning Satellites |
| **INL** | Idaho National Laboratory |
| **ISS** | International Space Station |
| **KRUSTY** | Kilowatt Power Using Stirling Technology |
| **LANL** | Los Alamos National Laboratory |
| **LBNL** | Lawrence Berkeley National Laboratory |
| **LLNL** | Lawrence Livermore National Laboratory |
| **LTBT** | Limited Test Ban Treaty |
| **LIBS** | Laser Induced Breakdown Spectroscopy |
| **LPS** | Lab Partnering Service |
| **MI** | Machine Intelligence |
| **MMRTG** | Multi-Mission Radioisotope Thermoelectric Generator |
| **MOU** | Memorandum of Understanding |
| **M&S** | Modeling and Simulation |
| **NASA** | National Aeronautics and Space Administration |
| **NEO** | Near-Earth Object |
| **NNSA** | National Nuclear Security Administration |
| **NOAA** | National Oceanic and Atmospheric Administration |
| **NSF** | National Science Foundation |
| **NTP** | Nuclear Thermal Propulsion |
| **ORNL** | Oak Ridge National Laboratory |
| **DOE OSPP** | Department of Energy Office of Strategic Planning and Policy |
| **Pu** | Plutonium |
| **RFI** | Request for Information |
| **RTG** | Radioisotope Thermoelectric Generator |
| **R&D** | Research and Development |
| **SHERLOC** | Scanning Habitable Environments with Raman & Luminescence for Organics and Chemicals |
| **SNL** | Sandia National Laboratories |

| | |
|---|---|
| **SNPP** | Space Nuclear Power and Propulsion |
| **SPD** | Space Policy Directive |
| **SPP** | Strategic Partnership Projects |
| **SSA** | Space Situational Awareness |
| **STEM** | Science, Technology, Engineering and Mathematics |
| **S&T** | Science and Technology |
| **TRISO** | Tristructural-Isotropic (Nuclear Fuel) |
| **USAF** | U.S. Air Force |
| **USNDS** | U.S. Nuclear Detonation Detection System |

**The reinvigorated U.S. space strategy has challenged us to think differently about the space domain.** To do so, the Department of Energy must be bold; it must apply its scientific and engineering talents to overcome the challenges of vast distances, extreme conditions, complex operations, and unfamiliar environments to propel and power exploration, security, and commerce in space. The Department has an accomplished history in America's space ventures – of reaching to, and beyond the horizon. And the Department stands ready to be an essential part of advancing America's space leadership in the future. Thus, I argue that in many ways, **DOE actually stands for the "Department of Exploration."**

**—Dan Brouillette, Secretary of Energy**

# The U.S. Strategy for Space Leadership

For decades, the United States has been the world's leading space power, with no equal in technical capability and operational presence. Over time, as with most of the world, the United States has become crucially reliant on space systems. Further, our allies and partners have benefited from joining and contributing to U.S. space missions, which in turn has advanced U.S diplomatic objectives such as strengthening standards of behavior in the space domain. From economic prosperity and national security to science and diplomacy, space activities provide practical as well as symbolic benefits to the nation. Consequently, the future sustainability and governance of space activities has evolved into a key U.S. strategic interest.

At the same time, space dominance by a malign competitor would dramatically increase the risk of severe, possibly irreversible, harm to the international position and technical leadership of the United States. Today and for the foreseeable future, the United States will be facing a space environment that is increasingly more diverse and competitive, with an increasing number of space-faring nations and commercial entities, as well as countries such as China and Russia that are growing space threats pursuing their own commercial and military advantage in the space domain.

## The National Space Strategy

The 2018 National Space Strategy[1], the 2020 National Space Policy[2], and SPD-1 call for a reinvigorated approach that prioritizes American interests in space by maintaining and enhancing America's leading position in space-based science, commerce, and security. Doing so requires a dynamic and cooperative interplay between the national security, commercial, and civil space sectors.

Additional Presidential directives build on SPD-1 to further advance American leadership in space through streamlining regulations to grow U.S. space commerce (SPD-2); enhancing space traffic management capabilities to ensure a safe, stable, and operationally sustainable space environment (SPD-3); establishing the U.S. Space Force to deter, counter, and defeat space-oriented threats to U.S. security (SPD-4); and protecting space systems from cyber threats (SPD-5).[3]

Further, the National Space Council recommended a specific timeframe—the decade of the 2020s—for achieving the primary objectives of SPD-1:

*Consistent with the overall goals of SPD-1, the United States will seek to land Americans on the Moon's South Pole by 2024, establish a sustainable human presence on the Moon by 2028, and chart a future path for human Mars exploration. NASA's lunar presence will focus on science, resource utilization, and risk reduction for future missions to Mars.*[4]

**"[The United States will] Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations."**

(Space Policy Directive 1, December 2017)

[1] The White House Fact Sheet, *America First National Space Strategy* (March 23, 2018), available at https://www.whitehouse.gov/briefings-statements/president-donald-j-trump-unveiling-america-first-national-space-strategy/.

[2] Executive Office of the President, *The National Space Policy,* 85 Fed. Reg. 81,755 (December 9, 2020), available at https://www.federalregister.gov/documents/2020/12/16/2020-27892/the-national-space-policy.

[3] See the list of Presidential Space Policy Directives in Appendix A.

[4] The White House/National Space Council, *A New Era for Deep Space Exploration and Development* (July 23, 2020) p. 3, available at https://www.whitehouse.gov/wp-content/uploads/2020/07/A-New-Era-for-Space-Exploration-and-Development-07-23-2020.pdf.

Establishing a sustained human presence beyond Earth within the next decade is new to U.S. national space policy and calls for different thinking about the United States' role in the space domain. Instead of limited steps into orbit and back, the future space arena will have a sustained human and robotic presence across the solar system, and an expanding sphere of commercial, non-government activities with increasing numbers of Americans living and working in space.

For this vision to be realized, critical technologies must be developed, such as space-capable power sources, long-term habitation infrastructure, and autonomous systems for planetary exploration and for the discovery and use of in situ resources. Initially, government support for research and demonstration will be needed to develop these technologies. In the future, commercial firms may take over routine operations to provide consumables and utilities, such as power and communications.

**"Americans will return to the Moon in 2024. Following this 2024 landing, we will develop a sustained, strategic presence at the lunar South Pole called the Artemis Base Camp. Our activities at our Artemis Base Camp over the next decade will pave the way for long-term economic and scientific activity at the Moon, as well as for the first human mission to Mars in the 2030s."**

(NASA's Plan for Sustained Lunar Exploration and Development, April 2020)

## The DOE Role in the National Space Strategy

Extending America's presence beyond Earth's orbitre quires a whole-of-government approach, and while NASA will remain the lead for U.S. government space exploration efforts, other departments and agencies will have increasingly important roles in space. For 60 years, DOE (and predecessor agencies) have been a key player in U.S. space activities, and DOE will continue that role in support of America's leadership in space. The Department's mission—to address America's energy, environmental, and nuclear challenges through transformative science and technology (S&T) solutions—simultaneously creates opportunities for DOE to advance American space innovation and drive American space exploration.

- **S&T Capacity**. As the largest sponsor of basic scientific research and development (R&D), DOE has built a diverse community of interdisciplinary S&T talent within the complex of National Laboratories and throughout U.S. colleges and universities. This world-leading S&T expertise can be brought to bear on answering the most difficult challenges facing U.S. space missions.
- **R&D Infrastructure**. DOE supports the world's most advanced and unique scientific facilities. These facilities support researchers both in the United States and abroad in advancing our understanding of the universe, from the subatomic scale to the cosmic scale. The discoveries made possible by these facilities push the boundaries of human knowledge across many scientific disciplines.
- **Emerging/Innovative Capabilities**. DOE provides expert knowledge and world-leading capabilities in nuclear and non-nuclear energy technologies, artificial intelligence (AI) and robotics, high-speed information technology, advanced manufacturing, microelectronics, materials for extreme environments, radiation science, isotope production, and a host of other areas. This engine of discovery can power crewed missions to the Moon and beyond, as well as pave the way for human habitats and a sustained presence on the surface of other planetary bodies.
- **Technology Commercialization**. DOE is one of the largest supporters of technology transfer in the federal government. Thus, DOE's R&D investments can aid in accelerating the commercialization and industrialization of space, forge new capabilities for sustainable expansion into the solar system, and provide benefits for life on Earth.

# The DOE Strategy for Space

## Vision

For the next decade (defined in this strategy as Fiscal Years 2021 to 2031), DOE will seek to enhance the Department's role in supporting U.S. national space policies:

**Vision**

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DOE's approach to these four strategic goals will be underpinned by three foundational principles:

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- DOE's scientific facilities and infrastructure will benefit from the additional work provided by other agencies sponsoring space research, experiments, and technology development across the DOE enterprise.
- DOE's flexible FFRDC contracting model, as well as strategic partnering with other Federal agencies, industry, and universities, will both support U.S. space initiatives as well as offer practical opportunities for DOE to improve the effectiveness and efficiency of contract administration and project management performance at the best value to the U.S. taxpayer.

## Implementation

DOE will implement this strategy through a series of programmatic objectives and lines of action within four broad S&T areas that align to the Department's space-related strategic goals: Space Power Systems; Space Fundamental Science Research; National Security; and Space Capabilities and Technology. DOE will make use of various implementing mechanisms, such as DOE program-directed activities and funding, DOE-sponsored cross-discipline S&T initiatives, externally sponsored National Laboratory projects (known as Strategic Partnership Projects, SPPs) funded by NASA and other agencies, National Laboratory-directed R&D activities, and technology transition and private sector partnership initiatives (e.g., InnovationXLab Summits, Cooperative R&D Agreements or CRADAs, etc.).

This strategy recognizes that DOE's role in support of U.S. national space policy is separate from, related to and integrated into, DOE's primary mission. DOE programs managing space-related S&T work reside under the DOE Under Secretaries of Energy, Science, and Nuclear Security/NNSA Administrator. Action plans appended to this strategy have been developed by the program offices reporting to these three Under Secretaries to illustrate how DOE will support other U.S. space agencies and industry needs within DOE's authorized mandate.

# Methodology

This *Energy for Space* strategy was developed using an internal coordination process that involved DOE Headquarters functional and program offices, working through the internal DOE Space Coordination Group. This Group is chaired by the DOE Office of Strategic Planning and Policy (DOE OSPP), which is the senior policy office reporting to the Secretary of Energy and responsible for, inter alia, the overall strategic planning of DOE's role in support of U.S. national space policies.

National space policy priorities are established by Executive Orders and Presidential Memorandum, which result from White House-led interagency policy coordination processes under the National Space Council, the National Security Council, and the Office of Science and Technology Policy. Working from these national space policy documents, DOE OSPP led development and coordination of this Energy for Space strategy through the DOE Space Coordination Group.

The process was also informed by consultations between the DOE OSPP and U.S. space departments/agencies, including NASA, the Department of Commerce's Office of Space Commerce, the Department of State, DoD, and U.S. Space Force. DOE actively participates in U.S. interagency working groups and committees on space policy coordination and implementation, and this space strategy and related programmatic actions align with the goals and guidance created through those interagency interactions.

The DOE complex of National Laboratories, plants, and sites will provide the capabilities and expertise needed to contribute solutions to the America's space exploration needs. The Laboratories' multidisciplinary S&T workforce and unique instruments and facilities can address the types of large scale, complex R&D challenges inherent in the new U.S. space policies. The Laboratories also will continue to leverage their collaborative relationships with other U.S. government research centers, universities, and private sector entities to expand the foundations of space science knowledge and grow the U.S. space industry. While DOE is not unique in having this expertise, it is unique in having this breadth of expertise concentrated within a single organization and having the experience of applying it (particularly through the National Laboratory complex) to highly diverse mission areas. Achieving U.S. space goals will ultimately require tight integration among DOE's National Laboratories, NASA's space flight and research centers, DoD service research laboratories, U.S. universities, private sector partners, and commercial industry. DOE has had decades of experience partnering with these entities to achieve outcomes that are mutually beneficial.


**Representation of DOE's National Laboratories, Plants, and Sites**

# Goals and Objectives

A series of programmatic objectives under each of the four DOE strategic goals for space are described in more detail here, highlighting the unique contributions that DOE can offer to support the mission requirements and needs of other U.S. space agencies and industry. General lines of action anticipated for DOE programs during the timeframe of this strategy are listed in the appendices to this document.

## Power the Exploration of Space

A sustained human and robotic presence in space, with expanding commercial and non-governmental activities and an increasing population of space inhabitants, will require the development of new energy technologies and support infrastructure capable of delivering long-term, reliable power. In space, energy must be generated, collected, stored, distributed, used for work, and managed within a system powering vehicles, equipment, and habitats. For example, NASA's plan for a sustained crewed presence on the Moon envisions the need for an integrated power system to support a lunar base camp and related infrastructure, as well as the orbiting Gateway lunar station.[5] This variety of conditions and mission requirements is leading NASA to consider a combination of multiple power systems, as well as power storage and transmission systems that can operate continuously over long periods while withstanding the harsh space and lunar environments.

These power requirements and challenges will increase as space missions become longer in duration, and further in distance. The U.S. national strategy for deep space exploration notes that lessons learned from Moon missions will inform development of more advanced space power systems, particularly at distances from the Sun where solar power generation may not be feasible or sufficient for extended missions to Mars and across the solar system.[6] With more complex human space missions projected in the future, there is a need to leverage all advanced power generation, distribution, and storage S&T to optimize power solutions for these longer missions.

DOE has worked with U.S. space programs for 60 years, supporting both defense and civilian missions. DOE is recognized as a leader in the design, development, and deployment of space nuclear power systems. Using authorities under the Atomic Energy Act, DOE can produce or acquire the nuclear materials needed to design various power systems on behalf of the U.S. Government, and DOE maintains the expertise and capabilities to develop, test, and demonstrate such power systems.

Thus far, DOE's space power systems work has focused primarily on space nuclear power and propulsion (SNPP) technologies, ranging from small radioisotope power systems (RPS) to fission power reactors, which have powered lunar experiments, satellites, planetary rovers, and deep space probes. DOE leverages synergies between SNPP systems development and several civil nuclear energy areas:  commercial nuclear energy R&D, testing, and demonstration expertise tied to the small modular reactor and microreactor programs; fuel development, testing, and qualification; and applied engineering solutions. One example of this kind of synergy was the NASA and DOE/NNSA collaboration on the Kilowatt Power Using Stirling Technology (KRUSTY) demonstration of a dynamic RPS design for greater power generation.[7] Furthermore, under the 2020 national strategy to restore America's nuclear energy industry, DOE is leading U.S. efforts to, inter alia, reestablish U.S. leadership in next-generation nuclear technology and revitalize the industry's highly skilled professional workforce.[8]  Developing new nuclear power solutions for future U.S. space missions and providing the needed nuclear material and technologies for those solutions, will also contribute to preserving assets and investments in the U.S. nuclear enterprise.

[5] See NASA, *NASA's Plan for Sustained Lunar Exploration and Development* (April 2020), available at https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf.

[6] See National Space Council, *Deep Space Exploration and Development*, p 6.

[7] See DOE/NNSA article "KRUSTY project demonstrates potential power sources for future space exploration", available at https://www.energy.gov/nnsa/articles/krusty-project-demonstrates-potential-power-sources-future-space-exploration, and NASA article "Kilopower", available at  https://www.nasa.gov/directorates/spacetech/kilopower.

[8] U.S. Department of Energy, *Restoring America's Competitive Nuclear Energy Advantage: A Strategy to Assure U.S. National Security* (May 2020), available at https://www.energy.gov/sites/prod/files/2020/04/f74/Restoring%20America%27s%20Competitive%20Nuclear%20Advantage-Blue%20version%5B1%5D.pdf.

[9] GaInP2/GaAs Tandem Cells for Space Applications, J.M. Olson, et. al., Proc 11th NASA Space Photovoltaic Research and Technology Conference (SPRAT), pp 107-115, CP-3121 (1991).

DOE also sponsors R&D on a variety of non-nuclear energy technologies that will be key components of future lunar and Mars missions. DOE's development of foundational multi-junction photovoltaic technology is powering virtually every spacecraft currently in operation. Building upon that success, DOE's advanced R&D of photovoltaics and concentrating solar-thermal power could be of great value at every stage of a sustained crewed presence on the Moon. DOE also supports research and has expertise in areas of energy storage in the form of batteries and fuel cells, which could be used on a lunar base camp to supply power to structures, surface vehicles, and transport to and from the Moon. DOE's work on electrical microgrid systems will also be valuable in informing NASA designs of similar systems supporting proposed lunar surface base camp concepts.

### Objective 1.1 Develop and Deploy Future Space RPS.

DOE continues to work with NASA, other Federal agencies, and commercial entities to create partnerships in developing and designing nuclear power systems for both near-term and future space missions. DOE has been partnering with NASA for many years to deliver RPS supporting Moon and Mars missions. RPS—which include radioisotope thermoelectric generators (RTG) and radioisotope heater units—are a type of nuclear energy technology that uses heat from the natural decay of radioisotopes (e.g. plutonium-238, Pu-238) to produce electric power for operating spacecraft systems and science instruments. RPS are compact, rugged, and provide reliable power in environments where solar arrays are not practical, offering a significant advantage of operating continuously over long-duration space missions, largely independent of changes in sunlight, temperature, charged particle radiation, or surface conditions (e.g., dust). As an added benefit, excess heat produced by some RPS can be used by spacecraft instruments and on-board systems to continue operating effectively in extremely cold environments.

DOE is supporting NASA in the design of new technologies leveraging Pu-238 as the radioisotope that has the established safety pedigree and meets NASA mission requirements for high power density, low radiation emissions, and stability at high temperatures. These new RPS technologies look to provide enhanced power conversion and improved thermocouple materials to support long-term mission needs and new applications.

### Objective 1.2 Develop Surface and Propulsion Space Nuclear Fission Power Systems.

The increased power demands of long-duration surface crewed missions and crewed flights beyond the Moon have led to consideration of surface fission power and nuclear propulsion technologies. Surface fission power reactors are envisioned to provide stable, base-load power to meet anticipated habitat and exploration missions on other worlds. Space nuclear propulsion systems offers advantages for exploration missions to Mars and beyond, including increased mission flexibility, mission abort modes, improved crew health and safety, and reduced mission cost.

DOE has a long history of advancing nuclear power solutions in support of the U.S. space goals. Starting in the 1960's, DOE's predecessor agency, the Atomic Energy Commission, actively designed and deployed the world's first space reactor for use as a satellite power system (SNAP-10A) and also demonstrated nuclear propulsion technology through the NERVA program. DOE is well qualified and will play a critical role in developing and supporting future space nuclear power systems such as fission reactors for crewed base camps on the Moon, as well as space nuclear propulsion systems that may carry crews to Mars. Further, as with RPS, DOE will be able to take advantage of this space nuclear power R&D in the ongoing efforts to revitalize the U.S. commercial nuclear industry, leveraging commonalities in fuel design, material and component testing, and demonstration of small reactors to expand the use of technology to remote locations.

### Objective 1.3 Enhance Solar and Energy Storage Space Systems.

Solar power generation is also expected to continue being used for satellites as well as for surface power, possibly on a significantly greater scale than in historic space-based applications. Energy storage will also be required for stationery and vehicle applications on the lunar surface and on Mars locations. DOE supports research and provides world-class tools to lay the scientific foundation for future energy generation, storage, and system integration technologies and to advance those technologies for eventual uptake (for Earth-based and possibly space-based applications) by other agencies and the private sector. DOE's renewable energy and electricity programs work on alternative fuel vehicles, alternative power generation and storage, and integrated energy management systems such as microgrids are also being leveraged to support space-based applications.

**Leveraging Nuclear Power Technology for Space Missions**

**DOE works with U.S. government agencies and private sector organizations to ensure nuclear power systems are available to meet space exploration needs. NASA and DOE have a long-standing relationship to provide RPS for deep space exploration missions, including the Mars Curiosity and Perseverance rovers and the future Dragonfly mission to Saturn's moon, Titan. NASA and DOE are collaborating on demonstrations for nuclear fission power systems, including a fission surface power capability for habitats and a nuclear thermal propulsion (NTP) capability for future human exploration missions. Idaho National Laboratory (INL), Los Alamos National Laboratory (LANL), and Oak Ridge National Laboratory (ORNL) are responsible for the RPS supply chain to manufacture fuel and generators for space use. DOE is also working with NASA and the DoD Strategic Capabilities Office on coated-particle nuclear fuel development, which will have both terrestrial and space applications. There are several synergies between these NASA and DoD collaborations and ongoing DOE commercial civilian nuclear power programs supporting fuel qualification and deployment of small modular and microreactors, which could benefit near-term deployment goals.**

DOE also supports research and has expertise in areas of energy storage in the form of batteries and fuel cells. DOE expertise in hydrogen and fuel cell technologies will be particularly critical for exploiting lunar water for synthesis of hydrogen fuel, as well as for power storage on the Moon surface and for powering other applications in a lunar base camp.

### Objective 1.4 Enhance Space Thermal Energy Use and Management Systems.

Thermal control is needed to keep electronics and systems from suffering extremes of hot or cold as well as dynamic temperature swings. In situ resource utilization processes and power systems will likely require thermal management and heat rejection techniques. Management of thermal energy is crucial in space, and thermal management is closely associated with energy management, an inherent skill of DOE. Integrated energy management systems such as direct current (DC) distribution systems and/or DC microgrids have been used for mission-critical space applications (such as those employed for powering spacecraft and the ISS) for many years. Recent studies have further analyzed applying advances made in terrestrial DC microgrids for space power systems that operate in hostile lunar environments, and these studies make note of areas in need for further development and testing.

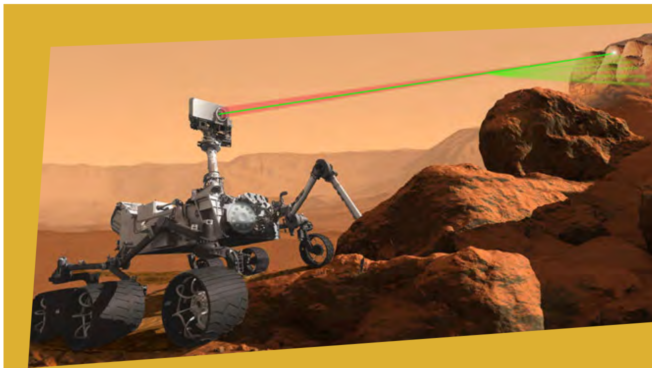
## Solve the Mysteries of Space

As a sustained human presence on the Moon is built, and as more missions extend to the exploration of Mars and into deep space, there will be new opportunities for scientific discovery in fields ranging from astronomy and astrophysics to material science and biology. Additionally, deep space exploration will require more use of autonomous robotic probes and rovers, as well as new capabilities to conduct data collection and analysis. This will increase the need for high-speed information technology, including advanced AI and technology and quantum information systems.

Further, the U.S. National Space Policy calls for strengthening U.S. leadership in space-related S&T by supporting basic and applied research to increase space capabilities, as well as by encouraging commercial space innovation and entrepreneurship through targeted investment in promising technologies.[10] Increased private sector R&D in space will be central to the U.S. commercial space industry taking advantage of the new scientific discoveries gained on the Moon, Mars, and in deep space. In addition, individual universities and university consortiums addressing these new space discoveries will deepen the understanding of the universe, as well as serve to inspire new generations of space scientists, educators, and technologists, and expand the U.S. STEM community.

DOE has a mission to deliver the scientific discoveries and major scientific tools that will transform our understanding of nature and advance the energy, economy, and national security of the United States. DOE is the largest supporter of fundamental research in the physical sciences. The research supported across the breadth of DOE's basic science portfolio—including many multi-disciplinary and multi-institutional scientific collaborations—and the unique, world-leading capabilities available at DOE's scientific user facilities[11] and throughout the laboratory complex, advancing a broad range of space interests.

The core expertise within DOE's community of researchers (U.S. universities and all 17 DOE National Laboratories), coupled with decades of experience conducting "science at scale," make DOE uniquely suited to tackle the biggest challenges in space-related science. An expanded human presence in space—from the ISS to the Gateway orbital platform, to the Moon, Mars, and beyond—requires new science and technological breakthroughs, many of which fall within the DOE existing mission areas ("science for space"). Just as important, an expanded human presence in space is an extraordinary opportunity to pursue completely new opportunities for science and technological research across many domains ("space for science"). Realizing both goals, as well as future scientific opportunities throughout the solar system, can be accomplished by DOE's diverse expertise in AI, advanced computing, materials science, systems biology, plasma science, space weather, radiation-tolerant microelectronics, and quantum information science among other areas.



**Sensing Systems for Space Exploration**

**Advanced scientific and technological sensing capabilities at DOE/NNSA's National Laboratories support many of NASA's past, current, and future space science and exploration missions in fields such as astrophysics, heliospheric science, Earth observations, and planetary exploration. For example, LANL has been a key technical partner in the development and operation of the ChemCam instrument on the Mars "Curiosity" rover mission (2011–present). ChemCam uses Laser Induced Breakdown Spectroscopy (LIBS) to measure the mineral composition of the Martian surface from distances up to 7 meters from the rover. Its observations from more than 800,000 individual laser shots are helping to understand environmental conditions in the distant past when Mars was more suitable for life. For the Mars 2020 "Perseverance" rover mission, LANL provided key contributions for two advanced sensing systems: SuperCam (an advanced LIBS system) and Scanning Habitable Environments with Raman & Luminescence for Organics and Chemicals (SHERLOC) that promise to further reveal the secrets of the Red Planet. The same remote sensing technologies are applicable to national security missions here on Earth, such as remote detection of explosives and chemical toxins.**

### Objective 2.1: Contribute Foundational Knowledge to Enable the Sustained Human Presence in Space.

DOE supports basic scientific research that provides the foundational knowledge needed to improve the understanding of complex physical processes that occur in the operating environments of low Earth orbit and beyond, which directly affect the ability to live and work in space, as well as to conduct scientific, economic, and security missions. As the United States works towards defined goals for the space program, unanticipated challenges and new opportunities will arise that prompt completely new directions of scientific inquiry. DOE's breadth of expertise in the physical

[10] Executive Office of the President, *The National Space Policy*.

[11] For a list and description of DOE's Office of Science user facilities, see https://www.energy.gov/science/science-innovation/office-science-user-facilities.

**Science for space...and space for science**

**DOE supports fundamental research that creates the foundational knowledge needed for the U.S. space program to meet its loftiest goals. DOE-supported scientists across the laboratory complex and at U.S. universities are making ground-breaking discoveries in materials science and chemistry, plasma physics, and systems biology that will help ensure we can protect our astronauts and equipment in space, as missions increase in duration and travel farther from Earth. At the same time, we are helping to create new opportunities for our communities to advance DOE's own missions in science, energy, and security. DOE will build on the extensive experience of working with our counterparts in the space program on complex science missions like the Alpha Magnetic Spectrometer, a particle detector installed on the ISS (pictured). Such partnerships can take advantage of future research environments in low Earth and/or lunar orbit, at future permanent lunar surface facilities, and on missions extending throughout the solar system. In so doing, we will continue to advance our understanding of the universe, from the largest scales to the smallest, in ways we cannot through terrestrial work alone.**

sciences will be essential to conducting this science and using the knowledge gained to solve those challenges and seize those opportunities.

## Objective 2.2: Leverage Space-based Experimental Assets to Advance the Physical Sciences.

Collaboration between DOE and NASA has been essential to push the boundaries of understanding how the universe works, from the smallest scales to the largest. DOE has unique missions and payloads in space (such as a continuing series of space environment instruments, needed for nuclear treaty monitoring payloads) that are leveraged by NASA and the space plasma community for basic science as well as space weather monitoring and prediction. DOE also has historically collaborated with NASA to develop technology for space science missions, such as the Large Area Telescope on the Fermi Gamma-ray Space Telescope. Even in the absence of a direct collaboration, technology developed and tested by DOE for ground-based applications, including next-generation detectors and sensors, has supported NASA space-based science. In all cases, the outcomes advance both the NASA and DOE science missions. New detector technology developed by DOE experts is supporting future missions for exoplanet detection and asteroid exploration. DOE's particle physics program collaborates with NASA on research using space platforms like the ISS, and some of the data generated from these experiments is used by the wider science community. NASA's goals for the future of space, including the future of the ISS and the Artemis Program, offer completely new platforms for scientific experimentation that can advance the DOE science mission in the domains of particle physics and astronomy, as well as in materials science, chemistry, geosciences, synthetic biology, genomic science, and advanced computing and networking.

## Objective 2.3: Facilitate Access to the Research Capabilities and Expertise Needed to Solve Scientific Challenges for the Space Program.

DOE has both the core expertise and scientific tools for the study of materials in extreme temperature and radiation environments. Basic research supported by DOE on materials for extreme environments offers a broad opportunity for relevance to, and collaboration with, NASA research and needs. Existing research covers a range of techniques, both experimental and computational, that help elucidate mechanisms of deformation at high temperatures, degradation in extreme environmental conditions, and degradation of materials and microelectronics under irradiation. This research, and the enabling tools that DOE has developed, have contributed to understanding a range of mechanisms underpinning advanced manufacturing processes used by NASA (e.g., friction stir welding, additive manufacturing). The ability to develop and synthesize both novel materials and materials capable of withstanding extreme conditions, across length scales and for a variety of environments, is a critical capability that DOE can provide toward addressing U.S. space mission challenges. Going forward, this work will be essential to ensuring that future technologies used on space missions are robust and long-lasting.

## Support the Secure and Peaceful Use of Space

Unfettered access and freedom to operate in space is necessary to advance America's security, economic prosperity, and scientific knowledge. The National Space Policy states that the safe, stable, and secure use of the space domain is in the shared interest of all nations, and that all nations have the right to explore and use space for peaceful purposes, and for the benefit of all humanity, in accordance with applicable law. This National Space Policy further notes that safeguarding the space components of critical infrastructure is vital to the security, economy, resilience, and public health and safety of the United States. The DoD Space Strategy also calls for a secure, stable, and accessible space domain whose use by the United States and allies and partners is underpinned by comprehensive, sustained military strength.

Securing the U.S. position in space also entails defending against planetary dangers such as impacts with large near-Earth objects (NEO), severe space weather events, and collisions between orbital satellites or with space debris. Surveillance, tracking, monitoring, predictive modeling, and potential defensive responses are central to early detection and risk mitigation of these space dangers to the United States and other nations.

Since the launching of the first artificial satellite in 1958, countries have come together to set expectations relative to the peaceful uses of outer space. Space technologies often have overlapping civilian and military applications. For example, satellites have civilian uses such as global navigational positioning, while also hosting sensors for detecting weapon detonations and space weather phenomena. DOE has unique capabilities to assist with national defense through treaty monitoring, indications, and warning programs, national defense of space assets such as satellites, and global defense such as the activities associated with planetary defense from NEOs. DOE uses Departmental capabilities—including experts, high performance computing platforms, computational codes, and experimental/testing facilities—to support and secure the peaceful use of space.

### Objective 3.1 Support National Security Space Capabilities for Treaty Monitoring, Indications, and Warning.

One of DOE's national security missions (which spans 60 years) is to provide technologies, space payloads, data analysis, modeling and simulation (M&S), unique understanding of space environments (both human-made and natural), facilities, and subject matter experts in support of DoD and other government agencies in ensuring safe and secure access to space. DOE/NNSA space payloads collect, analyze, and transmit to ground real time data that provides information about many aspects of the natural space environment as well as rapidly evolving environments with significant national security impacts.

> **"The Department [of Defense] will grow its space power capacity over the next 10 years to ensure space superiority and secure the Nation's vital interests. The Department will take action rapidly to leverage opportunities and U.S. strengths in close cooperation with our allies, partners, and industry."**
>
> (Defense Space Strategy Summary, Department of Defense, June 2020)

The origins of this work began under the Atomic Energy Commission with early research and ground-based demonstration of nuclear propulsion in space. Later, working with NASA and the USAF, DOE payloads were launched on the Ranger Lunar Mission to monitor space and lunar environments. During U.S. nuclear explosion testing, DOE deployed space and airborne sensing systems that monitored near-earth environments to better understand effects of these human-made events. At the same time, DOE sensors flew on the Vela satellites as critical technologies for nuclear test treaty monitoring and verification. That work continues today, informing various government agencies (including the National Command Authority) of environments and events from the ground up to the exo-atmosphere. Future DOE/NNSA systems and sensors are under study and development to provide higher fidelity data, which will be combined with more advanced M&S tools to better inform DoD and other U.S. agencies of real time situations, as well as provide data-based information for Space Situational Awareness (SSA) and Space Domain Awareness.

[12] The White House Fact Sheet, *America First National Space Strategy.*

[13] Executive Office of the President, *The National Space Policy.*

[14] U.S. Department of Defense, *Defense Space Strategy Summary* (June 2020), p. 2, available at https://media.defense.gov/2020/Jun/17/2002317391/-1/-1/1/2020_DEFENSE_SPACE_STRATEGY_SUMMARY.PDF.

### Objective 3.2 Develop Space Protection Capabilities to Protect Space Assets.

The United States continues to rely on space for almost every aspect of life, including financial transactions, communications, weather monitoring, navigation, treaty monitoring, surveillance, and nuclear force management. There are several current threats to U.S. assets in space. For example, decades of space missions have left debris in low Earth orbit. Debris can collide with other debris creating smaller particles that travel at high velocities and can damage space assets such as satellites. NEOs such as asteroids could pose collision threats to space assets, as well as impact threats to the Earth.

Additionally, while NEOs and space debris pose a natural threat to satellites, space warfare is a growing concern. Adversary nations could attempt to destroy space-based systems by sabotage or disruption, jamming, blinding, or dazzling satellites, and disabling their solar panels for navigation. The 2018 U.S. National Space Strategy recognizes that competitors and adversaries have turned space into a warfighting domain, and that the United States must seek to deter, counter, and defeat threats in the space domain that are hostile to the national interests of the United States and allies.[15] To address this concern, the United States has begun to aggressively invest to improve the defense and, more importantly, the resilience of the U.S. space enterprise.

DOE/NNSA's capabilities make it well suited to be a national leader in the development of technologies that can impact the U.S. Government's effort to protect space assets, in partnership with the U.S. Space Force, U.S. Space Command, and U.S. intelligence agencies. DOE/NNSA will be focused on tapping into the breadth of scientific and engineering capabilities across the DOE enterprise, as well as with university partners, to conduct research and develop the technologies needed to help ensure the resilience of U.S. space assets. DOE's legal mandate for energy infrastructure resiliency against space weather events and other disruptions (16 U.S.C. § 824o-1) gives DOE unique experience that can support designing resilient energy systems on orbital platforms or lunar bases (contributing to SPD-5 on cyber protection of space systems and to the NASA's Artemis program goals).

**Space-Based Sensors for Detecting Nuclear Detonations**

**DOE/NNSA develops sensor technologies that support U.S. national security objectives through space-based Earth observation missions and space domain awareness missions  For example, the U.S. Nuclear Detonation Detection System (USNDS) monitors compliance with the international Limited Test Ban Treaty (LTBT), in which 108 signatory countries have committed to the prohibition of nuclear testing in the atmosphere, outer space, and underwater. Sandia National Laboratories (SNL) and LANL have been key technical partners in the near 60-year partnership between the U.S. Air Force and DOE/NNSA on the USNDS. These payloads, including planned technology upgrades, reside on the U.S. Global Positioning System (GPS) satellites and other U.S. assets. Both LANL and SNL are responsible for advancing technologies for nuclear detonation detection instruments that improve system performance to meet changing national needs. Data from these sensors also contributes to studies of space weather, lightning, and Earth climate driven phenomena, which all contribute to improved modeling for SSA and forecasting.**

### Objective 3.3 Develop Technologies for NEO Deflection and Impact Studies.

The Near-Earth Object Preparedness Strategy and Action Plan[16] establishes a DOE/NNSA role in developing NEO collision mitigation and impact analysis capabilities. The analysis of mitigation and impact scenarios requires simulations employing NNSA high-performance computing capabilities. DOE/NNSA is also working with NASA on developing and validating technologies and techniques for deflecting and disrupting NEOs of varying physical properties. For

[15] See The White House Fact Sheer, *America First National Space Strategy.*

[16] The White House/National Science and Technology Council, *National Near-Earth Object Preparedness Strategy and Action Plan* (June 2018), available at https://www.whitehouse.gov/wp-content/uploads/2018/06/National-Near-Earth-Object-Preparedness-Strategy-and-Action-Plan-23-pages-1MB.pdf.


**Defending Against Near Earth Objects**

**DOE/NNSA actively collaborates with U.S. interagency work on defending the Earth from potentially hazardous space objects, such as asteroids or meteoroids on a collision course with Earth. DOE/NNSA participated in the Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects (DAMIEN) initiative, which developed the June 2018 National NEO Preparedness Strategy and Action Plan. DOE/NNSA and the National Laboratories of the nuclear security complex contribute to this strategy through NEO modeling, predictions, information integration, and developing technologies for NEO deflection and disruption missions. NASA leverages DOE/NNSA's unique engineering, scientific, and high-performance computing capabilities for analyzing asteroids and planetary defense scenarios. This NASA work has the added benefit of helping DOE/NNSA develop and exercise capabilities that are relevant to NNSA's weapons program. For example, researchers at Lawrence Livermore National Laboratory (LLNL) are using computer simulations to study and validate their ability to accurately simulate how an Earth-bound asteroid may be deflected. This LLNL work is contributing to the design of a modeling plan for NASA's Double Asteroid Redirection Test (DART) mission in 2021, which will be the first-ever kinetic impact deflection demonstration on a near-Earth asteroid.**

most NEO threat scenarios, Earth impact prevention capabilities should include the ability to rapidly reach the NEO, conduct necessary rendezvous and proximity operations, and deploy deflection/disruption technologies. Additionally, deploying an instrumented means of measuring the deflection over time can provide valuable assurance of mission success and critical post-mission situational awareness. If a mitigation measure is not successful, DOE/NNSA contributes to development of impact models that inform Federal Emergency Management Agency (FEMA) in planning and exercising NEO impact emergency procedures and action protocols.

## Enable the Development of Space

A sustained U.S. presence in space is grounded in expanding the commercial use of low Earth orbit, discovering and utilizing in situ resources on the Moon, and potentially on Mars, and developing a private, investor-based space industry and infrastructure that can service both commercial and U.S. government space activities.[17] Thus, an explicit U.S. national space policy objective is to expand America's economic activity in space by promoting and incentivizing the U.S. commercial space sector to develop and grow global and domestic markets for U.S. space goods and services, enhance the international competitiveness of U.S. companies, and strengthen and preserve the United States position as the country of choice for space commerce.[18]

As part of promoting the U.S. commercial space sector, one role of the U.S. government will be to encourage and support R&D of new technologies that lower the cost and risk of commercial space activities, create new opportunities for private sector innovation through reformed technology transfer and licensing practices to move early-stage technology developing into the private sector, and make U.S. government-owned scientific facilities and capabilities more accessible to academic and commercial communities to accelerate technology transition to commercial use.

Another need for a growing space market is to create a safe, sustainable, and predictable space environment, particularly in low Earth orbit. Among principles such as promoting best practices and responsible behaviors for space activities, there will be increasing need to improve the ability to manage satellite traffic, monitor

[17] See National Space Council, *Deep Space Exploration*.

[18] See Executive Office of the President, *The National Space Policy*.

space weather effects, and warn of potential collusion hazards from space debris. This will require new technologies for ground- and space-based observation platforms and sensors, as well as higher-speed information technologies to process collected data, and to conduct complex computational modeling and prediction.

Extracting, processing, and using in situ resources on the Moon and on other celestial bodies will be critical to a sustainable presence on the Moon and in fostering permanent private sector interest and investment in space. Any material resources that can be obtained on the Moon will reduce the expense and difficulty of transportation from Earth and increase the self-sufficiency of a lunar station. For example, through electrolysis, in situ lunar water can be used to produce hydrogen and oxygen, providing life support, a means to power spacecraft and vehicles, as well as stored energy for later use in fuel cells or other power applications.

DOE is active in R&D related to mining and minerals, primarily through the National Laboratories, which have significant capabilities in remote sensing, optimizing exploration strategies, advanced drilling techniques, robotic/autonomous equipment, advanced materials, separation technologies, and dewatering and water-reuse technologies.

*In situ* resource use could potentially lead to other longer-term applications, such as extraterrestrial metal processing and construction of habitats or other lunar surface structures using resources found on the Moon.[19] DOE funds R&D projects, consortia, and partnerships in advanced manufacturing at DOE National Laboratories. These projects could provide technologies relevant to lunar applications or support R&D to solve problems related to uniquely lunar challenges.

### Objective 4.1 Apply Emerging Technologies for Industries of the Future to the Space Domain.

Scientific machine learning is a core component of AI and a computational technology that can be trained, with scientific data, to augment or automate human skills. This technology has the potential to transform space science R&D. Breakthroughs and major progress can be achieved by harnessing DOE investments in massive data from scientific user facilities, software for predictive models and algorithms, high-performance computing platforms, and the national workforce.

The DOE is prioritizing advances in massive scientific data analysis, machine learning-enhanced modeling and simulation, and intelligent automation and decision-support for complex systems. Foundational computing capabilities for artificial and machine intelligence (AI/MI) applications are also being supported, including enhancements in domain-awareness, interpretability, and robustness. Machine-aided design and AI-related large-scale systems engineering are being developed to support DOE programs. These should be evaluated for application to space systems.

**A robust, innovative, and competitive commercial space sector is the source of continued progress and sustained United States leadership in space. The United States remains committed to encouraging and facilitating the continued growth of a domestic commercial space sector that is globally competitive, supports national interests, and advances United States leadership in the generation of new markets and innovation-driven entrepreneurship.**

(National Space Policy of the United States of America, December 9, 2020)

DOE-supported resources offer opportunities to leverage machine learning in the search for new materials and chemicals for energy storage systems tailored to space-based applications. Fundamental understanding of geochemical processes and the development of separation techniques under non-Earth conditions will be necessary for the extraction and use of in situ resources to support missions on other planetary bodies.

### Objective 4.2 Leverage Tools and Tactics to Encourage Use of DOE Technologies in Space Missions and Studies.

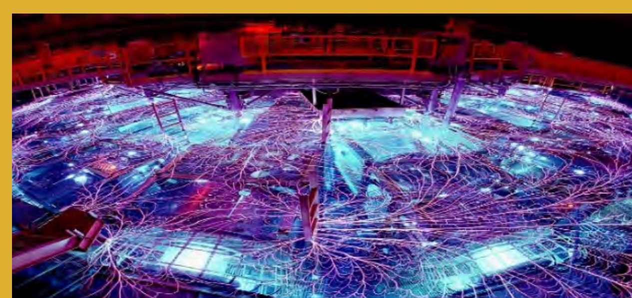
DOE has a long legacy of developing and commercializing technologies. DOE technology development and commercialization often includes partnerships that strengthen the U.S. economy and improve the standards of living of the American people. For example, DOE advances in clean room technology have contributed to micro-electronic technologies that are associated with current and planned space missions.

DOE also monitors and engages with Federal agencies and the private sector on general radio- and stable isotope needs, so that DOE can ensure adequate supply

[19] See National Aeronautics and Space Administration, Artemis Plan: *NASA's Lunar Exploration Program Overview* (September 2020), p. 28, available at https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf.


**Scientific User Facilities for Study and Development**

**DOE supports the design, construction, and operation of a suite of 28 world-leading experimental and computational facilities across the National Laboratories that serve the Nation's research enterprise. These facilities—including advanced supercomputers, particle accelerators, X-ray light sources, neutron scattering sources, specialized facilities for nanoscience and genomics, and others—are open to all interested users with allocation of time based on merit review of the proposed work. The National Synchrotron Light Source – II at Brookhaven National Laboratory (BNL) has been used to perform non-destructive analysis of samples returned from NASA space missions. The National Energy Scientific Research Computing Facility and Oak Ridge Leadership Computing Facility (home to Summit, the Nation's fastest computer) at ORNL have been used to process data from ground and space-based science missions and supported simulations leveraged for planning upcoming missions. The Atmospheric Radiation Measurement user facility, located at multiple sites around the U.S., generate data complimentary to NASA satellite missions and have supported test deployments and validation of NASA-funded instruments. Beyond the user facilities, DOE's laboratories are host to additional capabilities that contribute to science research and technology development of mutual interest to DOE, NASA, and other space-program agencies. DOE's 88-inch cyclotron at Lawrence Berkley National Laboratory (LBNL) allows researchers to better understand the effects of radiation on materials and electronics. Finally, the Z-Pulsed Power Facility at SNL produces conditions of extreme temperature and pressure found nowhere on earth, enabling high energy density research in materials, astrophysics, and planetary science.**



and develop new production capabilities for in-demand isotopes. Some of these isotope requirements are for specific space system applications, such as NASA's need for helium-3 isotopes for cryogenic systems, as well as other isotopes for satellite communications and nuclear batteries. DOE also works with industry and researchers in exploring the use of different isotopes for terrestrial RTGs, some of which could also have future applications for commercial space systems. DOE is currently making strontium-90 available for a technical feasibility demonstration of a new commercial RTG and recently resumed production of americium-241, another radioisotope of interest in certain RTG applications. DOE has also recently developed the production capability for promethium-147, which is of use in nuclear batteries.

DOE provides access to the hundreds of technologies, researchers, and facilities, and establishes partnerships with stakeholders involved with space across the public and private sectors. Partnerships can take the form of SPPs, CRADAs, and other collaborative work (including technology to market initiatives, as well as extramural funding opportunities such as grants and prizes). DOE's outreach initiatives, such as in-person events/webinars, InnovationXLab Summits,[20] and the Lab Partnering Service online portal[21] are examples of recent efforts to build new partnerships aimed at commercializing space-related technologies and provide access to DOE's National Labs, intellectual property, facilities, and experts.

[20] For more information, see https://www.energy.gov/technologytransitions/innovationxlab.

[21] For more information, see https://www.labpartnering.org.

# Conclusion

DOE and the National Laboratories are uniquely positioned to provide critical support to the ambitious U.S. plans for extending its exploration of space, enabling space S&T development, securing U.S. national interests in the space domain, and growing the American commercial space industry. By strategically organizing Departmental capabilities and programmatic efforts, DOE will focus efforts on the directives of the U.S. space policy and sharpen its priority tasks and deliverables to U.S. space missions.

DOE's National Laboratories are actively working on a portfolio of space-related R&D activities and will strive to be catalysts of U.S. space commercial growth. DOE senior leadership is committed to further develop DOE's cooperation and interaction with departments and agencies across the government, to proactively develop solutions for inherent and emerging space mission challenges. DOE is looking forward to the future by powering innovation and driving exploration, to reach beyond the horizon and into the farthest frontiers of space.

# Appendix A

## List of Legislation, Policy Directives, and Other Documents

DOE contributions to the U.S. national space strategy, as well as to the space missions of U.S. government departments and agencies, are made within the context of several laws, Presidential policy directives, interagency agreements and memoranda, and international agreements and instruments. An illustrative set of these documents is presented here.

### Laws

- *Atomic Energy Act of 1954, as amended,* 42 U.S.C. §§ 2011 *et seq.*
- *Atomic Energy Defense Act, as amended,* 50 U.S.C. §§ 2501 *et seq.*
- *Export Controls Act of 2018, as amended,* 50 U.S.C. § 4811 *et. seq.*
- *Department of Energy Organization Act*, as amended, 42 U.S.C. § 7101 *et. seq.*
- *National Nuclear Security Administration Act,* as amended, 50 U.S.C. § 2401 *et. seq.*
- National Defense Authorization Acts (Various).

### Presidential Policy Directives

- Exec. Order No. 13,803: *Reviving the National Space Council,* 82 Fed. Reg. 31,429 (July 7, 2017).
- Exec. Order No. 13,914: *Encouraging International Support for the Recovery and Use of Space Resources,* 85 Fed. Reg. 20,381 (April 10, 2020).
- The White House Fact Sheet, *America First National Space Strategy* (March 23, 2018).
- Executive Office of the President, *The National Space Policy,* 85 Fed. Reg. 81,755 (December 9, 2020).
- Executive Office of the President, Space Policy Directive-1: *Reinvigorating America's Human Space Exploration Program,* 82 Fed. Reg. 59,501 (December 14, 2017).
- Executive Office of the President, Space Policy Directive-2: *Streamlining Regulations on the Commercial Use of Space,* 83 Fed. Reg. 24,901 (May 30, 2018).
- Executive Office of the President, Space Policy Directive-3: *National Space Traffic Management Policy,* 83 Fed. Reg. 28,969 (June 21, 2018).
- Executive Office of the President, Space Policy Directive-4: *Establishment of the United States Space Force,* 84 Fed. Reg. 6,049 (February 25, 2019).
- Executive Office of the President, Space Policy Directive-5: *Cybersecurity Principles for Space Systems*, 85 Fed. Reg. 56,155 (September 10, 2020).
- Executive Office of the President, Space Policy Directive-6: *National Strategy for Space Nuclear Power and Propulsion,* 85 Fed. Reg. 82873 (December 16, 2020).
- Executive Office of the President, National Security Presidential Memorandum-20: *Launch of Spacecraft Containing Space Nuclear Systems* (August 20, 2019).
- The White House/National Space Council, *A New Era for Deep Space Exploration and Development,* (July 23, 2020).
- The White House/National Science and Technology Council, *National Space Weather Strategy and Action Plan,* (March 2019).
- The White House/National Science and Technology Council, *National Near-Earth Object Preparedness Strategy and Action Plan* (June 2018).

### Agency Strategy Documents

- National Aeronautics and Space Administration, *NASA's Plan for Sustained Lunar Exploration and Development* (April 2020).
- National Aeronautics and Space Administration, *The Artemis Accords: Principles for a Safe, Peaceful, and Prosperous Future* (May 2020).
- U.S. Department of Defense, Defense *Space Strategy Summary* (June 2020).
- U.S. Space Force, Space Capstone Publication, *Space Power Doctrine for Space Forces* (August 2020).

- National Aeronautics and Space Administration, *Artemis Plan: NASA's Lunar Exploration Program Overview* (September 2020).

## Interagency Agreements/Memoranda

- *Memorandum of Understanding Between National Aeronautics and Space Administration and U.S. Department of Energy Regarding Energy-Related Civil Space Activities,* October 19, 2020.
- *Memorandum of Understanding Between the National Aeronautics and Space Administration and the Department of Energy Concerning Radioisotope Power Systems,* October 31, 2016.

## International Agreements and Other International Instruments

- Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (also known as the Outer Space Treaty), opened for signature: December 19, 1966; entered into force: October 1967.
- Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water (also known as the Limited Test Ban Treaty, LTBT), signed August 5, 1963; entered into force October 10, 1963.

# Appendix B

## DOE Space Power Action Plan

This appendix further details the possible lines of action that the DOE enterprise can pursue under the strategic goal of powering the exploration of space, and the related objectives supporting that goal.

### Objective 1.1 Develop and Deploy Future Space RPS.

**Action 1.1.1:** *Deploy Radioisotope Power System for NASA's Dragonfly Mission*. By 2026, DOE's Office of Nuclear Energy (DOE NE) in partnership with NASA, will design, develop, and deploy an RPS for use in NASA's Dragonfly Mission, using expertise at the DOE National Laboratories. NASA will launch an RPS-powered rotorcraft to Saturn's moon, Titan, to explore this unique world. DOE NE will work with NASA and commercial industry to modify the current multi-mission radioisotope thermoelectric generator (MMRTG) technology (used to power the Mars Curiosity and Perseverance rovers) to power the Dragonfly rotorcraft.

**Action 1.1.2:** *Develop Advanced RPS technologies for Future Moon and Mars Missions.* By 2030, DOE NE (working with NASA and commercial industry) will design, develop, and deploy an advanced RPS that provides higher fuel efficiency and lifetime than existing RPS technologies to support robotic and human exploration of the Moon and Mars. NASA and DOE NE are partnering on technology development projects, such as dynamic RPS, to produce power using a closed thermodynamic cycle to increase efficiency and extend mission survivability for the harsh environments on the Moon, including technology design efforts with industry for thermoelectric materials and power converters.

**Action 1.1.3:** *Maintain RPS Production Capabilities at DOE National Laboratories*. DOE will maintain, on a full cost recovery basis, the capability and infrastructure at DOE's National Laboratories to develop, furnish, and conduct safety analyses for RPSs intended for use in U.S. Government space systems. DOE-NE will maintain this capability on behalf of DOE, including the ability to produce Pu-238 in the Advanced Test Reactor at INL and High Flux Isotope Reactor at ORNL, manufacture fuel and fuel components at LANL and ORNL, assemble and test RPS at INL, and perform safety analyses. In particular, DOE will manage the Constant Rate Production program, which by 2026 will provide a stable domestic supply of 1.5 kg/year of plutonium heat-source oxide fuel and 10-15 fueled clads, in order to meet future U.S. space mission requirements.

### Objective 1.2 Develop Surface and Propulsion Space Nuclear Fission Power Systems.

**Action 1.2.1:** *Design, Test and Demonstrate Surface Fission Systems.* By 2027, DOE NE and NASA will design, test, and demonstrate a 10 kilowatt-electric class surface fission system for use on the lunar surface, with potential future use on Mars. To accomplish this goal, NASA and DOE NE is engaging the commercial industry for innovative technology solutions capable of meeting NASA's mission requirements in the desired timeframe. Through INL, DOE NE recently released a Request for Information (RFI) to solicit industry feedback on a follow-on procurement effort. The overall effort is anticipated to be executed as two procurements with multiple teams selected for a Phase 1 award that will culminate with preliminary designs of a surface fission system. A subsequent Phase 2 procurement will fund the final design, manufacturing, testing, and delivery of a flight qualified unit that is ready for launch by 2027.

**Action 1.2.2:** *Advance Technologies for NTP.* DOE NE is working with NASA to establish by 2028, the technical foundations and capabilities (including identification and resolution of the key technical challenges) that will provide options for NTP to meet future NASA and DoD mission requirements. Near-term tasks are focused on fuel development, moderator development, high-temperature material development, reactor design, and integrated fuel system testing. DOE-NE, through INL, is also developing a solicitation to engage commercial industry on reactor design. These activities will support an eventual NTP demonstration mission sometime in the 2030s.

**Action 1.2.3:** *Establish Coated Particle-Fuel Production Capability.* DOE NE is working in coordination with NASA and DoD to reestablish the capability to produce coated particle-fuel in significant quantities by 2022. Both NASA and DoD have an interest in coated-particle fuel for their missions, including NTP and DoD's Project Pele microreactor demonstration effort. In July 2020, BWX Technologies was awarded a contract through INL to expand and upgrade its Tristructural-Isotropic (TRISO) nuclear fuel manufacturing line to produce production-scale quantities of coated-particle fuel. After completing this effort, subsequent contracts may be awarded for the actual production and delivery of coated particle fuel to NASA and DoD.

## Objective 1.3 Enhance Solar and Energy Storage Space Systems.

**Action 1.3.1:** *Consider Lunar-Based Use Cases in Advancing Emerging Technologies.* DOE will support NASA and/or other U.S. space agency technology evaluations and down selects (e.g. batteries, hydrogen-oxygen electrolyzers and fuel cells) and follow-on technology maturation for lunar-based energy storage and energy management systems for habitat and vehicle applications in the late 2020s.

**Action 1.3.2:** *Pursue Multiple Technologies and System Integration for Lunar Solar Power.* DOE will support initiatives to develop improved lunar applications of solar power generation with photo-voltaic technologies, concentrating solar-thermal power (CSP), manufacturing evaluations and system integration expertise in the 2020s.

**Action 1.3.3:** *Advance Microgrid Technologies for Lunar Application.* DOE will support NASA and/or other U.S. space agency initiatives to develop and test DC microgrids, with autonomous and optimal energy management, to serve as the backbone for a robust electric infrastructure system to power sustained living, transportation, and surface exploration activities in space.

DC microgrids have gained increasing recognition for their development in applications where electricity generation, storage, and consumption are predominantly using direct current. A recent demonstration by the DOE Office of Electricity (DOE OE) further validates the viability of operating a DC microgrid at Kirtland Air Force Base to achieve long-term, self-sustained operations under a variety of normal "blue-sky" and abnormal "black-sky" scenarios. DOE will continue to support development and testing of DC microgrids for enhanced reliability, resiliency, and efficiency in applications to integrate renewable energy sources (such as solar) and energy storage systems to serve end-use loads that largely consume DC electricity. Simulation and hardware-in-the-loop testbeds at NASA will be used to further test the developed DC microgrid control system, along with other components (or their models), to qualify and validate performance for intended space-based applications.

## Objective 1.4 Enhance Space Thermal Energy Use and Management Systems

**Action 1.4.1:** *Advance Thermal Energy Technologies for Space-based Use Cases* – Assess thermal energy use and management technology across DOE for potential application to space systems.

# Appendix C

## DOE Space Science Action Plan

This appendix further details the possible lines of action that the DOE enterprise can pursue under the strategic goal of solving the mysteries of space, and the related objectives supporting that goal.

### Objective 2.1: Contribute Foundational Knowledge to Enable the Sustained Human Presence in Space.

**Action 2.1.1:** *Conduct Use-Inspired Basic Research for Space Applications.* DOE will maintain a robust program of basic and use-inspired research to create the foundational knowledge necessary to develop future technologies for space applications.

The success of future space missions, including in science, will require new technologies in energy, biology, resource extraction and processing, and sensing. Research in solar photochemistry, catalysis science, and materials design and synthesis will provide the understanding of fundamental processes in solar energy capture and conversion into electrical and chemical energy, which can meet the unique demands of space missions. The knowledge gained through advances in genomic science will enable the development of sustainable biomass for energy and agriculture in space environments. The development of next-generation sensors in the DOE complex will advance space-based astronomy and astrophysics. DOE will continue to provide robust support for these and other core research areas and work to ensure the knowledge generated is made available to support the full suite of missions of the U.S. space program.

**Action 2.1.2:** *Advance Understanding of Plasma Astrophysics.* DOE will conduct plasma scientific research that also contributes to the astrophysics field, including research involving the Earth's magnetospheric, heliospheric, and astrophysical magnetized plasma processes.

DOE-supported frontier plasma science advances the understanding of heliospheric and astrophysical systems that are of interest to NASA, while helping advance DOE's development of fusion science. This research can also provide new knowledge and invaluable data that improves understanding of complex space weather phenomena and enables more accurate models, and ultimately predictions, of this behavior. Such predictions are essential to all missions in space, which can be adversely affected by unanticipated space weather events. DOE will continue to support plasma science research of mutual interest to agencies involved in the space program through a diverse suite of experiments at U.S. universities and National Laboratories, ensuring the data generated and models developed are available to support a range of space S&T missions.

### Objective 2.2: Leverage Space-based Experimental Assets to Advance our Understanding of Large, Complex Systems.

**Action 2.2.1:** *Pursue Collaborative Space-Based Research Infrastructure and Equipment.* DOE will continue to lead and support current science collaborations and identify new opportunities to advance high-priority national science objectives of mutual interest.

Collaboration between DOE and NASA, as well as international partners, has been integral to the success of major scientific experiments hosted on NASA space platforms, as well as scientific research conducted through DOE space payloads. The Alpha Magnetic Spectrometer (a particle physics experiment supported by DOE and international partners and hosted on the ISS) continues to search for various types of unusual matter in the cosmos and advances understanding of dark matter, cosmic domains of antimatter, and the characteristics of cosmic rays. DOE led the fabrication of the Fermi Gamma-ray Space Telescope's main instrument, the Large Area Telescope, and DOE continues to play an essential role in the LAT Instrument Science Operations Center. DOE-led neutron spectroscopy experiments on NASA's Lunar Prospector and Mars Odyssey missions discovered and mapped the global distribution of water on the Moon and Mars, respectively. The understanding of the universe is dramatically advancing, thanks to coordination and/or collaboration on these and other space-based experiments, as well as on current and future ground-based experiments supported by DOE and other science agencies, and through the DOE-stewarded high-performance computing centers. DOE will continue to work closely with NASA to support existing science missions, to leverage DOE-developed technology for NASA missions, and to identify opportunities where collaboration between agencies can advance future DOE science priorities in astrophysics, cosmology, and particle physics.

**Action 2.2.2:** *Leverage Space-Based Infrastructure for Scientific Progress.* DOE will identify new opportunities for space-based astrophysics that will be enabled by an expanded human presence in the solar system.

The development of new, permanent infrastructure in space presents unique opportunities for the physics and astronomy communities to develop the next-generation of experiments that will follow from the DOE-supported ground-based Vera C. Rubin Observatory (formerly the Large Synoptic Survey Telescope) and the Cosmic Microwave Background Stage-4 ground-based experiments, as well as radio astronomy facilities. DOE and partners across government and academia will explore in detail how future space assets can complement these and future terrestrial experiments, contributing to meeting the broad scientific goals of the community in the coming decades.

**Action 2.2.3:** *Advance Models of System Interfaces.* DOE will seek to understand and model terrestrial and atmospheric systems, including the interactions among natural systems, human systems, and biotic and abiotic variables from local to global scales.

The coordination between DOE-supported ground and aerial experimental platforms, and NASA, other government agencies, and private industry satellite observatories is a key component of DOE programs in atmospheric science and terrestrial ecology, including in the polar region. DOE infrastructure and measurements help test and validate experiments for NASA missions. Together, the two agencies (along with other interagency partners like the National Science Foundation (NSF) and National Oceanic and Atmospheric Administration (NOAA)) are greatly advancing understanding of the complex Earth system at local, regional, and global scales. DOE will continue to work closely with NASA and other partners to provide mutual support for scientific discovery and technology development needed to both enhance understanding of the Earth system and advance future studies of other planetary bodies in the solar system.

**Action 2.2.4:** *Improve DOE Mission Achievement through Space-Based Research.* DOE will identify new research opportunities available from current and future space-based experimental platforms to advance core DOE missions in science and support scientific discovery for the U.S. space program.

Platforms for research on the ISS, the Gateway, or the Moon will present unique conditions for the study of materials science, chemistry, and genomic science, while presenting novel opportunities to advance remote and automated science techniques that could be transferrable to terrestrial laboratories. As new space-based platforms are developed, in low Earth orbit and beyond, DOE will focus and emphasize the Department's diverse scientific communities to identify these new opportunities for science and technical innovation, and ways in which these can be used to the benefit of both DOE's missions and the missions of other space program agencies.

## Objective 2.3: Facilitate Access to the Research Capabilities and Expertise Needed to Solve Scientific Challenges for the Space Program.

**Action 2.3.1:** *Leverage DOE Core Competencies in High-Performance Computing.* DOE will provide opportunities for enhanced collaboration with the U.S. space community on the development and application of high-performance computing and networking and access to research infrastructure.

The computing and networking research infrastructure developed and maintained by DOE plays a central role in advancing research of importance to space science, exploration, security, and commerce. DOE's expertise and infrastructure for advanced computing will be central for supporting science missions to improve understanding of the Earth or the fundamental mysteries of the universe, as well as for sustaining the explosive growth in commercial space activities and the need for greater SSA and space traffic management. Furthermore, future remote space missions, including those that are highly automated and supported by advanced AI technology, can benefit from DOE-supported advances in edge computing and long-distance, high-bandwidth wireless communication in extreme environments. Finally, DOE's ground-based research in quantum networking can benefit from NASA expertise in ground-to-space networking, including quantum-based communication. DOE will work closely with NASA and the rest of the

U.S. space community to ensure DOE-led advances in computing and networking can be leveraged broadly to support space science, security, and commerce.

**Action 2.3.2:** *Leverage DOE's Capabilities in Materials Development and Testing.* DOE will make scientific and experimental facilities available to researchers investigating material properties under the environmental conditions of space.

The reliability of materials used for long-duration missions in space (e.g., vehicle shielding and electronics) is of critical importance for mission assurance. DOE's suite of scientific user facilities, as well as other DOE-supported experimental facilities available at DOE laboratories and U.S. universities, provide the world's most complete collection of tools to study how materials behave under the extreme conditions of space and develop new materials to meet exacting mission requirements. X-ray light and neutron sources give atomic-level insight into the mechanical behavior of materials under extreme stresses of temperature, pressure, and radiation. Accelerator facilities enable single event testing and reliability assessment to determine how electronics will behave when exposed to the extreme radiation environment of space. DOE's nanoscale science research centers have expertise in the development of materials with novel properties needed to meet specific mission requirements. DOE will work to raise awareness of the suite of unique experimental facilities and collaborate with Federal partners to explore new approaches to expanding the availability of space mission-critical test capabilities.

**Action 2.3.3:** *Develop Virtual User Facilities*. DOE will develop virtual facilities that combine experimental and computational capabilities across the DOE complex and with other government and academic laboratories to solve future challenges more effectively and efficiently in meeting U.S. space policy goals.

The challenges that will need to be overcome to meet the goals of the U.S. space program, including returning a diverse team of U.S. astronauts to the Moon and landing the first human on Mars, will require the convergence of the full suite of scientific disciplines and technological capabilities within the U.S. research complex, including the DOE National Laboratory system. Through virtual networks that tightly integrate terrestrial facilities across Federal, university, and private sector labs, access to the suite of capabilities, and subject matter expertise needed to solve a given challenge can be expedited. Ultimately, as future space-based research assets become available, these capabilities can be plugged into existing virtual capabilities. DOE will work closely with its labs, university community, and private companies to identify new opportunities to create virtual facilities and virtual laboratories that can nimbly and efficiently tackle future challenges to our exploration and use of space.

**Action 2.3.4:** *Promote Data Sharing.* DOE will coordinate the use of data and promote more data sharing among agencies to enhance our understanding of the working environment in space.

Data collected from DOE-supported science experiments, including experiments currently operating in space, are not only advancing fundamental understanding of the universe, but also have the potential to advance other missions. For example, data collected by the DOE-supported Alpha Magnetic Spectrometer operating aboard the ISS is helping researchers better understand the radiation environment in space, thereby promoting human health on current and future space missions and the survivability of space-based electronic assets. DOE will work with partners across the U.S. government and in academia to make its scientific data available to a broad range of users to support non-scientific missions and take advantage of data collected by other agencies to support its own scientific programs.

# Appendix D

## DOE Space National Security Action Plan

This appendix further details the possible lines of action that the DOE enterprise can pursue under the strategic goal of supporting the secure and peaceful use of space, and the related objectives supporting that goal.

### Objective 3.1 Support National Security Space Capabilities for Treaty Monitoring, Indications, and Warning.

**Action 3.1.1:** *Interagency Collaboration.* DOE/NNSA will collaborate with the National Laboratories and the interagency community to improve data analysis and space models. The data and models from this work have been instrumental in treaty verification and have exemplary values such as characterizing space weather data. There are merits in further collaborating between SNL, LANL, DoD, and NASA to better use current and historic space environment data from DOE-built sensors and models to improve understanding and forecasting of cis-lunar space environment. This collaboration will also focus on utilizing data in conjunction with other national technical means.

**Action 3.1.2:** *Studies and Simulations.* DOE will work with U.S. interagency to conduct and complete a space constellation architecture study, based on emerging threat scenarios and recent DoD directives for space operations. This study will inform mission requirements to drive technology investments, including those investments made by DOE/NNSA. The study will use many M&S inputs and should identify necessary improvements in M&S capabilities.

**Action 3.1.3:** *Sensor Development.* DOE will continue improving the development of new sensors. DOE/NNSA has been successful in building, deploying, and operating more than 400 instruments on more than 90 satellites. DOE/NNSA is continuing sensor R&D to meet DoD endurability, reliability, and robustness requirements. NNSA must develop new methods and models to inform these requirements. To meet these and other requirements, NNSA payloads and sensors will need to serve multiple roles as part of a broader system. New sensor technologies in the areas of radio antennas, receivers, and transmitters; autonomous, collaborative networking and information processing across satellite arrays; radiation hardening; and advanced manufacturing will be employed. DOE/NNSA will capitalize on inherent radiation hardening and radiation tolerant technologies, manufacturing foundries, and advancements in additive manufacturing to improve sensor designs and performance.

### Objective 3.2 Develop Space Protection Capabilities to Protect Space Assets.

**Action 3.2.1:** *Threat Assessments and Requirements.* DOE/NNSA will seek to better understand requirements for ensuring protection and availability of space assets and understand future threats. There needs to be a clear understanding of operational requirements and the natural or human-made threats that can impact meeting those operational requirements. For example, using the Department's high-performance computing, multi-physics codes, and workforce expertise, DOE/NNSA has analyzed high-velocity debris interactions with satellites. This information has been useful in assessing satellite resiliency. More research and analysis of this nature will be needed in the future.

**Action 3.2.2:** *Space Asset Protection and Resilience.* DOE/NNSA will contribute to increasing the U.S. Government's protection and resilience of space assets.

Three approaches to protection and resiliency will continue to be pursued: threat-defended hardware; sensor protection; and cognitive analytics. Threat-defended hardware will focus on the development of technologies and models for understanding the impact of hostile (natural and human-made) environments on critical satellite systems. Research will also be conducted to develop approaches to harden the systems to these environments. Sensor protection will discover and develop technologies for protecting critical satellite systems and sensors by preventing exposure to identified threats and attacks on the satellite system. Cognitive analytics will focus on research to make satellite systems self-aware of subtle anomalies in their function. This awareness must continue to self-refine as threats and intrusions adapt to protective strategies. Attention must be paid to developing detection strategies that do not impose excessive burden on the space system itself. Also, designs that protect satellite instruments such as telescopes will continue to be developed capitalizing on DOE's expertise in laser optics.

**Action 3.2.3:** *Space Protection Partnerships.* DOE/NNSA will support the technological and analytical means to address space protection through partnerships. DOE/NNSA will use its extensive reach-back to academic partners (including academic alliances) to develop technologies for improving space asset resiliency.

## Objective 3.3 Develop Technologies for NEO Deflection and Impact Studies.

**Action 3.3.1:** *NEO Characterization.* DOE/NNSA will support space missions to collect information that characterize NEOs for subsequent analyses. M&S of mitigation scenarios require an understanding of NEO characteristics such as density, equation-of-state, shape, and mass. This data can be obtained by employing telescopes and actual missions designed to fly-by or rendezvous with actual NEOs and collect samples. NNSA is supporting future missions by collaborating with NASA in deciding on the types of data collecting instruments that will be employed on reconnaissance spacecraft.

**Action 3.3.2:** *NEO Modeling and Analysis.* DOE/NNSA will assess the adequacy and validity of modeling and analysis through annual exercises, test problems, comparison to experiments, and peer review activities. DOE/NNSA will structure exercises to identify gaps, formulate needed improvements, test connections within the national framework, and improve operational readiness. DOE/NNSA will also conduct M&S analyses based on NASA-generated NEO characteristics using high-performance computing of multiple cases where the NEO may be a large asteroid (hundreds of meters in diameter) with a long or short warning time and a three-dimensional shaped comet. Other NEO configurations and warning timelines will be studied in the future. The two mitigation strategies that will be studied are a kinetic impactor and a nuclear device. DOE/NNSA brings unique capabilities of employing the fastest computers in the world coupled to the multi-physics codes that run on the machines and a unique workforce expertise capable of studying both the kinetic impactor and nuclear device mitigation scenarios. In addition, DOE/NNSA is positioned to conduct independent peer reviews, which are important when expert judgement is an integral part of the analyses.

**Action 3.3.3:** *NEO Deflection*. DOE/NNSA will assist development of preliminary designs for NEO deflection mission campaigns. This action includes preliminary designs for a kinetic impactor mission campaign in which the spacecraft is capable of either functioning as a kinetic impactor or delivering a nuclear explosive device. Designs should include reconnaissance spacecraft and methods to measure the achieved deflection. DOE/NNSA will continue to bring expertise in radiation, aerodynamics, and device design through participation in Mission Design Laboratory exercises.

# Appendix E

## DOE Space Development Action Plan

This appendix further details the possible lines of action that the DOE enterprise can pursue under the strategic goal of ensuring the development of space, and the related objectives supporting that goal.

### Objective 4.1 Apply Emerging Technologies for Industries of the Future to the Space Domain.

**Action 4.1.1:** *Develop Emerging Technologies.* DOE will evaluate possible application of DOE's emerging technologies and research efforts to the space domain (such as AI, quantum information systems, advanced communications networks/5G, advanced manufacturing, and biotechnology[22]) and pursue technology transfer and partnerships to strengthen the U.S. industrial base and U.S. leadership in the space innovation ecosystem.

**Action 4.1.2:** *Pursue Technology Applications.* DOE will evaluate possible application of DOE machine-aided design and AI-related large-scale systems engineering to space science data, systems design, and engineering management.

### Objective 4.2 Leverage Tools and Tactics to Encourage Use of DOE Technologies in Space Missions and Studies.

**Action 4.2.1:** *Seek External Advice.* DOE will seek advice and recommendations from outside experts and forums (e.g., the National Academies of Science, the Secretary of Energy Advisory Board, space industry groups, etc.) on technologies and capabilities across the DOE complex that can be brought to bear on national space needs, and recommendations to improve DOE support to national space objectives.

**Action 4.2.2:** *Convene Events.* DOE will conduct an InnovationXLab Summit focused on space technologies. If the event proves valuable, DOE will consider repeating space-focused Summits at a regular cadence. The InnovationXLab series, in collaboration with DOE laboratories, is designed to expand the commercial impact of the substantial investment in the National Lab innovation portfolio by convening relevant stakeholders to foster networks of innovation.

**Action 4.2.3:** *Promote Online Portals.* DOE will seek to increase the visibility and utility of the Lab Partnering Service (LPS) platform and space-specific landing page, which can be found here: https://space.labpartnering.org/. The LPS provides easy access to DOE intellectual property, scientific user facilities (including specialized scientific equipment and infrastructure), and subject matter experts via a single location. Interested parties can connect with leading DOE National Laboratory technical experts

**Action 4.2.4:** *Improve Partnership Policies and Practices.* DOE will survey interagency partners, academia, and industry (including via use of RFIs) to identify policies and practices that impede effective collaboration (including access to technology, experts, or facilities), expand planned work scope to accommodate additional applications to space, and consider joint development of technology roadmaps and action plans where applicable.

**Action 4.2.5:** *Collaborative Partnerships.* DOE will pursue and develop new strategic partnerships and partnership mechanisms (e.g. MOUs, consortia, working groups) with external partners to accelerate the commercialization of DOE-developed technologies relevant to the space sector.

[22] M-20-29, "Fiscal Year (FY) 2022 Administration R&D Budget Priorities and Cross-cutting Actions," OMB and OSTP, 8-14-20, https://www.whitehouse.gov/wp-content/uploads/2020/08/M-20-29.pdf