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Thomas D. Olszewski
Jericho Locke

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POLICY INSTITUTE
1701 Pennsylvania Ave., Suite 500
Washington, DC 20006-5825

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For More Information

Bhavya Lal, Project Leader
blal@ida.org, 202-419-3724

Mark S. Taylor, Acting Director, Science and Technology Policy Institute
mtaylor@ida.org, 202-419-5491

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Executive Summary

The White House Office of Science and Technology Policy (OSTP) asked the IDA Science and Technology Policy Institute (STPI) to research the role of Federal agencies other than the National Aeronautics and Space Administration (NASA) in creating a sustainable U.S. presence on the Moon by:

1. identifying which Federal agencies could be involved,
2. describing what the roles of those agencies might be, and
3. determining if there will be a need for interagency coordination.

As directed by the OSTP sponsor at the start of the project, STPI's analysis focused on a field station at the lunar South Pole and the role of the U.S. Government in promoting private sector commercial activity as well as science and exploration. We identified civil agencies other than NASA that have expertise, resources, or authority that could contribute to or benefit from U.S. plans for Moon development. In addition, the OSTP sponsor asked STPI to look into the U.S. Antarctic Program for lessons in establishing and operating a lunar field station, including balancing interagency interests and equities.

STPI considered a total of 90 cabinet-level departments, high-level intra-departmental agencies and offices, and independent agencies, 47 of which were identified as having the potential to play a role in a sustained U.S. lunar presence at some point in its development. Agencies within four cabinet-level departments (Commerce, Energy, Interior, and State) and two independent agencies (the Federal Communications Commission and the National Science Foundation) were identified as having technical expertise, research, or authority highly relevant (*high* level of relevance in the table below) to U.S. lunar development, and are already active in space or lunar affairs. Three additional departments (Agriculture, Defense, and Health and Human Services) plus one independent agency (the Environmental Protection Agency) were deemed as having relevant technical expertise or supporting research and development (*medium* level of relevance in the table below) in areas critical to establishing a sustainable presence on the Moon, including mobility, in situ resource utilization, and environment/life support.

Opportunity for U.S. Government support for commercial development related to the Moon is widespread among agencies through Small Business Innovation Research and Small Business Technology Transfer Programs, although lunar development is not a targeted priority of these programs at this time. Regulatory and oversight activities of most Federal agencies represent extensions of their terrestrial authority over U.S. facilities rather

than reflecting authority specifically aimed at space or lunar activities (*low* level of relevance under Regulation & Oversight in the table below).

Numerous Federal agencies covering a diverse array of scientific, exploration, commercial, military, and intelligence equities have the potential to contribute to or benefit from a sustained U.S. presence on the Moon. No single existing agency has the full range of authorities or expertise spanning science, exploration, commercial development, and regulatory enforcement that a lunar field station supporting both research and private sector activity will require. There may be a need for interagency coordination in establishing a common strategy for U.S. activities on the Moon at some point, but current interagency processes are likely sufficient to manage U.S. lunar policy for the immediate future.

Summary of Potential Agency Contributions to a Sustainable Lunar Presence

L – Low - has expertise or research that could be relevant, and has authority that could extend to Moon

M – Medium - has expertise or research that is relevant, but not specifically space or Moon-oriented

H – High - has expertise, research, or authority already supporting lunar or space development

Department/Agency	Operations Management	Technological Expertise/ Research & Development	Basic Science	International Relations	Regulation & Oversight	Commercial Development
Department of Agriculture						
Agricultural Research Service		M	L			
Animal and Plant Health Inspection Service					L	
National Institute of Food and Agriculture		M				
Department of Commerce						
Bureau of Industry and Security				L	L	
Economic Development Administration						M
International Trade Administration				L	L	L
National Institute of Standards and Technology		H	L			M
National Oceanic and Atmospheric Administration		M	M		H	M
National Telecommunications and Information Administration					H	
U.S. Patent and Trademark Office					L	
Office of Space Commerce						H
Department of Defense						M
Defense Advanced Research Projects Agency		M				
Office of Naval Research		M				
U.S. Army Corps of Engineers		L				
Department of Energy						M
Advanced Research Projects Agency-Energy		M				
Loan Programs Office						M
Office of Cybersecurity, Energy Security, and Emergency Response		M				
Office of Efficiency & Renewable Energy		H				
Office of Nuclear Energy		H				
Office of Science			H			
National Labs	L	H				

Department/Agency	Operations Management	Technological Expertise/ Research & Development	Basic Science	International Relations	Regulation & Oversight	Commercial Development
Department of Health and Human Services						
Centers for Disease Control and Prevention		M				
Food and Drug Administration			L		L	
National Institutes of Health		M				
Department of Homeland Security		L				
Department of the Interior						
Bureau of Ocean Energy Management					L	
National Park Service					L	
U.S. Geological Survey		H	H			
Department of Justice						
U.S. Marshals Service					M	
Department of Labor						
Occupational Safety and Health Administration					L	
Mine Safety and Health Administration					L	
Department of State				H		
Department of Transportation						
Federal Highway Administration		L				
Federal Aviation Administration					M	
Office of Secretary – Research and Technology		L				
Department of Treasury						
Internal Revenue Service					L	M
Independent Agencies						
Environmental Protection Agency		M			L	
Federal Communications Commission					H	
National Science Foundation	M	H	H			M
Nuclear Regulatory Commission					M	
Small Business Administration						M
United States Postal Service					L	
Smithsonian Institution			M			

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1. Introduction

Fifty years ago, Apollo 11 successfully sent Americans to explore the lunar surface and return to Earth for the first time. With an eye toward maintaining America's scientific and economic leadership in space, the President issued Space Policy Directive 1 (SPD-1) in December 2017, which committed the United States to:

> 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 (EOP 2017; EOP 2010; emphasis added).

The Vice President told the National Space Council (NSpC) in March 2019 that the United States intends to return American astronauts to the Moon by 2024 to prepare for an eventual mission to Mars (Pence 2019), and later the same year, the National Aeronautics and Space Administration (NASA) Administrator made clear, "We will go with innovative new technologies and systems to explore more locations across the surface than was ever thought possible. *This time, when we go to the Moon, we will stay*" (Bridenstine 2019; NASA 2019a; emphasis added).

In addition to the basic requirements for survival, the emphasis on *sustainability* conveys U.S. ambitions for our presence on the Moon to become a source of scientific discovery, economic growth, and a platform for continued human expansion into space. To achieve these long-term goals, a prospective Moon field station will require making use of in situ resources and building durable, reusable infrastructure, and ultimately, becoming a generator of economic value through scientific, exploratory, and commercial activities.

The White House Office of Science and Technology Policy (OSTP) asked the IDA Science and Technology Policy Institute (STPI) to research the role of Federal agencies in creating a sustainable presence on the Moon, particularly with an eye to establishing a field station on the lunar South Pole, by:

1. identifying which Federal agencies could be involved,
2. describing what the roles of those agencies might be, and
3. determining if there will be a need for interagency coordination.

As requested by OSTP, this report focuses only on scientific and commercial activities, not defense or intelligence activities, although scientific research and operations in support of civil activities by defense and intelligence agencies are considered.

Currently, the immediate focus of U.S. Moon strategy is to establish Gateway, a Moon-orbiting space station that will provide a platform to launch crewed expeditions to the lunar surface by 2024 as well as serve as a stepping stone to the rest of the solar system (NASA 2019b). This report picks up with the next major stage of a human presence on the lunar surface, a human-tended field station—most likely at the Moon's South Pole, where near-surface ice could be extracted to supply water and access to sunlight for extended periods could be used to generate power (Hurley et al. 2016). Although a wide array of visions of human occupation of the Moon have been proposed, STPI found none that has explicitly explored the potential roles of different agencies across the Federal landscape.

To address the three objectives of this project, STPI systematically examined the missions, activities, and statutes of Federal agencies[1] to identify any that could conceivably have a role in fostering or managing science, exploration, commerce, and any other activities on the Moon. In order to understand when and how different agencies could contribute to the U.S. Moon presence, STPI also reviewed publicly available literature and asked experts on lunar development to determine the factors required for a long-term sustainable presence at the Moon's South Pole. Lastly, STPI assessed the possible need for interagency coordination.

[1] U.S. Government entities evaluated included cabinet-level departments and agencies, independent agencies, and intra-departmental offices and bureaus recognized as agencies on the Index of U.S. Government Departments and Agencies (https://www.usa.gov/federal-agencies).

2. Notional Elements of a U.S. Lunar Field Station

Many suggestions for what a lunar field station might look like, when it might be established, and how it might evolve over time have been proposed, but NASA has not issued any official plans or announced a chosen architecture (Duke et al. 1985; Hoffman and Niehoff 1985; NASA 2004; Sherwood 2017). Previous proposals differ widely in details, but have many fundamental aspects in common, including habitation systems, in situ resource utilization (ISRU), mobility, power, exploration and science systems, and support capabilities (e.g., orbital support and transportation). STPI focused on these components of a lunar field station.

Initially, a field station would probably be somewhat minimal, akin in many ways to the current U.S. modules on the International Space Station (ISS). Like the ISS, the field station would be continuously occupied, have limited extra-vehicular activity (EVA) capabilities, and prioritize field experiment deployments (NASA 2004). Subsequently, it might evolve to become more extensive, analogous in some ways to the U.S. Antarctic Program (USAP), which has a staff numbering in the hundreds, working to maintain and operate three year-round stations plus numerous seasonal camps that accommodate over a thousand visiting researchers every year (NSF 2016).

The United States Government was drawing up plans for a base on the surface of the Moon even before the first humans landed. An early U.S. Air Force report called for a human-tended lunar expedition in 1968 (U.S. Air Force 1961), while an earlier Army report set out an operational concept for a lunar outpost initially capable of sustaining 10 to 20 personnel, comparing the priority and authority required to the Manhattan Project (U.S. Army 1959). Interest in concepts for a lunar field station continued even after the termination of the Apollo program, culminating in the Space Exploration Initiative (The Synthesis Group 1991), which included the First Lunar Outpost Design Reference Mission (Lofgren 1993).

NASA most recently studied lunar architectures under the Constellation Program and the Exploration Systems Architecture Study program (Cooke et al. 2008; NASA 2004). This work included an investigation of an outpost at an unspecified location intended to support four people for 6-month intervals, with a focus on transportation to and from the Moon. The goals of the proposed outpost were to enable a continuous, sustained presence, frequent near-field (3–15 km) mobility, high-frequency science work (mainly field work), and demonstrations of ISRU. The architecture would also have the capability to enable

logistics support for a growing array of activities, like further-field EVAs (e.g., 30 km and more), additional science infrastructure (e.g., laboratories or astronomical observatories), and large-scale ISRU production.

The proposed outpost consisted of five modules meant to be landed on sequential missions, and not moved once grounded. These modules included a habitation unit, power supply, logistics unit, and two lander/ascent modules. These pieces could either be pre-deployed or emplaced incrementally with successive human missions. The habitation would provide the primary living space for the astronauts, while other modules would be accessed by EVA. Each module would be connected with cables to the power source through a power management and distribution system.

The power source was selected to be a fission reactor in the 100 kW range. Mobility could be provided through EVA suits and unpressurized rovers, with extension options to include pressurized rovers or other forms of mobility. The logistics module would land supplies, and provide a hub for the rovers as well as any equipment needed for ISRU extraction and processing. The outpost would provide a demonstration mission for ISRU, including a lunar miner/hauler, a polar resource extractor, oxygen production hardware, and a logistics carrier. The assessment concluded that one or more relay satellites would be needed to provide uninterrupted contact with Earth from an outpost at the lunar South Pole, but that a satellite constellation for surface positioning and navigation would be prohibitively expensive.

Recent studies have contributed novel ideas that could factor into a lunar outpost beyond the proposed Constellation architecture (Gibney 2018; Pittman et al. 2016). In particular, future outposts could rely more heavily on ISRU, including using regolith to shield modules, pave surfaces, or even to construct habitation units (e.g., Benaroya et al. 2008). However, the most significant ISRU opportunity is the confirmation of water ice at the surface of the Moon (Li et al. 2018), which would provide a critical resource for sustaining life and generating fuel to power activities. Excavating water ice at the lunar South Pole will require advanced mobility and a means to power mining activity (e.g., power beaming). Beyond current U.S. concepts, international involvement and commercial activity would require a more extensive architecture, such as the European Space Agency's Moon Village concept (Sherwood 2017).

3. Potential Roles of Federal Agencies in Creating a Sustainable Presence on the Moon

The potential roles of Federal agencies on a lunar field station range from direct involvement in operations and research to more peripheral regulatory and advisory roles. As this project proceeded, OSTP refined and expanded its request of STPI to consider all Federal agencies that could contribute directly to U.S. activities on the Moon as well as agencies without direct interests in space or the Moon but which might have experience or know-how that could be usefully applied in the development of a sustainable lunar presence. STPI considered a total of 90 cabinet-level departments, high-level intra-departmental agencies and offices, and independent agencies, of which 47 were found to have the potential to play a role in a sustained U.S. lunar presence at some point in its development.

In order to organize the large number of agencies and their diverse connections to U.S. lunar activity, the potential activities were grouped into six categories: operations management, technical expertise/research and development, basic science, international relations, regulation and oversight, and supporting commercial development. Technical expertise/research and development included knowledge in areas identified as being of particular interest by OSTP: in situ resource utilization; power generation, storage, and distribution; surface mobility; communications and data transmission; habitation and construction; and health, environment, and life support. Basic science included lunar and planetary geoscience; Earth observation; astronomy and astrophysics; heliophysics; other physical science; and life science.

To focus attention on those agencies with the greatest interest or most to contribute to developing a sustainable U.S. presence on the Moon, each Federal agency's potential level of engagement was identified as low, medium, or high. A low potential for engagement indicates that the organization has expertise or research that *could be* relevant, and has authority that *could* extend to Moon. A medium potential for engagement indicates that the organization *does have* expertise or research that is relevant, but is *not specifically space or Moon-oriented*. A high potential for engagement indicates that the organization *does have* expertise, research, or authority that is *already supporting lunar or space development*.

Table 1 lists all agencies that STPI identified as having any potential for engagement in a sustainable U.S. presence on the Moon, identifies the categories of activity each agency would engage in, and provides brief descriptions of the nature of their engagement. A table

of all Federal agencies considered, their missions as they relate to activity in space, the basis for their potential engagement ranking, and additional detailed information are available in the spreadsheet entitled *Federal Agencies with Potential Roles in U.S. Lunar Presence*. A narrative description of each of the six broader areas of activity and the nature of each agency's potential contribution follows Table 1.

Table 1. Nature and Potential of Agency Contributions to a Sustainable Lunar Presence

L – Low - has expertise or research that could be relevant, and has authority that could extend to Moon

M – Medium - has expertise or research that is relevant, but not specifically space or Moon-oriented

H – High - has expertise, research, or authority already supporting lunar or space development

Department/Agency	Operations Management	Research and Development	Basic Science	International Relations	Regulation and Oversight	Commercial Development
Department of Agriculture						
Agricultural Research Service		M Closed-system agriculture	L Life science			
Animal and Plant Health Inspection Service					L Inspects agricultural products entering U.S. territory	
National Institute of Food and Agriculture		M Automated vehicles				
Department of Commerce						
Bureau of Industry and Security				L Export control and treaty compliance system and promoting continued U.S. strategic technology leadership	L Export control and treaty compliance system and promoting continued U.S. strategic technology leadership	

Department/Agency	Operations Management	Research and Development	Basic Science	International Relations	Regulation and Oversight	Commercial Development
Economic Development Administration						M Opportunity zones
International Trade Administration				L Strengthens the competitiveness of U.S. industry, promotes trade and investment, and ensures fair trade through the rigorous enforcement of our trade laws and agreements	L Strengthens the competitiveness of U.S. industry, promotes trade and investment, and ensures fair trade through the rigorous enforcement of our trade laws and agreements	L Strengthens the competitiveness of U.S. industry, promotes trade and investment, and ensures fair trade through the rigorous enforcement of our trade laws and agreements
National Institute of Standards and Technology		H Building and construction; ISRU mining technologies	L Physical science			M SBIR/STTR
National Oceanic and Atmospheric Administration		M Space weather monitoring; Earth observation	M Helio-physics; Earth observation		H Licenses private remote sensing space systems (National Environmental Satellite, Data, and Information Service)	M SBIR/STTR

Department/Agency	Operations Management	Research and Development	Basic Science	International Relations	Regulation and Oversight	Commercial Development
National Telecommunications and Information Administration					H Allocates electromagnetic spectrum	
U.S. Patent and Trademark Office					L Patent and licensing regulations	
Office of Space Commerce						H Supports U.S. space industry
Department of Defense						M SBIR/STTR
Defense Advanced Research Projects Agency		M Com-munications technology; position, navigation, and timing systems; automated vehicles				
Office of Naval Research		M Com-munications technology				
U.S. Army Corps of Engineers		L ISRU mining				

Department/Agency	Operations Management	Research and Development	Basic Science	International Relations	Regulation and Oversight	Commercial Development
Department of Energy						M SBIR/STTR
Advanced Research Projects Agency-Energy		M Advanced energy				
Loan Programs Office						M Loans and SBIR/STTR
Office of Cybersecurity, Energy Security, and Emergency Response		M Space weather resilience				
Office of Efficiency & Renewable Energy		H Solar technologies; fuel cell technologies; ISRU advanced manufacturing				
Office of Nuclear Energy		H Radio-isotope thermoelectric generators; fission reactors				
Office of Science			H Astronomy and astrophysics; life science; physical science			

Department/Agency	Operations Management	Research and Development	Basic Science	International Relations	Regulation and Oversight	Commercial Development
National Labs	L Science user facilities	H ISRU mining technology; ISRU advanced manufacturing				
Department of Homeland Security		L Satellite position, navigation, and timing (Science and Technology Directorate)				
Department of Health and Human Services						
Centers for Disease Control and Prevention		M Human health and biomedical research				
Food and Drug Administration			L Life science		L Safety and security of drugs, biological products, medical devices, food supply, and products that emit radiation	
National Institutes of Health		M Health				

Department/Agency	Operations Management	Research and Development	Basic Science	International Relations	Regulation and Oversight	Commercial Development
Department of the Interior						
Bureau of Ocean Energy Management					L Lease block auctions for mineral rights	
National Park Service					L U.S. historical monuments and sites	
U.S. Geological Survey		H ISRU mapping	H Planetary geology			
Department of Justice						
U.S. Marshals Service					M Law enforcement	
Department of Labor						
Occupational Safety and Health Administration					L Workplace safety	
Mine Safety and Health Administration					L Mine safety and health	
Department of State				H Outer Space Treaty (Office of Space and Advanced Technology)		

Department/Agency	Operations Management	Research and Development	Basic Science	International Relations	Regulation and Oversight	Commercial Development
Department of Transportation						
Federal Highway Administration		L ISRU building materials				
Federal Aviation Administration					M Launch and re-entry licensing (Office of Commercial Space Transportation)	
Office of Secretary – Research and Technology		L Position, navigation, and timing systems				
Department of Treasury						
Internal Revenue Service					L Tax collection	M Tax incentives
Independent Agencies						
Environmental Protection Agency		M Envi-ronmental monitoring			L Quality of human environments	
Federal Communications Commission					H Licenses electromagnetic communication in space	

Department/Agency	Operations Management	Research and Development	Basic Science	International Relations	Regulation and Oversight	Commercial Development
National Science Foundation	M Models for Moon station (USAP, IODP)	H Automated vehicles	H Planetary geology; astronomy; heliophysics; life science; physical science			M SBIR/STTR
Nuclear Regulatory Commission					M Nuclear energy	
Small Business Administration						M SBIR/STTR; small business loans
United States Postal Service					L Mail service and logistics	
Smithsonian Institution			M Planetary geosciences and astronomy			

A. Operations Management

Establishing and running a lunar field station will require careful management and coordination of a complex operation with many interdependent parts. NASA already runs the U.S. operation on the ISS. A commonly cited non-NASA model for operating a large-scale scientific field station under extreme environmental conditions outside the territory of the United States is USAP, which falls under the National Science Foundation's (NSF's) Office of Polar Programs. USAP operations and logistics are run by a primary contractor (currently Leidos) and additional subcontractors, including operating research facilities; managing equipment and supplies; designing and constructing facilities; maintaining three year-round stations, two research vessels, and numerous seasonal field camps; arranging medical clearance and travel of USAP staff and researchers; transportation of passengers and cargo; marine terminal operations; and complying with safety, health, and environmental requirements (NSF 2016).

In addition to private sector contractor support, a number of Federal departments and agencies contribute to the U.S. presence on Antarctica, although NSF reimburses them. The Department of Defense (DOD) provides shipborne deliveries of fuel and cargo, airlift within Antarctica and with New Zealand, weather forecasting, air traffic control, ground NAVAID electronics maintenance, radiofrequency spectrum management, information security/information assurance management, and domestic postal services, and the U.S. Coast Guard provides icebreaker services.

International cooperation in lunar activities is explicitly called out in SPD-1, and one possible model for coordinating a complex, international scientific exploration program is the International Ocean Discovery Program (IODP), funded by NSF's Division of Ocean Sciences. IODP is a multinational research program aimed at advancing scientific understanding of the Earth through drilling, coring, and monitoring the ocean floor. It involves two drill ships, one funded by NSF and the other by Japan's Ministry of Education, Culture, Sports, Science, and Technology. The European Consortium provides additional mission-specific platforms for Ocean Drilling Research, and additional funds are contributed by science agencies in China, Korea, Australia-New Zealand, and Brazil. Drilled materials are stored at three core repositories in the United States, Germany, and Japan. The drillship provided by the U.S., the *JOIDES Resolution*, is owned by Overseas Drilling Limited, and operations are overseen by a non-profit contractor, the JOIDES Resolution Science Operator, based at Texas A&M University. The overall management of the U.S. portion of the program is handled by the U.S. Science Support Program, a contractor based at Columbia University's Lamont-Doherty Earth Observatory.

B. Technological Expertise/Research and Development

Activities necessary for establishing and maintaining a sustainable lunar presence include ISRU; power generation, storage, and distribution; surface mobility; communications and data transmission; habitation and construction; and health, environment, and life support (NASA 2004; Sherwood 2017). Various agencies carry out or support research and development in these areas that could be applied to a lunar presence or have experience implementing lunar-relevant technology in terrestrial settings.

1. In Situ Resource Extraction and Utilization

Extracting, processing, and utilizing lunar resources will be critical to enabling a sustainable presence on the Moon. 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.

A wide variety of resources have been discussed as available on the Moon, ranging from relatively far-out ones such as helium-3 as a fuel for future fusion-generated power, to ilmenite (a titanium oxide mineral) as a source of oxygen from the lunar regolith. However, the immediate focus of U.S. lunar ISRU activities will be on water and building materials. Water is not only a critical resource to sustain life, but splitting water into hydrogen and oxygen provides the basis to store energy in fuel cells. Producing building materials using resources like regolith and basalt that are ubiquitous on the surface of the Moon could be critical to building infrastructure that can withstand the extreme lunar environment. Building materials can either be fabricated into pavers, blocks, and bricks or can serve as raw material for additive manufacturing of more specialized field station components.

The Federal agency that is most active in research and development related to mining and mineral extraction is the Department of Energy (DOE), primarily through its 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 (NRC 2002).

The U.S. Geological Survey (USGS) has long-standing expertise in geologic mapping, which is critical to identifying potential areas with mineral resources, whether intended for initial establishment of a lunar presence or future commercial exploitation (David 2018). Its Geologic Division has mapped the lunar surface in preparation for the Apollo landers, has continued to be involved with the Lunar Reconnaissance Orbiter, and has been the lead agency in generating high-resolution maps of other planetary bodies

(Skinner 2009).[2] In addition to making maps, the USGS Mineral Resources Program develops geologic ore-deposit models, which could be important for future resource extraction. In cooperation with NASA, USGS also processes and releases the Landsat images of Earth's land surface including reflectance and spectral indices—experience that could prove valuable in using remote sensing to detect near-surface resources on the Moon.

Other Federal agencies that have capabilities that could prove useful in finding and developing mineral resources on the Moon include the Army Corps of Engineers (USACE), whose Waterways Experiment Station runs a geotechnical laboratory with expertise in soil and rock mechanics, slope stability, and dust control. Another DOD entity conducting research and development that could advance mineral resource extraction on the Moon is the Army Research Laboratory, which supports work on robotics and excavation technologies. Lastly, National Institute of Standards and Technology's (NIST's) Advanced Technology Program includes support for research in intelligent control, membrane and other separation technologies, microsystem and nanosystem technologies, and catalysis technologies, all of which have potential applications in processing lunar mineral resources (NRC 2002).

Utilizing in situ resources requires not just finding and extracting them, but also using them to fabricate necessary items and materials. Lunar regolith and basalt have been proposed as a basis, either alone or mixed with components brought from Earth, for additive manufacturing (i.e., 3D printing) and building and paving material. The Federal Government funds numerous projects in advanced manufacturing that could be relevant to lunar infrastructure. This includes DOE's Advanced Manufacturing Office within the Department's Office of Energy Efficiency and Renewable Energy (OEERE), which funds research and development projects, consortia, and partnerships in advanced manufacturing; work at DOE National Laboratories; NIST's Advanced Manufacturing Technology Consortia program; and advanced manufacturing research funded by NSF. The Federal Highway Administration within the Department of Transportation (DOT) supports research on pavement and concrete that has potential to provide useful knowledge to develop materials for similar uses on the Moon. These projects could provide technologies relevant to lunar applications or support research and development to solve problems related to uniquely lunar challenges.

2. Power Generation, Storage, and Distribution

All activity on the Moon will require generation, storage, and distribution of power. The two possible sources for energy are solar and nuclear, and the agency with the most to

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[2] The USGS has expanded authority to examine "geologic structure, mineral resources, and products of the national domain" outside of the national domain where the Secretary of the Interior determines it to be in the national interest (43 U.S.C. §31(b)).

offer in designing, building, and operating a power source of either type is DOE. DOE's Solar Energy Technologies Office within OEERE supports research and development of photovoltaics and concentrating solar-thermal power that could be of great value at every stage of Moon station development. DOE is also one of only two Federal agencies (along with the Nuclear Regulatory Commission) with the authority to acquire, possess, own, or authorize the use of special nuclear material and related systems (42 U.S.C. §20703).[3] In past space missions, DOE's Office of Nuclear Science has worked with NASA to provide radioisotope thermoelectric generators for satellites, landers, and rovers, and the roles of the two agencies regarding space nuclear systems is specified in a 1991 memorandum (NASA and DOE 1991). In cooperation with DOE, NASA has also explored the possibility of using a nuclear fission reactor to power a human-tended outpost on the Moon (NASA 2004).

In addition to energy generation, DOE also supports research and has expertise in areas of energy storage in the form of batteries and hydrogen fuel cells. DOE expertise in its Office of Fuel Cell Technologies within OEERE will be particularly critical for exploiting lunar water ice for fuel cells, which will have a wide array of applications including powering structures, surface vehicles, and transport to and from the Moon. Fuel derived from lunar water also offers an important power source for spacecraft operating in Earth's vicinity and traveling farther into the solar system.

Additional expertise in advanced energy technologies (solar, nuclear, storage, transmission, etc.) is also present in the Advanced Research Projects Agency-Energy within DOE. DOE is also responsible for ensuring that energy infrastructure on Earth through its Office of Cybersecurity, Energy Security, and Emergency Response is resilient to space weather and other disruptions (16 U.S.C. § 824o-1) and could extend this experience to ensuring the resilience of energy infrastructure on the Moon.

3. Surface Mobility

A core capability for a sustained U.S. presence on the Moon will be the ability to move personnel and cargo around the surface in robotic rovers as well as vehicles with human drivers (on-board or remote).

Research on automated vehicles (i.e., robotic rovers) is supported by or carried out by numerous Federal agencies. In the context of agriculture, the Department of Agriculture's (USDA's) National Institute of Food and Agriculture supports research into sensor development, artificial intelligence and machine learning, and control systems for robotic ground vehicles to carry out precision operations (e.g., herbicide application, pollination), all of which are potentially relevant to robotic activities on the Moon. DOD's investments

[3] DOD can manufacture, produce, or acquire nuclear weapons or utilization facilities as authorized by DOE (42 U.S.C. § 2121b).

in automated vehicles are spread among a large number of programs, most of which focus on developing automated systems that can extend and complement human capabilities. Grand Challenges sponsored by DARPA since 2004 have successfully provided incentive for numerous teams to design and demonstrate autonomous vehicles on increasing difficult test courses. Lastly, NSF's Engineering Directorate and Computer and Information Science and Engineering Directorate have supported research in computer vision and sensing, real-time machine learning, and spectrum allocation for vehicle-to-vehicle and vehicle-to-individual communication. All of these technologies could contribute to operations on the Moon.

4. Communications and Data Transmission

A sustainable lunar surface presence will require reliable communication both on the Moon itself and between the Moon, Gateway, and Earth. In addition, communication will be required between crewed sites, automated stations, and vehicles (crewed, autonomous, and remotely controlled).

The two primary means of communicating on the Moon and between the Moon and Earth are radio and laser. NIST's Communications Technology Laboratory supports theoretical and experimental work in antennas and wireless propagation, microchips that generate and process signals, and communications-related materials science. Among defense agencies, the Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency (DARPA) carry out research and have expertise in advanced technologies intended to improve connectivity and exchange of information over wireless media.

Although recent evaluations indicate that the need for a satellite-based location positioning system to support a U.S. Moon presence cannot justify the cost, position, navigation, and timing (PNT) systems may be needed in the future. Although PNT solutions that are commercially available on Earth might be readily adapted to the Moon, technical expertise can be found in various Federal agencies: DOD continues to research and develop advanced PNT systems, and the Science and Technology Directorate of the Department of Homeland Security and DOT (Office of Secretary – Research and Technology) both have operational experience working with these systems.

5. Habitation and Construction

Experience constructing and maintaining stable habitation and work structures in extreme environments that could be adapted to or carry lessons for the Moon can be found in several branches of the Federal Government. DOD regularly establishes temporary and permanent bases in a wide variety of sizes and environmental conditions, and NSF oversees USAP, which maintains three permanently occupied field stations and numerous seasonal facilities on Antarctica, one of the most isolated and environmentally extreme settings on

Earth. In both cases, the role of the Federal agencies is mainly to oversee contractors responsible for building and maintaining the facilities rather than research and development, but they do require expertise in evaluating whether proposed solutions will meet designated requirements.

As extreme and resource-limited as terrestrial environments can be, the Moon presents another level of isolation and difficulty that may require novel and innovative solutions to solve unprecedented problems. NIST's programs on buildings and construction could provide valuable inroads into novel construction solutions. NIST has already played a role in hazard modelling and prevention on the ISS.

6. Health, Environment, and Life Support

Several Federal agencies have expertise that could be valuable to keeping astronauts safe and healthy on the lunar surface. The National Institutes of Health (NIH) and DOD have extensive experience monitoring and maintaining human health in isolated, extreme environments that could be leveraged through established external advisory groups (Goldin 1999). During the Apollo missions, the Centers for Disease Control and Prevention (CDC) were responsible for monitoring the astronauts' quarantine after they returned from the Moon. The Environmental Protection Agency (EPA) has expertise in monitoring environmental quality in confined spaces such as a lunar habitat. USDA's Agricultural Research Center also researches vertical and microgravity farming that would be relevant to growing food on the Moon.

In addition to health and environment, the absence of an atmosphere on the Moon will make people and infrastructure vulnerable to space weather hazards. The National Oceanic and Atmospheric Administration (NOAA) is likely to play a role in a U.S. lunar presence by issuing space weather warnings.

C. Basic Science

One of the primary objectives of establishing a human-tended station on the Moon's surface is to carry out discovery-oriented scientific research and exploration. A sustained lunar presence will provide an exceptional opportunity to advance fundamental research in numerous fields including Earth science and observation, planetary geology and solar system evolution, astronomy and astrophysics, heliophysics, biology and medicine, and other physical sciences (e.g., material science) (LEAG 2016; NRC 2007a; NRC 2011; LExSWG 1995).

With respect to ensuring that federally managed lunar research facilities (labs, observatories, areas designated for field research and testing) are accessible to all researchers (government, academic, and private), the network of National and other Federal Labs (including the ISS) can provide a useful example for how to conduct and

manage research in outer space. Individual National Labs and other Federal science facilities are each associated with a designated agency (e.g., DOE, NASA, NSF, NIH), but most are operated or managed by a separate non-profit entity, often a university consortium or a federally funded research and development center, which provide administrative mechanisms to give academic and private sector researchers access to their often unique facilities. For large projects, researchers typically have to submit proposals for peer review to use equipment (for small requests, there is typically an expedited internal approval process) and are usually required to make any data generated using a Federal research asset publicly available. At some facilities, private sector users can choose to keep their research proprietary, but to do so, they are charged for personnel time and use of equipment.

1. Lunar and Planetary Geoscience

Surveying and geology are fundamental to lunar research (NASA 1988). The USGS mapped the landing zones during the Apollo missions and has subsequently been the lead agency in generating high-resolution maps of planetary bodies (Skinner 2009). It will likely be involved in surveying the Moon's surface to support establishment and expansion of a U.S. lunar presence, and currently participates on the Lunar Reconnaissance Orbiter Team. The USGS will also likely have a role in geological research to determine the distribution and genesis of rock types at and under the surface of the Moon. In addition to providing fundamental scientific insight, high-resolution maps of topography and geology will be critical for future efforts to explore for commercial mineral deposits on the Moon (David 2018).

NSF also supports investigator-based research in solar system evolution and planetary geology, but does not have a dedicated division or directorate in these areas. The most relevant office within NSF is the Petrology and Geochemistry Program in the Geoscience Directorate, which supports basic research on the accretion and early differentiation of the Earth, including the formation and evolution of the Moon.

2. Earth Observation

In addition to providing insights into Earth's evolution as a planetary body in the solar system, a lunar field station will provide a valuable vantage point for Earth observation. The primary civilian agencies involved with Earth sensing are NOAA, which operates a fleet of satellites that support its mission as the primary weather and climate agency in the United States, and USGS, which provides the digital access portal for data from the Landsat program.[4] Both agencies cooperate closely with NASA in their satellite operations. The

[4] DOD and the intelligence community also have large equities in joint sensing. Although USGS analyzes and distributes Landsat data, NASA and DOD have statutory responsibility for the Landsat program (51 U.S.C. § 6011).

balance of agency needs for sustained observations is managed by the U.S. Group on Earth Observations (USGEO) Satellite Needs Working Group, which has representation from 12 Federal agencies, most of which do not, however, operate their own space-borne Earth observation instruments.

3. Astronomy and Astrophysics

The Moon, particularly its far side, will provide a unique, stable platform sheltered from electromagnetic noise from the Earth for observing the universe beyond the solar system. A number of agencies and government entities in addition to NASA fund research in astronomy and astrophysics, including NSF, DOE, and the Smithsonian Institution. The Astronomy and Astrophysics Advisory Committee (AAAC) advises NSF, NASA, and DOE on astronomy and astrophysics of mutual interest and concern (AAAC 2019). In addition to funding research grants in astronomy, NSF also operates a number of observatories on Earth under its Astronomical Sciences Program. Similar NSF-funded facilities could be established on the Moon. (Note that many astronomical observatories on Earth, like the W.M. Keck Observatory on Mauna Kea in Hawaii, are operated by non-profit foundations partially or entirely funded by private monies; such private scientific infrastructure could also be deployed on the Moon.)

4. Heliophysics

In addition to looking at the Earth, the Moon will also serve as a platform to study the effects of the Sun on the solar system. A number of agencies currently fund heliophysical and space weather research in addition to NASA including NSF, DOD, USGS, and NOAA. DOE also funds some research as part of its mission to protect electrical infrastructure in the U.S. from the effects of space weather (16 U.S.C. § 824o-1) and served as lead in an interagency and international consortium to design and deploy the Alpha Magnetic Spectrometer now operating on the ISS.

5. Other Physical Science

In addition to serving as a platform for observing the Earth and the distant universe, the Moon provides a natural laboratory for conducting experiments in a low-gravity, no-atmosphere environment. The Moon is expected to have a substantial role in research intended to develop and test materials and equipment designed to explore other planetary bodies, including Mars, and improve the quality of life on Earth. Such advances will require basic physical research focused on testing novel engineering solutions, developing novel fabrication processes, and creating advanced materials. While NASA will support research that is critical to operating on other planets, other agencies like NSF, NIST, and DOE fund experiments designed to understand materials and physical processes in space and would likely support similar research on the Moon.

6. Life Science

The Moon provides a unique environment to explore many aspects of the life sciences including growing food under non-terrestrial conditions and developing advanced pharmaceuticals. In the arena of biological and health research, NIH funds research on the ISS focused on the effects of deep space radiation and microgravity on human health as well as developing long-lasting drugs for deep space travel (NASA and NIH 2016). Other agencies that could contribute to bioscience research on the Moon based on their current research portfolios and areas of interest include NSF, DOE (life in harsh environments, biomanufacturing), the Food and Drug Administration (FDA; tissue-engineered products), and USDA (closed-system food production).

D. International Relations

The international framework governing activities in space (including the Moon) is defined by the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (i.e., the Outer Space Treaty), which went into force in 1967 and to which the United States is a party. (The subsequent Agreement Governing the Activities of States on the Moon and Other Celestial Bodies of 1979 [i.e., the Moon Treaty] attempted to establish a stronger degree of international oversight, but neither the United States nor any nation engaged in self-launched human spaceflight has ratified this treaty.)

Interpreting treaty provisions and dealing with international organizations as well as bilateral partners is the responsibility of the Department of State (Office of Space and Advanced Technology), which represents the United States in international fora, fosters domestic and international environments conducive for U.S. companies conducting space activities, and pursues bilateral and multilateral engagements to enable space science and exploration, resilient space services, and burden sharing. The Department of State leads the U.S. delegation at meetings of the United Nations Committee on the Peaceful Uses of Outer Space.

E. Regulation and Oversight

The Outer Space Treaty makes States responsible for national space activities whether carried out by governmental or non-governmental entities. As such, Federal regulations that apply to many activities on Earth would apply to the same activities in any U.S. facility on the surface or in orbit around the Moon. In most cases, this would not require any special engagement with space or Moon policy by an agency. For example, appropriate Occupational Safety and Health Administration (OSHA) rules on workplace safety would be applicable on a public or private U.S. lunar facility, and the Internal Revenue Service (IRS) would still collect Federal income tax from individuals and corporate entities that earned income from activities on the Moon. Other agencies with Federal authority that

would apply to U.S. lunar facilities and personnel but would not require new authority or substantive engagement with space or Moon policy include the Animal and Plant Health Inspection Service (USDA), Bureau of Industry and Security (Department of Commerce [DOC]), International Trade Administration (DOC), Food and Drug Administration (Department of Health and Human Services [HHS]), National Park Service (Department of Interior [DOI]), Mine Safety and Health Administration (Department of Labor [DOL]), Patent and Trademark Office (DOC), Environmental Protection Agency, and Postal Service. This list should not be considered comprehensive, and the involvement of any Federal agency within the current scope of its mission is dependent on whether and when activities falling under its mandate begin on the Moon.

Other agencies have mandates specifically concerning activities in space that would presumably extend to the same activities on the Moon. For example, DOT's Office of Commercial Space Transportation within the Federal Aviation Administration (FAA) has authority to license the launch and re-entry of spacecraft from Earth and has some oversight regarding payloads (51 U.S.C. § 50904),[5] and the Federal Communications Commission (FCC) licenses communications between Earth and satellites and among space objects, including reserving bandwidth for government use (47 U.S.C. § 151). NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) licenses the operation of private remote sensing space systems, which could be deployed in near-Moon space or on the Moon's surface.

As the U.S. lunar presence eventually grows to include commercial activities, new authorities or entities may need to be established in order to regulate private sector activity. The Space Resource Exploration and Utilization Act of 2015 (the Space Act) gives U.S. firms and citizens the rights to own and sell natural resources mined from bodies in space, including the Moon. Although the Outer Space Treaty forbids national appropriation or claims of sovereignty over celestial bodies, it was the sense of Congress that the Space Act does not assert such claims. Although the Space Act creates the right to develop natural resources, it does not provide a mechanism to register claims for their commercial extraction. One model for assigning resource rights in publicly held territory that could be applied by either a U.S. or international agency on the Moon is the auction mechanism overseen by the Bureau of Ocean Energy Management (BOEM) to lease blocks of the U.S. continental shelf for oil and gas exploration and development.

DOC's National Telecommunications and Information Administration (NTIA) manages the Federal Government's use of the electromagnetic spectrum. It has authority to assign frequencies to radio stations and coordinate the activities of government agencies for telecommunications, and it is responsible for ensuring that both commercial wireless

[5] In fact, DOT has already granted mission authorization to Moon Express, a private entity, to launch a payload intended for the Moon (FAA 2016).

operators and Federal agencies have access to sufficient spectrum. Any need for spectrum in lunar operations beyond those already in force will likely require designation by the NTIA.

Long-term presence of humans on the Moon may require law enforcement, which could follow the model of the USAP, where the base manager is deputized into the U.S. Marshals Service. DOD could conceivably play a role in ensuring the physical security of an established Moon base and access to space between the Earth and Moon. Lastly, U.S. intelligence agencies could provide useful guidance in ensuring that communications are secure (NASA 2004).

F. Commercial Development

It is a stated priority of the United States' space exploration program that private partners will come with the government to space and should carry on as direct government participation diminishes (EOP 2017; NASA 2018). The United States has endeavored to increase the rate of space commercialization through efforts such as procuring commercial launch for government activities (e.g., delivery of cargo and crew to the ISS), increasing the number of commercial activities on the station itself, and funding entrepreneurial experiments such as small satellites and Moon landers.

DOC's Office of Space Commerce was specifically created to foster the conditions for the economic growth and technological advancement of the U.S. commercial space industry, including lunar activity. Examples of prospective private sector commercial activity on the Moon include mining and mineral resource extraction, provision of services to non-Federal entities (e.g., transportation of people and cargo), establishment of private laboratory development facilities, manufacturing, tourism, souvenir sales, and personal services (e.g., burials on the Moon). Government activities fostering commercial development on the Moon could include public-private partnerships, investment or loan guarantees for new enterprises, tax incentives to encourage lunar economic development, providing utilities and managing necessary infrastructure, and issuing leasing rights for commercial exploration or development. Increasingly, Federal agencies are requiring that private sector partners invest their own capital into the systems they design, while allowing them to retain the rights to profit from the technology that results from the partnership in other applications. (NASA has already begun moving in this direction with its contracts in the Artemis program.)

A primary component of commercial development is access to capital and funding opportunities. Many space companies developing new technologies are small businesses, giving them access to the Federal Government's Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs. NASA funds a number of SBIR contracts, but other agencies, including DOD, DOE (through various internal offices including the Loan Programs Office), NIST, NOAA, and NSF, can also

fund SBIR and STTR contracts applicable to the Moon. The U.S. Government can also provide loan guarantees to companies investing in or planning to innovate on the Moon through the Small Business Administration's 7(a) standard business loan guarantees and 504 loans to acquire fixed assets.

Another powerful tool available to the Federal Government to incentivize growth in the lunar economy is tax policy. Although Congress alone has the power to set tax rates and define exemptions, the IRS would be responsible for publicizing and collecting any Moon-focused taxes.

4. Interagency Coordination of a U.S. Lunar Presence

Based on STPI's review of Federal agencies' authorities, missions, and previous involvements in space, multiple Federal agencies have the potential to contribute to or benefit from a sustained U.S. presence on the Moon, although the likely degree, nature, and timing of involvement of various agencies will be very different. In addition, no single existing agency has the full range of authorities or expertise spanning science, exploration, commercial development, and regulatory enforcement that a lunar field station supporting both research and private sector activity will require. However, STPI identified no gaps or conflicts among agencies regarding current U.S. plans for the Moon that would require an interagency process to resolve beyond existing mechanisms managing broader U.S. space policy. Although there may be a need for interagency coordination in defining a common strategy for U.S. activities on the Moon at some point, current interagency processes are likely sufficient to manage U.S. lunar policy for the immediate future.

As a potential model for a lunar field station, STPI was asked to examine the U.S. Antarctic Program, including how interagency equities are managed. Presidential Memorandum 6646 for U.S. Antarctic Policy and Programs assigned NSF the responsibility to manage the entire U.S. Antarctic Program. In order to ensure that other agencies could also carry out science on Antarctica, the memo established an interagency Antarctic Policy Group, which was authorized to make scientific recommendations for activities to be coordinated within the framework of NSF operational support. Importantly, the memo also specified that the Office of Management and Budget would provide specific budgetary guidance for USAP in order to ensure that it not be funded at the expense of other NSF programs.

One important difference between Antarctica and the Moon is that resource extraction and military activities are forbidden by the Antarctic Treaty that went into force in 1961. This effectively limits activity on Antarctica to scientific research and exploration, which relieves NSF from regulatory or commercial responsibilities. Although the Outer Space Treaty forbids military activity on the Moon, it does not restrict commercial development.

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Appendix B. Abbreviations

AAAC	Astronomy and Astrophysics Advisory Committee
BOEM	Bureau of Ocean Energy Management
CDC	Centers for Disease Control and Prevention
DARPA	Defense Advanced Research Projects Agency
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of Interior
DOL	Department of Labor
DOT	Department of Transportation
EDA	Economic Development Administration
EOP	Executive Office of the President
EPA	Environmental Protection Agency
EVA	Extra-vehicular Activity
FCC	Federal Communications Commission
FDA	Food and Drug Administration
HHS	Department of Health and Human Services
IDA	Institute for Defense Analyses
IODP	International Ocean Discovery Program
IRS	Internal Revenue Service
ISRU	in situ resource utilization
ISS	International Space Station
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data, and Information Service
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NSpC	National Space Council
NTIA	National Telecommunications and Information Administration
OEERE	Office of Energy Efficiency and Renewable Energy
ONR	Office of Naval Research
OSHA	Occupational Safety and Health Administration
OSTP	Office of Science and Technology Policy
PNT	position, navigation, and timing
SBIR	Small Business Innovation Research
SPD-1	Space Policy Directive 1
STPI	Science and Technology Policy Institute

STTR	Small Business Technology Transfer
USACE	United States Army Corps of Engineers
USAP	U.S. Antarctic Program
USDA	Department of Agriculture
USGEO	U.S. Group on Earth Observations
USGS	United States Geological Survey

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The White House Office of Science and Technology Policy (OSTP) asked the IDA Science and Technology Policy Institute (STPI) to research the role of Federal agencies other than NASA in creating a sustainable U.S. presence on the Moon by: 1) identifying which Federal agencies could be involved, 2) describing what the roles of those agencies might be, and 3) determining if there will be a need for interagency coordination. STPI's analysis focused on a field station at the lunar South Pole and the role of the U.S. Government in promoting private sector commercial activity as well as science and exploration. We identified civil agencies other than NASA that have expertise, resources, or authority that could contribute to or benefit from U.S. plans for Moon development. In addition, OSTP asked STPI to look into the U.S. Antarctic Program for lessons in establishing and operating a lunar field station, including balancing interagency interests and equities. STPI found that numerous Federal agencies spanning a diverse array of scientific, exploration, commercial, military, and intelligence equities have the potential to contribute to or benefit from a sustained U.S. presence on the Moon. No single existing agency has the full range of authorities or expertise spanning science, exploration, commercial development, and regulatory enforcement that a lunar field station supporting both research and private sector activity will require. There may be a need for interagency coordination in establishing a common strategy for U.S. activities on the Moon at some point, but current interagency processes are likely sufficient to manage U.S. lunar policy for the immediate future.

15. SUBJECT TERMS

interagency; Moon base; U.S. lunar presence

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