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Back to Stay: NASA's Campaign to Sustainably Return Humans to the Moon

Tara Ruttley[a1*], Neysa Call[ab2], Patrick Besha[c3], Sam Scimemi[d4], Rhianna Clemons[a5], Skyler Hornback[a6], Daniel Kennedy[a7], Clara Jones[a8], James Green[a9]

[a] *Office Of The Chief Scientist, National Aeronautics and Space Administration, Headquarters, 300 E St SW, Washington, D.C., United States, 20546, [1]tara.m.ruttley@nasa.gov [2]neysa.m.call@nasa.gov [5]rclemons@bellarmine.edu [6]skyler.hornback@uky.edu [7]djke234@uky.edu [8]claraeg@uci.edu [9]james.green@nasa.gov*
[b] *Directorate for Geosciences, National Science Foundation, 2415 Eisenhower Ave, Alexandria, VA 22314*
[c] *Office Of The Administrator, National Aeronautics and Space Administration, Headquarters, 300 E St SW, Washington, D.C., United States, 20546, [3]patrick.besha@nasa.gov*
[d] *Human Exploration and Operations Mission Directorate, National Aeronautics and Space Administration, Headquarters, 300 E St SW, Washington, D.C., United States, 20546, [4]sam.scimemi@nasa.gov*
* Corresponding Author

Abstract

The Artemis program has catalyzed NASA to develop principles of sustainability as the agency and its partners contemplate returning humans to the Moon, and then to Mars, for long-term exploration. The Office of Chief Scientist collaborates with directorates within NASA, as well as with other government agencies and stakeholders, to represent the scientific endeavors in the agency, including developing a working definition of sustainability. The stays on the lunar surface under the Artemis program will be longer that those via the Apollo missions. Studying the requirements, challenges, and lessons learned from decades of human spaceflight and from analog sites in hostile environments on Earth will inform a framework for human sustainability requirements. This paper will provide an overview of the core sustainability goals as identified by NASA's Office of the Chief Scientist and describe several activities underway to support a broad-based lunar program with a long-term view of success and achievement.
Keywords: analog, Artemis, heritage, Mars, Moon, sustainability

1. Introduction

The development of the Artemis program is actively underway to enable humans to live sustainably on the surface of the Moon. While on the lunar surface, humans will explore new landscapes, perform high value science activities, and prepare operationally to visit Mars. The program consists of a series of shorter visits around and to the lunar surface, beginning with robotic missions. Longer, sustainable missions to the surface are expected to begin in 2028. These longer stays on the Moon will exceed durations of the lunar exploration activities under the Apollo program roughly fifty years ago and has prompted the National Aeronautics and Space Administration (NASA) to define lunar sustainability goals. NASA's Office of the Chief Scientist has identified four main sustainability goals that capture efforts necessary for sustainability, which is defined here as the implementation a broad-based lunar program with a long-term view of success and achievement.

2. Goal 1: Sustaining a Human Presence

The Moon's South Pole region (defined as the area within 6° of latitude from the lunar south pole) has been selected as the location for the third Artemis mission landing site and subsequent human exploration missions. Operationally, this location provides two main benefits [1]. First, many areas of the lunar surface are illuminated by very low Sun angles throughout most of the year, providing favorable temperatures for astronauts and critical infrastructure, reduced duration of lunar nights, and plentiful access to solar power. Second, the same topography at the South Pole that produces areas of consistent sunlight also effectively blocks much of the sunlight at very low Sun angles in other areas, keeping them in near-constant darkness. These regions are called permanently shadowed regions (PSRs). The freezing temperatures in these PSRs create cold traps for volatiles, such as hydrogen and oxygen. These elements could be used as natural resources for sustaining human life and operational activities. Sustaining a long-term presence on the Moon requires the development of infrastructure that contributes to both a long-term human lunar presence and risk reduction for human Mars exploration. This infrastructure will span many core functions.

2.1 Access to and from the Moon

For the early Artemis missions, NASA's Space Launch System rocket will launch four astronauts aboard the Orion spacecraft for a multi-day journey to lunar orbit. There, two crew members will transfer to the Human Landing System (HLS) for the final descent to the surface of the Moon. After approximately a week of surface exploration, the astronauts will reboard the lander for their trip back to orbit, followed by a return to Orion before heading back to Earth. On later Artemis missions with longer crew stays on the lunar surface, the astronauts will first arrive at the orbiting Gateway aboard Orion before descending to the lunar surface. The Gateway, an orbiting outpost, will provide living and science facilities for crew on their way to and from the lunar surface [1].

2.2 Habitability and Mobility

For longer stays at the lunar South Pole, NASA and its partners will develop an Artemis Base Camp to support one- to two-month expeditions on the lunar surface. Planned Artemis Base Camp components include a habitable mobility platform (pressurized rover, or PR), a Lunar Terrain Vehicle (LTV, or unpressurized rover), a habitation module, power systems, and in-situ resource utilization systems that will support science and exploration activities.

The unpressurized LTV will carry the crew for short distances for exploration and science activities. To meet the sustainability requirements of the Artemis program, the LTV will be designed to have a 10-year, rechargeable service life. Remotely operated from HLS, Gateway, and Earth, the LTV could be used crewed or uncrewed. The LTV will interface with science instruments and payloads and will also be able to survive lunar eclipse periods.

For longer science and exploration activities further from the astronaut's habitat, the crew will have access to the Pressurized Rover (PR). This rover will have a spacesuit port for quick and multiple extravehicular activities (EVAs) as well as capabilities to provide radiation protection, nutrition, hydration, waste management options, exercise, and treatment of injuries.

The surface habitat, a primary asset for a sustained lunar presence, will host two to four crewmembers. Its capabilities will include medical, exercise, science, and living spaces as well as an EVA airlock. NASA is working with industry and international partners to develop the first habitat to be placed on the lunar surface and its associated systems for deep space transport. The surface habitat and PR will provide a platform to achieve lunar sustainability for human exploration and science, test systems for future Mars mission applications, and enable commercial and international opportunities.

During exploration activities, Artemis astronauts will be confined to a range dictated by their spacesuit capabilities. Activities on the Moon's surface will require spacesuits that have improved mobility, can tolerate the lunar environment, and can be serviced on the Moon. The Apollo and International Space Station (ISS) EVAs have given NASA over fifty years of experience in lessons learned on suit design and use, both on the lunar surface and in Low Earth Orbit (LEO).

The next generation space suit, called the ExEMU Suit, is being designed specifically for sustained use on the lunar surface for maximal mobility, with a full range of sizes for a diverse astronaut corps. Of critical importance is the suit's capability to handle the unique environment of the Moon. There, environmental conditions include challenges not experienced in LEO such as dust, thermal, radiation, lighting, and plasma. The ExEMU will also fit a larger, more diverse population of men and women, support multiple missions, minimize injury, allow crew to work on the Moon flexibly like a geologist would on Earth, and require less servicing and maintenance time. The ExEMU suit is expected to be tested in 2023 on the ISS as a technology demonstration EVA.

2.3 Maintaining Human Health

NASA's Human Research Program (HRP) has identified five significant hazards of human spaceflight that must be mitigated to enable sustained human presence in spaceflight [2]:

- Space radiation: Increased radiation exposure raises cancer risk, damages the central nervous system, and can alter cognitive function, reduce motor function and drive behavioral changes.
- Isolation and confinement: long stays in a confined space vehicle increases risks in areas such as behavior, sleep, and team dynamics.
- Long distances from Earth: Communication delays and no means for a quick return to Earth

drive the need for more autonomous medical capabilities.

- Changes in gravity: Varying gravitational environments such as LEO, the Moon, and Mars, contribute to potential balance disorders, fluid shifts, cardiovascular deconditioning, muscle atrophy and bone loss.
- Hostile and closed environments: The vehicle environment is a critical component to keeping astronauts happy and healthy. Important habitability factors include temperature, pressure, lighting, noise, and quantity of space.

Humans experience these deep space hazards on route to the Moon and during their stay on the lunar surface. The HRP has linked these hazards with more than 30 human health risks [3]. Of these risks, the highest priorities are space radiation and cancer, cognitive health, cardiovascular disease, Spaceflight-Associated Neuro-ocular Syndrome (SANS), adverse behavioral health and performance, and inadequate nutrition and food [3].

The HRP's current research strategy, portfolio, and evidence base--described in the HRP Integrated Research Plan (IRP)--are available online in the Human Research Roadmap, a managed tool used to convey these plans (https://humanresearchroadmap.nasa.gov/). Mitigating risks from these hazards relies on lessons learned from decades of space experience, including the last twenty years of ISS operations; Earth-based simulated lunar habitats and operations analogs; and LEO analogs and technology demonstrations for transit to Mars and crew performance after landing.

Though robots will pave the way in Artemis for smarter, safer human exploration, sending humans to the Moon is paramount for exploration and implementation of critical science objectives. The innate attributes of human intuition, adaptability, and judgement enable explorers to naturally make rapid decisions as they perceive new information in ways that robots cannot. Activities such as optimizing scientific instrument placement for ground truthing; instrument deployment, repair, and replacement; and progressive iterations of science experiments are just some examples of the human advantage.

3. Goal 2: Sustaining a Science Program

The revolutionary scientific insights gained from the Apollo expeditions came from extensive investigations in field geology, experimental packages on the Moon's surface, and the samples brought to Earth for analysis. These insights have, in turn, driven many new scientific questions over the last few decades. Soon, the Artemis missions will give scientists a chance to answer those questions.

Of particular interest are questions regarding trapped volatiles in the lunar soil. What can they tell us about the origin of the Earth-Moon system? Analysis of Apollo samples has taught us that the Moon had an early strong magnetosphere [4]. Modeling of the relationship between this magnetosphere and the Moon's close proximity to the early Earth shows that as the early Earth's atmosphere evaporated, volatiles likely traveled along its Moon-coupled magnetic field lines where they could be stored in the lunar surface soil. Analyzing those volatiles can give scientists insights into early Earth activities and help answer questions about the development of our solar system.

A separate analysis of the "late heavy bombardment" period of the Moon shows that the strong magnetosphere would have provided the right protection for transporting volatiles from both the Earth and Moon across the lunar surface for deposition in the lunar regolith, including in the cold traps of the PSRs at the lunar poles. Later, with the loss of the magnetosphere and the small lunar atmosphere that likely existed at that time, only those volatiles trapped at the cold PSRs would have been spared from leaching out of the soil. Therefore, these polar regions are of interest scientifically [4].

Remote sensing data has also revealed that the Moon's polar PSRs hold significant amounts of frozen water (H_2O) and hydroxyl (OH), in addition to many other important volatiles capable of supporting sustained human exploration activities. Accessing these natural lunar resources would lessen payload needs from Earth to support life and exploration activities. For example, water ice at the poles would provide a critical way for humans to potentially access water and make rocket fuel on the Moon [4].

Robotic precursor missions will precede human landings under the Artemis program. They will provide important information about the lunar surface, driving operational designs for a sustained human exploration program. For example, the Volatiles Investigating Polar Exploration Rover (VIPER), a commercial investigation currently planned for lunar arrival in 2023, will perform critical surveys of a south pole area, locating and analyzing volatile deposits. VIPER will also determine the concentration and physical state of the deposits, and look for any other potentially useful resources, paving the way for sustained human presence [4].

Beyond the questions of volatiles and history of the Earth-Moon system, the Artemis program seeks to answer scientific questions about our fundamental planetary processes through a strong, sustainable scientific program. NASA's Artemis science priorities will [1]:

- "Achieve the decadal survey objectives across the disciplines that can be addressed at the Moon or near the Moon
- Perform all research to the standards of NASA Science, including competitive selections, open data policies, etc.
- Enable competitive research through the Mission of Opportunities or otherwise on or around the Moon."

These Artemis Science Goals were developed based on the U.S. and international science communities' priorities. These include recommendations in the 2007 National Research Council (NRC) Report on the Scientific Context for the Exploration of the Moon [5], the 2013-2023 Planetary Decadal survey [6], the Lunar Exploration Roadmap maintained by the NASA Lunar Exploration Analysis Group [7], the LEAG Next Steps on the Moon Report [8], and the 2018 LEAG Advancing Science of the Moon Report [9]. The Artemis Science Goals are multi-disciplinary investigations that can be enabled by the lunar environment and include:

- Understanding Planetary Processes
- Understanding the Character and Origin of Lunar Volatiles
- Interpreting the Impact History of the Earth-Moon system
- Revealing the Record of the Ancient Sun and Our Astronomical Environment
- Observing the Universe and the Local Space Environment from a Unique Location
- Conducting Experimental Science in the Lunar Environment
- Investigating and Mitigating Exploration Risks

To achieve these goals, NASA has identified an implementation strategy based both on collaborative opportunities with international partners and a public-private partnership of commercial entities to deliver investigations to the lunar surface through the Commercial Lunar Service Provider (CLPS) program. The CLPS program will provide a series of robotic precursors to provide data about the lunar environment and will also enable some biological and physical science investigations, paving the way for human explorations. Human exploration capabilities will include field geology experience, sample collection and return, and instrumentation for data collection on the surface. Access to cold regions and the lunar far side are also important components of the implementation strategy [1].

In 2020, a team of experts internal and external to NASA developed an Artemis III Science Definition Team Report [5] to prioritize science activities based on the seven overarching science objectives from the Artemis Plan. Artemis III is expected to be the first mission planned for human activities on the lunar surface. The team based its recommendations on compelling science and what could feasibly be accomplished during the first lunar surface mission. Study recommendations included field surveys, deployable experiments, surface sampling, and sample return. The team also provided factors for consideration in the future selection process of candidate landing sites. Such factors include [5]:

- Sufficient illumination to solar power long-term surface experiments
- Access to a variety of crater sizes for sampling
- Sampling opportunities of the landing site for optimal understanding of the local geology
- Access to sampling of large crater ejecta
- Accessibility to the PSRs to sample volatiles
- Access to multiple geologic units to test differing time-stratigraphic age
- Proximity to areas that enable the recommended high-priority investigations

Such high-priority investigations will help scientists better understand fundamental planetary processes that occur within and external to our own solar system and will also help NASA understand the risks and potential resources of the Moon's South Pole. While the Artemis III mission is only one single human mission to the lunar surface, it will be a firm foundation for future discovery and pave the way for subsequent crewed Artemis missions to iterate on the data collected with each human mission thereafter. As a result, new hypotheses and research goals will arise and evolve in community science priorities.

4. Goal 3: Sustaining the Lunar Environment

The ability to safeguard the Moon's natural environment and landscape, including the preservation of Moon heritage sites must be considered when designing a sustainable program of lunar exploration. To maintain a sustainable lunar program, participants must be intentional about how to manage the materials generated from long-term stays on the lunar surface. In the past, NASA and other international space agencies have left materials ranging from rovers and spacecraft to tools and food packaging [10]. In fact, nearly sixty anthropogenic impacts of spacecraft lie across the surface of the Moon in addition to another 21 soft-landed anthropogenic structures [11].

In 2018, the White House Office of Science and Technology Policy (OSTP) released a report on the protection and preservation of Apollo lunar heritage sites [12]. The report recognizes that "the increasing technical capabilities of other countries and of commercial entities throughout the world potentially increases the number of lunar missions in the near future" and that associated activities "can generate a significant amount of damage" to heritage sites [12]. The report also recommended leveraging the then relevant or active Space Policy Directive-1 (SPD-1) that charged NASA to develop "an innovative and sustainable program" to return humans to the Moon, to engage all participants in a way that collectively enables opportunities to preserve and protect lunar artifacts and heritage sites [13].

In absence of a government-driven, multilateral approach to protect lunar heritage sites, NASA's Lunar Historic Site (LHS) team has developed technical guidelines [14] that do provide recommendations for lunar vehicle design and mission planning teams to consider helping preserve and protect lunar historic artifacts and potential science opportunities for future missions. The LHS team found that "carefully approaching these sites is potentially beneficial and can yield new science, capture new visions of historic events, and support the emerging commercial spaceflight communities" [14].

Plans are underway to define the science and exploration activities for the lunar surface that will undoubtedly alter the overall lunar landscape [15]. The question arises: how can we minimize impacts to environmental and heritage sites in order to preserve them for future scientific analysis?

The International Space University (ISU) prepared several goals and recommendations for a sustainable lunar exploration program, considering both environmental protection and protection of lunar heritage sites [16]. ISU's environmental protection goals include preventing contamination of the lunar surface and of astronauts through improved commitments on existing Committee On Space Research (COSPAR) processes and preserving the Moon's natural environment through actions that lunar actors such as limiting light and dust pollution, limiting the use of destructive technologies, and encouraging stronger planetary protection policies addressing the safeguard of the Moon's natural landscape [16]. ISU also recommends that preservation of the lunar environment include heritage sites, which are areas of cultural, scientific, and natural significance [16]. For the United States, heritage sites have been identified as areas with historical and societal significance, such as the Tranquility Base (Apollo 11) and Apollo 17 [12]. Scientific sites are identified as areas that are mostly natural or with unique characteristics, such as the shielded zone of the Moon. These may include non-natural areas such as the Apollo sites. Natural sites are identified as areas containing all-natural features of the lunar surface, such as polar ice and splosh craters [16].

The Artemis Accords, grounded in the Outer Space Treaty of 1967, establish a practical set of principles to guide space exploration of the Moon, Mars, and other astronomical objects [17]. The Accords include commitments to preserve outer space heritage (such as historically significant human or robotic landing sites, artifacts, and spacecraft), reinforce that space resource extraction and utilization can and will be conducted pursuant to the obligations contained in the Outer Space Treaty, and commit signatories to plan for the mitigation of orbital debris, including the safe, timely, and efficient passivation and disposal of spacecraft at the end of their missions. The path to implementation of these principles should flow from the Artemis Accords into the requirements documents as teams begin to design and build components of the program in its early phases. Artemis partners should consider the development of lunar environmental protection policies at the highest level.

While NASA technical guidelines surround the protection of lunar heritage sites, the question remains: are there guidelines the international community should follow surrounding protection of the lunar environment? An important precedent from which we can begin discussions of such guidelines can be found in the Protocol on Environmental Protecting to the Antarctic Treaty [18], in which the international parties committed to the comprehensive protection of the Antarctic environment and dependent and associated ecosystems and designated Antarctica as a natural reserve, devoted to peace and science. The protocol encompasses the following principles:

- Protect the Antarctic Treaty Area as a fundamental consideration.
- Limit adverse impacts on the Antarctic environment and dependent and associated ecosystems.
- Avoid adverse effects on climate or weather patterns; air or water quality; the atmospheric, terrestrial, glacial, or marine environments; and degradation of or substantial risk to areas of biological, scientific, historic, aesthetic or wilderness significance.
- Allow prior assessments of, and informed judgments about, the possible impacts on the Antarctic environment and dependent and associated ecosystems.

The Protocol on Environmental Protection of the Antarctic Treaty designates Antarctica as a natural reserve, “dedicated to peace and science” and requires that all proposed activities be subject to an assessment of environmental impacts. The protocol further establishes a Committee for Environmental Protection, which has developed workplans for managing activities that could pose environmental consequences, such as impacts of tourism and climate change.

In 2020, NASA released the agency’s most recent planetary protection policy for lunar environment protection in the interim directive entitled “Planetary Protection Categorization for Robotic Crewed Missions to Earth’s Moon” [19]. This directive defines NASA’s implementation of obligations to avoid harmful contamination, specifically the control of terrestrial biological contamination. Compliance is managed by NASA’s Office of Planetary Protection. However, “this directive does not apply to other countries or private sector firms, if their missions do not involve NASA” [19].

Whatever policies or guidelines are to be considered for sustaining the lunar environment, the notion of reusability is always a major element of NASA’s approach to sustainability. Designing program elements for reusability not only enhances affordability within existing budgets, it also intentionally reduces unintentional excessive amounts of material we produce on the Moon’s surface.

5. Goal 4: Sustaining Partnerships

Developing and maintaining Artemis partnerships, both commercially and internationally, is imperative to enabling the sustainable return of humans to the Moon.

5.1 Commercial Partnerships

NASA’s Commercial Lunar Payload Services (CLPS) program enables NASA to be as efficient as possible in procuring a series of Artemis robotic precursor missions through public-private partnerships. As part of this program, NASA has selected fourteen public companies as CLPS vendors, soliciting bids for six awarded contracts to deliver 29 science and technology payloads beginning with three landers in 2022, followed by three in 2023.

The NextSTEP program, a public-private partnership model, solicits commercial development of deep space exploration capabilities to support more extensive human spaceflight missions. At the core of the NextSTEP partnership model is opportunity for NASA and industry to partner to develop capabilities that not only meet NASA human space exploration objectives, but also advance industry commercialization plans. For example, earlier this year through the NextSTEP program, SpaceX was awarded a contract for the development of the first commercial human lander to safely carry the next two American astronauts to the lunar surface [20].

5.2 International Partnerships

We have learned from the ISS program the value of international partnerships through twenty years of experience in the ISS’s intergovernmental agreements. We have successfully collaborated across time zones, culture, politics, and differing mission objectives. There is power in partnerships, and the U.S. or NASA will not be going back to the moon alone.

With numerous countries and private sector players conducting missions and operations in cislunar space, the Artemis Accords were developed to establish a common set of principles to govern the civil exploration and use of outer space [17]. The Artemis Accords describe a shared vision for principles, grounded in the Outer Space Treaty of 1967, to create a safe and transparent environment that facilitates science, exploration, and commercial activities on the Moon. The main tenants of the Artemis Accords are as follows:

- Peaceful Purposes: The Artemis program strengthens space exploration while also enhancing peaceful relationships between nations.
- Transparency: Artemis partner nations will be required to publicly share their policies and plans in a transparent manner.
- Interoperability: Artemis partners will use open international standards, develop new standards when necessary, and strive to support interoperability to the greatest extent practical.
- Emergency Assistance: The Artemis Accords reaffirm NASA's and partner nations' commitments to the Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched into Outer Space.
- Registration of Space Objects: Artemis partners commit to register any vehicle visiting the Moon to help maintain a coordinated, safe, and sustainable environment.
- Release of Scientific Data: Artemis partners plan to release their scientific data publicly to ensure that the entire world can benefit from Artemis discoveries.
- Protecting Heritage: Artemis partners will commit to the protection of sites and artifacts with historic value.
- Space Resources: Artemis partners will ensure that space resource extraction and utilization can and will be conducted in a manner compliant with the Outer Space Treaty, with specific emphasis on Articles II, VI, and XI.
- Deconfliction of Activities: Artemis partners will provide public information regarding the location and general nature of operations on the Moon to ensure safety zones and the principle of due regard.
- Orbital Debris and Spacecraft Disposal: Artemis partners will plan for the mitigation of orbital debris, including the safe disposal of spacecraft upon their completed missions.

6. Lessons Learned on Sustainability

NASA relies on decades of experience in the spaceflight environment and with Earth-based analogs in extreme environments to guide in the development of a sustainable presence on the Moon.

6.1 The ISS

One of the major goals of the ISS is to prepare humans and technology to explore the Moon and Mars. The program has been delivering lessons of operations, design, international relations, and policy over the past 20 years. Some examples include [21]:

- Policy: Assembling political support, collaboration, and partnership (domestically and internationally), accommodating partners' objectives, and establishing a plan for evolving public policy
- Engineering and Management: Budget and schedule planning, risk management, internal and external communications, and systems engineering
- Design, Development, Test, and Evaluation: Planning mission architecture, interoperability of components, use of Commercial Off-The-Shelf (COTS) parts, and integration testing
- Operations: Logistics and maintenance, crew operations and medical, and science utilization activities

For example, the ISS commercial cargo services were the first commercial partnerships of their kind, which are now paving the way for Artemis commercial partnerships. NASA learned how to apply common standards and tools, how to conduct operations at all time zones around the world, and how to develop schedules and plans that make scientific activities a priority. Issues we have encountered over this long-duration human spaceflight program have consisted of waste management, storage and inventory management, food and medicine resupply, astronaut health, and allocation of crew time and resources for science activities across international partners and competing agency mission objectives. Many of the same lessons will undoubtedly be extended to the planning and implementation of the Artemis program.

6.2 Analog Examples in Extreme Environments

Living and working in space requires specially designed habitats and vehicles for protection, safety, and prosperity. Many factors and conditions in space are readily present on Earth. Substitute analogs on Earth allow familiarization with novel conditions as well as extreme conditions and environments. Analog sites are used to train crews; design and validate technologies; and develop and verify protocols and countermeasures for sustainable space missions.

Earth analogs have physical similarities to extreme space environments. Their major attributes include geographic remoteness, isolation, hostility, limited life-sustaining resources, and unique ecologies. Limited opportunities for rescue and evacuation occur in cases of emergencies. Tests in these environments include new technologies, robotic equipment, vehicles, habitats, communications, power generation, mobility, infrastructure, and storage. The effects on human health, including behavioral effects such as isolation and confinement, team dynamics, menu fatigue, and others, are also observed [22]. Ideal analog locations include Antarctic, the Arctic oceans, deserts, and volcanic environments. Long-term experiments in these locations also provide key insights into best practices and proven approaches for development and operations.

Located on Devon Island, the Haughton-Mars project is part of a research facility located on the world's largest uninhabited island [23]. This harsh climate mimics the environmental conditions on Mars and other planets. Devon Island's barren terrain, freezing temperatures, isolation, and remoteness offer scientists and personnel unique research opportunities. The Arctic day and night cycle, and restricted communications capabilities offer fitting analogs for the challenges of a long-duration space flights. In addition to communications, equipment testing, and vehicular and extra-vehicular operations, Devon Island is the site of the Exploration program, which aims to develop new technologies, strategies, and operational protocols to support the future exploration of the Moon, Mars, and other planets. The NASA Haughton-Mars Project (HMP) and several collaborating organizations performed the successful field testing of new spacesuit technologies for future astronaut science and exploration operations on the Moon and Mars at this location very recently, for example

Antarctica, the most isolated and harshest of the continents of Earth, possesses a variety of lunar and Mars analog environments. Regular access to a limited set of facilities is provided by NSF and various foreign governments during the austral summer. In operation since 1958, it is the only site on Earth combining fidelity characteristics with available infrastructure that also provides a terrestrial testbed to prove out systems of use to industry [24]. Moreover, access by air creates a condition of extreme physical and psychological isolation. The lack of quick rescue opportunities in the case of a medical emergency and the environmental extreme closely parallels the remoteness and isolation of a planetary outpost. Medical practice in Antarctica has clear parallels to space medicine [24].

At the same time, the history and in-process redesign of McMurdo, the largest station in Antarctica, offers sustainable approaches to consider for long-term space outposts. In 1955, McMurdo was an expeditionary base from which to construct a South Pole station. Today, McMurdo—the primary entry point for U.S. scientists in Antarctica—hosts 1,200 people during the 4-month austral summer. To accommodate this growth, the Station was built out in a piece-meal approach instead of designing the station for long-term sustainability and science at inception [25]. A needed redesign that is in process will reduce McMurdo from 91 scattered buildings to 21 buildings, maximizing energy efficiency and increasing the logistical logic of the site while also providing for the mental and physical needs of the people at the base. The modernization will ensure that McMurdo remains a viable platform for supporting Antarctic science for the next 35-50 years. Organically evolving architecture versus a highly planned architecture from the onset will be critical to building sustainable extraterrestrial outposts [25]. Fast-forwarding to the new design offers lessons for long-term sustainable, space outposts, including:

- More energy and operationally efficient stations, optimized to support local and deep-field science.
- Predictable operational costs, personnel requirements, and operational efficiency.
- Sustainable energy consumption for facilities and operational support.
- Reliable, safe, healthy working environments for personnel and visitors.
- Flexibility to adapt to the changing station and U.S. science needs, for example, accommodate year-around arrivals and movable power and water stations, if needed.
- Reflection of an “active and influential presence” in Antarctica in a manner consistent with U.S. stature in the international research community.

Artemis missions to the Moon will provide a unique opportunity to evaluate the hazards astronauts will face in the deep space environment, before embarking on the years-long journey to Mars. Lunar missions will enable researchers to address the challenges of living farther from Earth than ever before, and test new technologies and procedures needed for the round-trip to Mars. Past generations used analog missions to prepare for leaving Earth's atmosphere, landing on the Moon, and permanently orbiting our planet. In keeping with this concept, NASA is using analog missions to actively prepare for deep space destinations, such as an asteroid or Mars, and to build long-term, sustainable outposts. Earth analogs provide a valuable testing ground for future approaches to exploration.

7. Conclusions

The Artemis program will serve as a catalyst for the growth of sustainable space exploration to the Moon, and beyond. Crewed and uncrewed missions will usher in a new, long-term human presence on the lunar surface, and the presence of humans will optimize adaptability and opportunity. A sustainable presence must consider maintaining the environment as well as heritage sites on the lunar surface, while also heralding in a new era a scientific investigation and maintaining optimal human health through cutting-edge technical assets and in-situ resource utilization systems. For NASA to fulfill the sustainability goals of the Artemis generation, commercial and international partnerships are critical. Building on a legacy of partnerships across global time zones, cultures, politics, and goals, the Artemis program will fuel a new era of partnerships between different planets. Chief among the considerations to enable a sustainable, long-term presence beyond LEO are the requirements to maintain healthy, safe, and productive humans; an innovative, and forward-looking scientific program; preservation and protection of the Lunar environment; and developing and expanding public-private, international, and other creative partnerships.

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8 References

[1] Artemis Plan. September 2020, https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf (accessed 22.09.2021).
[2] https://www.nasa.gov/hrp/hazards (accessed 10.09.2021).
[3] Z.S. Patel, T.J. Brunstetter, W.J. Tarver, A.M. Whitmire, S.R. Zwart, S.M. Smith, J.L. Huff, Red risks for a journey to the red planet: the highest priority human health risks for a mission to Mars, NPJ Microgravity 6:33(2020) 1-13.
[4] J. Green and D. Draper, 2021, Evolution of volatiles on the Moon, https://room.eu.com/article/evolution-of-volatiles-on-the-moon (accessed 22.09.2021).
[5] National Research Council (NRC) Report on the Scientific Context for the Exploration of the Moon, https://www.nap.edu/catalog/11954/the-scientific-context-for-exploration-of-the-moon, (accessed 22.09.2021).
[6] 2013-2023 Planetary Decadal survey, https://www.nap.edu/catalog/13117/vision-and-voyages-for-planetary-science-in-the-decade-2013-2022, (accessed 22.09.2021).
[7] Lunar Exploration Roadmap, https://www.lpi.usra.edu/leag/roadmap/, (accessed 22.09.2021).
[8] LEAG Next Steps on the Moon Report, https://www.lpi.usra.edu/leag/reports/, (accessed 22.09.2021).
[9] 2018 LEAG Advancing Science of the Moon Report, https://www.lpi.usra.edu/leag/reports/, (accessed 22.09.2021).
[10] NASA History Program Office, 2012. Catalog of Manmade Material on the Moon. [online] Available at FINAL Catalogue of Manmade Material on the Moon (nasa.gov), (accessed 30.08.2021).
[11] https://nssdc.gsfc.nasa.gov/planetary/lunar/lunar_artifact_impacts.html, (accessed 22.09.2021).
[12] Protecting & Preserving Apollo Program Lunar Landing Sites & Artifacts, https://trumpwhitehouse.archives.gov/wp-content/uploads/2018/03/Protecting-and-Preserving-Apollo-Program-Lunar-Landing-Sites-and-Artifacts-2.pdf, (accessed 22.09.2021).
[13] https://trumpwhitehouse.archives.gov/presidential-actions/memorandum-space-policy-directive-7/, (accessed 22.09.2021).
[14] "NASA Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts," (Technical Guidelines) published in 2011 https://www.nasa.gov/pdf/617743main_NASA-USG_LUNAR_HISTORIC_SITES_RevA-508.pdf, (accessed 22.09.2021).
[15] H. Satish, P. Radziszewski, and J. Ouellet, 2011. A Review of Mining Technologies for Space, https://www.researchgate.net/publication/277203603_A_REVIEW_OF_MINING_TECHNOLOGIES_FOR_SPACE, (accessed 22.09.2021).
[16] https://www.sustainablemoon.com/, (accessed 22.09.2021).
[17] The Artemis Accords, October 2020, https://www.nasa.gov/specials/artemis-accords/index.html, (accessed 22.09.2021).
[18] Antarctic Treaty Environmental Protection Protocol, https://www.ats.aq/e/antarctictreaty.html, (accessed 30.08.2021).
[19] Planetary Protection Categorization for Robotic Crewed Missions to Earth's Moon, 2020, https://www.nasa.gov/feature/nasa-updates-planetary-protection-policies-for-robotic-and-human-missions-to-earth-s-moon, (accessed 30.08.2021).
[20]https://www.nasa.gov/press-release/as-artemis-moves-forward-nasa-picks-spacex-to-land-next-americans-on-moon), (accessed 22.09.2021).
[21] International Space Station Lessons Learned for Space Exploration, 2014, https://www.nasa.gov/content/iss-lessons-learned-report, (accessed 22.09.2021).
[22] A.E. Nicogossian, D.R. Williams, R. S. Williams, V.S. Schneider. Simulations and Analogs (Test-beds) in Space Physiology and Medicine From Evidence to Practice. 4th Edition. Springer. 2016 (17); 441-461.
[23] Haughton-Mars Project (HMP) https://www.marsinstitute.no/hmp, (accessed 28.09.2021).
[24] J.D. Rummel. 1993. Planetary Surface Exploration: Recent Results and Analog Environments. SAE Transactions, Vol. 102, Section 1: Journal of Aerospace. 1460- 1463.
[25] NASA Workshop on Lunar Sustainability, Jan 2021