NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA)
HEADQUARTERS
SPACE TECHNOLOGY MISSION DIRECTORATE
300 E Street SW
Washington, DC 20546-0001

SPACE TECHNOLOGY RESEARCH GRANTS PROGRAM,

LUNAR SURFACE TECHNOLOGY RESEARCH

OPPORTUNITIES APPENDIX

to

NASA Research Announcement (NRA): Space Technology – Research, Development, Demonstration, and Infusion 2021 (SpaceTech–REDDI–2021), 80HQTR21NOA01

APPENDIX NUMBER: 80HQTR21NOA01-21LUSTR-B5

Appendix Issued: *July 22, 2021*
Amendment 1 Issued: *August 13, 2021*
Notices of Intent Due: *August* 20*, 2021* (5 PM Eastern)
Proposals Due: *September* 17*, 2021* (5 PM Eastern, 2 PM Pacific)

NASA Assistance Listing Number 43.012

OMB Approval Number 2700-0092

Summary of Key Information

Appendix Name: Lunar Surface Technology Research (LuSTR) Opportunities, hereafter called “Appendix,” to the SpaceTech-REDDI-2021 NRA, hereafter called “NRA.”

Goal/Intent: LuSTR is focused on the development of early- to mid-TRL lunar surface technologies of high priority to NASA’s Mission Directorates.

Eligibility: Accredited U.S. universities are eligible to submit proposals; teaming and collaboration are permitted as per section 3.0.

Key Dates:

Release Date:	July 22, 2021
Notices of Intent Due:	August 20, 2021
Proposals Due:	September 17, 2021
Selection Notification:	February 2022 (target)
Award Date:	May 2022 (target)

Selection Process: Independent subject matter expert peer review.

Technology Readiness Level (TRL): TRL 2 to TRL 4 at the beginning of the effort.

Award Details:

Anticipated Total Number of Awards:	4
Award Duration:	Maximum of two years
Award Amount:	$1M to $2M total per award

Type of Instrument to be used for awards: Grants. Cost sharing is not required.

Selection Official: NASA Space Technology Mission Directorate Associate Administrator or designee.

Point of Contact: Claudia Meyer
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Note: The organization and section numbering of this Appendix mirror the SpaceTech-REDDI-2021 NRA for convenience when cross-referencing content between the two documents.

Lunar Surface Technology Research Opportunities

1.0 SOLICITED RESEARCH/TECHNOLOGY DESCRIPTION

1.1 Program Introduction/Overview

NASA's Space Technology Mission Directorate (STMD) hereby solicits proposals from accredited U.S. universities for innovative lunar surface space technology research and development of high priority to NASA's Mission Directorates.

This Lunar Surface Technology Research (LuSTR) Opportunities Appendix is one of five calls for proposals from STMD's Space Technology Research Grants (STRG) Program. LuSTR continues STRG's long tradition of engaging the talent base that exists at our Nation's universities. Early Career Faculty (ECF), Early Stage Innovations (ESI), Space Technology Research Institutes (STRI), in applicable years, and NASA Space Technology Graduate Research Opportunities (NSTGRO) appear as Appendix B1, Appendix B2, Appendix B3, and Appendix B4, respectively, under the SpaceTech-REDDI NRA.

Our Nation's universities couple research with education, encouraging a culture of innovation based on the discovery of knowledge. Universities are, therefore, ideally positioned to both conduct space technology research and diffuse newly developed knowledge and technologies into society at large through graduate students and industry, government, and other partnerships. STMD investments in space technology research at U.S. universities promote the continued leadership of our universities as an international symbol of the country's scientific innovation, engineering creativity, and technological skill. These investments also create, fortify, and nurture the talent base of highly skilled engineers, scientists, and technologists to improve America's technological and economic competitiveness.

This LuSTR Opportunities Appendix is being released in support of STMD's Lunar Surface Innovation Initiative (LSII); LSII technologies will enable human and robotic exploration of the Moon and future operations on Mars. As part of the LSII portfolio, LuSTR solicits ideas from universities for the creation of requisite technologies for lunar surface exploration and to accelerate the technology readiness of key systems and components. A tenet of the STRG program, and this LuSTR opportunity, is to foster interactions between NASA and the university-led teams to accelerate the infusion of technologies into NASA missions.

1.2 Program Goals and Objectives

The STRG Program within STMD is fostering the development of innovative technologies for advanced space systems. The goal of the LuSTR endeavor is to accelerate the development of groundbreaking technologies that support and enable lunar surface activities to be conducted both by NASA and the commercial space sector under Artemis - the core of NASA's exploration and human spaceflight plans for the next decade. This LuSTR Appendix solicits efforts that can be integrated into Artemis' sequence of missions that start with the near-term development of enabling infrastructure and lay the foundation for a sustained human and robotic presence. More information on Artemis can be found here.

The *starting* TRL of the efforts to be funded as a result of this Appendix will be TRL 2 - TRL 4; TRL advancement is required. See Attachment 2 of the NRA for TRL definitions.

The LSII portfolio features six focus areas:

- **In-Situ Resource Utilization** – Development of technologies for the collection, processing, storage, and use of materials found or manufactured on the Moon or other astronomical objects;
- **Surface Power** – Development of technologies, which can provide the capability for continuous power throughout the day and night for lunar surface missions. The technologies required can be grouped into three categories: Power Generation, Power Management & Distribution, and Energy Storage;
- **Extreme Access** – Development of technologies that enable humans or robotic systems to efficiently access, navigate, and explore previously inaccessible lunar or planetary surface or subsurface areas;
- **Extreme Environments** – Development of cross-cutting technologies that enable systems to operate throughout the full range of lunar surface conditions;
- **Excavation/Construction** – Development of technologies that enable affordable, autonomous manufacturing or construction;
- **Dust Mitigation** – Development of active, passive, and operational technologies to mitigate lunar dust hazards on lunar surface systems, such as cameras, solar panels, space suits, habitats, and instrumentation.

This release of the LuSTR Opportunities Appendix features 4 topics that address specific challenges in 2 of the LSII focus areas: **Excavation/Construction** and **Extreme Environments**. Proposals that are not responsive to one of these 4 topics, as specifically described in 1.3, will be considered non-compliant and will not be submitted for peer review. NASA anticipates featuring additional topics, including topics in other focus areas, in future Appendix releases.

The topics described in 1.3 are aligned with the 2020 NASA Technology Taxonomy and are also consistent with the NASA Strategic Plan.

1.3 Topics

LSII Focus Area: Excavation/Construction

The manipulating, excavating, mining, delivering, and processing of regolith on the lunar surface is critical in order to establish the necessary infrastructure and provide in-situ resources that will enable a sustained human presence and economy on the Moon. Typical surface infrastructure elements may include, but are not limited to: pressurized habitats, unpressurized shelters, walls, berms, roadways, and launch and landing pads. Thus, lightweight and durable autonomous excavation, mining, and construction equipment that can support the development of this essential infrastructure is needed.

Topic 1 – Autonomous Systems for Excavation and Site Preparation

The objective of this topic is to develop and demonstrate autonomous surface construction technologies, specifically those for excavation and site preparation, required to enable a sustained human presence on the lunar surface.

While the NASA Apollo program demonstrated that it is possible to land on an unprepared lunar surface, the long-term, sustained objectives of NASA's Artemis program will require the landing of multiple, proximal assets with lander vehicles larger than those of Apollo. If performed on unprepared surfaces, these landings would pose an unacceptable risk to nearby hardware from landing plume ejecta and blast effects [1] and possibly the lander vehicle itself. Thus, early technology demonstrations will likely require numerous site-preparation activities for the construction of prepared launch and landing pads (LLPs), roads, dust-free zones, foundations, blast protection, radiation shielding, unpressurized shelters, and pressurized habitats. Area clearing and leveling, surface compaction and stabilization, trenching, berm building, and in-situ verification of geotechnical properties are likely to be required [2]. These robotic construction technology demonstrations will need to be performed with single or multi-robot autonomous systems while maintaining consistency with Artemis Program goals and milestones.

While civil engineering and construction are well established practices on Earth, lunar applications remain at low technology readiness levels (TRLs); the design requirements for the equipment needed are very different, primarily due to the reduced gravity environment, and constrained mass and power budgets. In addition, hardware will need to operate for long periods of time in the harsh lunar environment: abrasive and electrostatically charged lunar dust, vacuum, and extreme thermal cycles [3]. To date, basic lunar civil engineering and site preparation tests have been performed on Earth but only for short periods of time and with limited environmental and operational fidelity. Outside NASA, both industry and academia have pursued the development of autonomous construction systems (grading and leveling in particular) [4, 5, 6, 7, 8] but a comprehensive end-to-end autonomous working solution has yet to be developed. In-situ geodetic site survey systems exist but often require the use of the Global Positioning System (GPS) satellite network with ground-based augmentations for enhanced surveying accuracy. Real time Light Detection and Ranging (LIDAR) scanning is currently in use with data fusion from other sensors to inform machine decision making capabilities. Aerial drones and crane-mounted cameras are used for verification of construction progress and desired topography with the use of photogrammetry techniques and other three-dimensional (3D) mapping enhanced methods.

Significant gaps remain in our understanding related to the design of lunar surface structures and the corresponding construction systems and implements. Uncertainties surrounding the properties of near-surface regolith yield additional challenges to the robust design of excavation and site preparation systems that must adapt to a broad range of conditions. Designs that account for these uncertainties with adequate margin and supporting design rationale are needed. Highly-compacted or large rock-bearing regions pose a particular challenge to the effectiveness of both mobility systems and regolith manipulation implements due to the limited normal and shear forces that can be imparted by a low-mass system [9], or systems, operating in 1/6th of Earth's gravity. The coupling of mechanism design and autonomous control requires unique approaches to real-time site characterization and system state estimation during operations, task planning and execution, and task verification (post-activity site inspection, data collection, and documentation). In addition, data communications constraints (availability, bandwidth, and latency) between the Earth and the Moon pose new challenges for tele-operation and supervised autonomy that must be addressed. Moreover, environmental conditions (radiation, temperature, etc.) and flight system design constraints (mass, power, etc.) limit, or prevent, the use of high-performance technologies (computing, sensors, etc.) currently being employed for terrestrial applications.

Prototypes of lunar regolith excavation robots have been developed over the last 20 years and can be reviewed in the literature [10, 11, 12], but very limited work has been dedicated to autonomous lunar site preparation robotics.

This solicitation topic seeks the development and demonstration of autonomous site preparation systems for LLPs, a high-priority application. For LLPs, autonomous robotic systems that can perform cut, fill, grading, and compaction operations (i.e., providing a flat, level, and compacted surface for construction) are sought. For this Topic, the following definitions apply: "Cut" is the removal of regolith materials by artificial means, also referred to as excavation. "Fill" is the deposition of regolith materials by artificial means. "Compaction" is the densification of a fill by mechanical means. "Grading" is the moving of regolith materials on, off, or through a site to achieve the desired topography.

Proposals that offer the development of system or subsystem-level hardware, coupled with autonomous systems and robotics are required. Proposals shall include a plan for demonstration of at least TRL 4, which may be performed in Earth-ambient conditions. Demonstrations shall include a mobile autonomous robotic system prototype that has a maximum mass of 83 kg and maximum dimensions of 1.5 m width x 1.5 m length x 2.5 m height stowed volume. While all sensors must be mounted on the vehicle, computation may occur offboard; that is, a benchtop computer may be used and will not count towards the mass or volume budgets. Note that communication between any offboard computer and the mobile system must be performed wirelessly and not via a tether. The robotic system may deploy beyond this volume envelope once unstowed. These Earth-based prototype constraints are derived from an envisioned full-scale lunar flight version of about 500 kg mass which, when operating in 1/6 g, will be equivalent to an 83 kg system in 1 g.

Offerors shall base their proposals on the “Site Initial Conditions and Assumptions” and “System and Demonstration Requirements” information provided below. Demonstrations shall be performed in a laboratory or outside facility with a simulated lunar surface as described below. No special accommodations for simulating the extreme lunar environmental conditions are necessary (e.g., low temperatures, vacuum, radiation, etc.).

<u>Site Initial Conditions and Assumptions:</u>

- Area: Circular, 10 m diameter;
- Regolith Simulants: Proposers are encouraged to use a lunar regolith simulant (commercially available or self-produced) for system design and demonstration. Rationale on the simulant(s) used and their fidelity should be provided [13]. Lunar regolith properties are specified in the Lunar Source Book [14]. Example simulants used by NASA include JSC-1A and NU-LHT-2M high-fidelity simulants (appropriate for laboratory work) and GRC-3 or BP-1 low-fidelity physical simulants (appropriate for larger scale development and demonstrations);
- Slope: the initial site condition shall be a terrain that is level within +/- 1° of a level grade;
- Topography: For the purposes of this LuSTR solicitation, it is assumed that the primary source of lunar surface topology variation is a result of randomly distributed small degraded impact craters (i.e. with gentle slopes and mostly eroded rims). Based on data contained in the NASA SLS-SPEC-159, the required features and their distribution for a simulated lunar surface topology are:
    - One 2-m-diameter crater, randomly distributed;
    - Five 1-m-diameter craters, randomly distributed;
    - Eleven 0.5-m-diameter craters, randomly distributed;
    - Simulated craters should have a depth-to-diameter ratio, d/D, equal to 0.2.
- Contours: all spot elevations within the circular area (excluding craters) shall be within +20 cm of the initial level grade. Initial contours shall be randomly created and use a volume of regolith simulant above grade that is equal to or greater than the volume of the craters;

- Rock distribution and mass: 5 rocks randomly distributed across the test area. Rock sizes should range from 10 cm to 30 cm in diameter and can be constructed of low-density materials (~0.5 g/cc) that mimic the weight of similarly sized rocks under 1/6th g.

System and Demonstration Requirements:

- The primary objective of the design and demonstration efforts is to provide a lunar regolith surface prepared to within ±1° of the horizontal grade, and to 1 cm root mean square height (roughness) measured perpendicular to the slope (i.e., absolute surface feature heights should be adjusted to account for the surface slope, thus allowing for independent measurements of slope and roughness);
- The prepared regolith surface shall be compacted to >90 % relative density to a depth of 30 cm;
- Demonstrate the ability to remove rocks and any unused regolith material from the working area.

Design Considerations

Proposers should consider the following:

- While this topic does not constrain the system architecture, proposers should consider feed-forward to future flight systems in terms of overall system complexity, reliability, cost, the number of unique components, efficiency, total mass, and power consumption as part of their proposal. While the demonstration may be performed in terrestrial conditions, the prototype designs must address how they are extensible to lunar flight qualified systems;
- Proposers are encouraged to consider systems that are scalable/extensible to the preparation of sites of 100 m diameter and greater;
- Proposers need to consider operations and hardware designs that can autonomously perform excavation and site preparation without relying on external infrastructure (e.g., GPS-based positioning for system control);
- This topic is not intended to address all aspects of autonomy and robotics, but rather should focus on identifying and addressing specific technical gaps for site preparation for LLPs. This may include:
  - Perception and state estimation (implement, vehicle, terrain);
  - Planning (action, motion, terrain manipulation);
  - Diagnostics and fault management;
  - Task execution (could involve multiple, cooperating vehicles);
  - Remote human-robot interaction (intermittent control and intervention by ground control).
- Prototype systems and demonstrations shall include a mobile autonomous robotic system. Proposers are encouraged to refrain from designing specific

mobility units if they are available commercially or through other development activities. However, specialized mobility systems may be required for certain architectures and system concepts and thus the design of these are deemed appropriate. Rationale must be provided;

- The system, excluding any offboard computer, shall not exceed a maximum total mass of 83 kg and initial maximum dimensions of 1.5 m width x 1.5 m length x 2.5 m height stowed volume. The robotic system may deploy beyond this volume envelope when unstowed.

Proposals must include the following:

- A rationale for the design methodology of regolith manipulation tools. Offerors must discuss tool mechanical design for use in/on regolith of unknown and/or varying properties (e.g., density, strength). Design approaches that present inherent robustness to varying terrain properties and that require low weight-on-bit (WOB) are encouraged;
- A description that addresses the manner in which regolith manipulating tools will be mounted to, and articulated from, a mobile asset or assets;
- A detailed description of the intended autonomy architecture, including: the suitability of any proposed software framework (e.g., ROS, F', OROCOS, YARP), proposed sensing modalities, methods of state estimation both for the mobility platform(s) and terrain, approaches to the coordination of the mobility-manipulator system in the context of a changing environment, and methods for verification and validation of task success. Note that externally mounted sensors (external to the circular test site) such as motion capture systems, total stations, or mast-mounted LIDAR/cameras should not be proposed, since they will not be available on the lunar surface.

References:

[1] Metzger, P., *Dust Transport and Its Effects Due to Landing Spacecraft*, Lunar Dust 2020, Impact of Lunar Dust on Human Exploration Workshop, Lunar and Planetary Institute, Houston, TX, 2020, https://www.hou.usra.edu/meetings/lunardust2020/pdf/5040.pdf

[2] Moses, R. and Mueller, R., *Requirements Development Framework for Lunar In-Situ Surface Construction of Infrastructure*, 17th Biennial International Conference on Engineering, Science, Construction, and Operations in Challenging Environments, Virtual Conference, 2020, https://ascelibrary.org/doi/10.1061/9780784483374.106

[3] SLS-Spec-159, Rev. G. *Cross-Program Design Specification for Natural Environments (DSNE) - Section 3.4*, 2019. https://ntrs.nasa.gov/citations/20160004378

[4] Melenbrink, N. and Werfel, J., *Autonomous Sheet Pile Driving Robots for Soil Stabilization*, International Conference on Robotics and Automation, Montreal, Canada, 2019, https://ieeexplore.ieee.org/document/8793546

[5] Jud, D., Hurkxkens, I., Girot, C., and Hutter, M., *Robotic Embankment: Free-Form Autonomous Formation in Terrain with HEAP*, Journal of Construction Robotics, 2021, https://www.research-collection.ethz.ch/handle/20.500.11850/491087

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[7] Glover, M., *Caterpillar's Autonomous Journey-The Argument for Autonomy (No. 2016-01-8005)*. SAE Technical Paper, 2016, https://www.sae.org/publications/technical-papers/content/2016-01-8005/

[8] Castro-Lacouture, D., *Construction automation*, In Springer handbook of automation (pp. 1063-1078), Springer, ISBN 978-3-540-78831-7, 2009.

[9] Skonieczny, K., *Lightweight robotic excavation*, PhD Thesis, CMU-RI-TR_13-09, Carnegie Mellon University, 2013, https://www.proquest.com/openview/f0d733f7221175dc5986c239ab654565/1?cbl=18750&pq-origsite=gscholar

[10] Mueller, R., and van Susante, P., *A review of lunar regolith excavation robotic device prototypes* In Proc. AIAA SPACE Conference & Exposition (p. 7234), Long Beach, CA, 2011.

[11] Mueller R. and Schuler, J., *A Review of Extra-Terrestrial Regolith Excavation Concepts and Prototypes*, Tenth Joint Meeting of the Space Resources Roundtable, Golden, Colorado, https://isruinfo.com/public/index.php?page=srr_20_ptmss#SRR_20_1

[12] Mueller, van Susante, P., Reiners, E., and Metzger, P., *NASA Lunabotics Robotic Mining Competition 10th Anniversary (2010–2019): Taxonomy and Technology Review*, In Proc. Earth and Space 2021, pp: 497-510, 2021.

[13] Planetary Simulant Database, Colorado School of Mines, available online at https://simulantdb.com/, 2021.

[14] Heiken, G., Vaniman, D., and French, B., *Lunar Sourcebook, a user's guide to the Moon,* Cambridge University Press, 1991, https://www.lpi.usra.edu/publications/books/lunar_sourcebook/

Please refer to Section 7 – Points of Contact for Further Information of this Appendix if you have technical questions pertaining to this topic. Please note that NASA is unable to comment on whether a proposed area of research is responsive to this topic.

Topic 2 – Lunar Regolith Mineral Beneficiation

The goal of this topic is to enable greater efficiency and ultimately reduce waste during the physical separation and concentration of lunar surface minerals of importance to In-Situ Resource Utilization (ISRU) and Manufacturing and Construction processes.

NASA's goal of establishing a sustained human presence on the Moon will, in part, be enabled by the capabilities provided by ISRU and Manufacturing & Construction technologies. Important and valuable resources (such as aluminum and oxygen) are available in some of the minerals present in the lunar regolith along with other minerals that do not contain valuable elements. Separation and purification of valuable minerals would enable the production of useful feedstock for anticipated applications, including, but not limited to: material sintering, carbothermal reactors, ionic liquid element extraction devices, and hydrogen regolith reduction instruments. The efficacy of these technologies depends to a large extent on the properties of the input feedstock material and stands to benefit greatly from the ability to concentrate minerals of interest – a process called *mineral beneficiation*. Two example applications are provided here for context:

- Construction materials: For a lunar construction material requiring large quantities of extracted calcium or aluminum, the beneficiation of a calcium/aluminum-rich mineral (i.e., anorthite, $CaAl_2Si_2O_8$) would provide more calcium and aluminum-rich feedstock for the extraction process. Consequently, less time and energy would be required for the extraction process to provide the required mass of calcium and aluminum;
- Oxygen from regolith: Chemically, more oxygen can be derived from feldspar minerals than others such as pyroxene and olivine. The processing of the mineral ilmenite ($FeTiO_3$) to obtain oxygen is well-known and efficient; however, the effectiveness and efficiency of that processing decreases proportionally to the abundance of other less-efficiently processed minerals. Mineral beneficiation technology decreases the amount of less-efficiently processed minerals before the feedstock material reaches the extraction or processing step.

In addition, for oxygen/metal extraction from regolith or Manufacturing and Construction with regolith, process efficiency and reactivity can be greatly influenced by regolith grain size. Being able to tailor or limit regolith grain size ranges, such as eliminating fines and larger particles, *in addition to* mineral beneficiation, could significantly increase ISRU and Manufacturing and Construction process performance and product quality.

The current state-of-the-art (SOA) in mineral beneficiation comes both from the mining industry and academia. Such methods of mineral beneficiation include:

- Density-based liquid separation;
- Floatation, which changes a mineral's surface to be more or less attracted to water molecules;
- Flocculation, which employs the use of another material to encourage bonding of a specific mineral to other particles of similar composition, thus making larger aggregated particles that can easily be separated;
- Magnetic separation, which exploits the magnetic susceptibility of minerals;
- Triboelectrostatic separation, which operates via the electrostatic charging of grains;
- Biological beneficiation, which employs the use of bacteria and other organisms for the concentration of specific elements or minerals via bioleaching, bioflocculation, and biofloatation.

Advancements in mineral beneficiation are needed to adapt the above technologies for operation on the lunar surface. The challenges to advancing the SOA include the Moon's reduced gravity, regolith geotechnical properties and chemical composition [1], the lunar thermal and radiation environments, magnetic nanophase iron in vapor-deposited rims, water-soluble minerals, and the lack of a lunar atmosphere.

This solicitation topic specifically seeks proposals to address one or more of the following research areas:

- Plausibility and efficacy assessments and associated considerations when using one or more of the aforementioned Earth-based mineral beneficiation techniques with lunar regolith - proposals must consider regolith electrostatic charging, the presence of nanophase iron, glass content, and friability of the grains [1];
- Separation demonstrations of lunar regolith simulant minerals or glasses to a mineral/glass purity greater than 70%. That is, the final separates must be comprised of 70% or greater of the desired mineral or glass;
- Design for lunar surface mineral beneficiation hardware, taking into account the angularity, abrasiveness, friability, and static charge of regolith [1];
- Beneficiation hardware testing in a vacuum chamber – tests should be performed at a range of temperatures between approximately -200 °C and 120 °C.

Proposals should focus on grain sizes and shapes on the Moon of 1 mm and less in size, chemical variation between highlands and mare lunar regolith types [2], the multiple solid solution compositions of feldspar, pyroxene, and olivine, the presence of ilmenite and nanophase iron, and techniques to minimize dust generation during processing.

For those proposals focusing on mineral beneficiation science, expected outcomes would include:

- Laboratory demonstrations of separation techniques using commercially available lunar regolith simulants;
- An assessment and ranking of beneficiation techniques for the lunar surface based on known lunar regolith properties;
- Demonstrations of separation for minerals, glasses, and different compositions of minerals from a known mixture of the materials;
- An assessment of the efficiency of each investigated mineral-beneficiation process. Proposers are encouraged to include chemical analyses (X-ray Diffraction, Energy Dispersive Spectrometry, or similar) of pre- and post-processed materials as part of their research plan;
- Beneficiation processes capable of sorting minerals by grain size after mineral beneficiation are desired.

For those proposals focusing on hardware design, expected outcomes would include a Preliminary Design Review (PDR)-level hardware design that 1) is suitable for lunar regolith; 2) minimizes mass, power, volume; and 3) is capable of operating in the lunar environment. Research products would include a Concept of Operations, as well as the PDR, emphasizing the systems engineering aspects of the design and hardware. The final report would detail the design and lessons learned during its development and reviews, including an assessment of efficiency and identified risks, and a potential path to flight for the hardware.

References

[1] Heiken G., Vaniman D., and French B., *Lunar sourcebook: A user's guide to the Moon*, Cambridge University Press, 1991, https://www.lpi.usra.edu/publications/books/lunar_sourcebook/

[2] Papike J., Ryder G, and Shearer C., *Lunar Samples*, Reviews in Mineralogy vol. 36, 234pp, Mineralogical Society of America, 1998.

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LSII Focus Area: Extreme Environments

The near-term, sustained human exploration of the Moon requires a new generation of technologies to address lunar extreme environments including ionizing radiation from the Sun and Galactic Cosmic Rays, thermal exposure ranging from 25K in permanently shadowed regions to nearly 400K at the lunar equator, and electrostatic surface charging. Lunar missions are likely to include landers, crew habitats, robotic systems, and in situ consumables production that are expected to operate through lunar day-night cycles and in permanently shadowed regions. The lunar dust, radiation, thermal, and vacuum environments present unique challenges for the reliable deployment, operation, and sustainment of surface systems across the various lunar destinations. Candidate technologies required to satisfy the goals of the Artemis program are still in their infancy and must be rapidly matured to meet NASA's ambitious schedule. Although there are a diverse number of technologies in need of advancement in the extreme environments focus area, this opportunity is limited to the following two specific topics.

Topic 3 – Cold-Temperature Analog Integrated Circuits

The goal of this topic is to develop analog integrated circuits and analog-to-digital electronics, fabricated using standard foundry processes that will function under the extreme low temperatures of the lunar night and shadowed regions.

Lunar nights average approximately 14 Earth days and reach temperatures below 100 K (equatorial) and 70 K (closer to the poles) [1]. Permanently shadowed regions (PSRs) of the Moon never receive direct sunlight and are thus extremely cold (25 K to 70 K). Due to their extremely low temperatures, PSRs contain volatiles (ammonia, methane, etc.) and there is strong evidence that polar craters contain significant amounts of water ice [2]. If significant deposits of volatiles are confirmed to exist in these regions, they could provide valuable resources, making detailed knowledge of their interiors of key importance to future human and robotic exploration. The ability to survive and ultimately operate through the lunar night and inside PSRs is fundamental to NASA's goal of a sustained presence on the Moon.

One of the key challenges of exploration in the lunar environment is the lacking availability of high-reliability, cold-tolerant electronics and electronic packaging technologies. While significant advances have been made in analog integrated circuit (IC) technology for extreme-cold temperatures, the focus of research and technology development to date has been on device scaling and noise reduction while increasing the transistor density. Conventional silicon (Si) ICs degrade at low temperatures due to hot carrier damage. State-of-the-art silicon germanium (SiGe) technologies solve many of these issues but present other challenges including device-to-device variation of the terminal current [3, 4] and are fabricated and packaged using non-standard processes that are costly and time-consuming. While survival temperatures of dormant ICs can be as low as 70 K, their operational temperature range is much higher (> 200 K), thus requiring pre-operational heating [5]. Due to the limited availability of reliable and cost-effective, cold-tolerant electronics, conventional practice is to house the electronics in a protected, centralized, warm electronics box (WEB) [5]. In addition to increasing the overall system size, weight, and power (SWaP), the use of WEBs often requires highly complex wiring and signal routing schemes.

Advancements in cold-temperature-tolerant electronics are needed to reduce both the SWaP and development cost of lunar payloads. This solicitation topic specifically seeks proposals for cold-temperature-tolerant electronics solutions and innovative circuit-design methodologies using commercial foundry processes to significantly advance the technical readiness of analog IC technology for NASA's lunar surface applications. Proposals must address one or more of the following research areas:

- Analog to digital convertors (ADCs) designed and fabricated using standard foundry processes with performance that is degraded by no more than 20% when compared to SOA ADCs operating at nominal room temperature for their technology of choice and with a lifetime of 3 years. The lifetime definition here is that the performance should not degrade by more than 20% during a 3-year period at 70 K;
- Analog IC modules, with a lifetime of 3 years and power consumption increased by no more than 20% of the same design operated at room temperature, using foundry design kits. For example, if an ultra-high-frequency (UHF) low-noise amplifier is proposed with noise figure (NF) of 0.5 dB at room temperature with total power consumption of 50 mW, the power consumption may not exceed 60 mW at 70 K with similar NF and bandwidth performance;
- Device-level or wafer-level packaging technologies that increase the lifetime of standard analog ICs operated at 70 K to more than 3 years;
- Innovative methodologies and protocols for the early qualification of cold-temperature-operable ICs, to be performed during the *design phase* and prior to fabrication and physical testing [6]. Offerors must provide a plan for the verification and validation of their methods and protocols through empirical means at 70 K.

Hardware validation may be performed at the laboratory scale, and lifetime testing can be designed using accelerated testing processes such as tests performed at lower temperatures for shorter periods of time. Plans for accelerated lifetime testing must include the identification of key, time-temperature dependent failure/degradation mechanisms, around which accelerated test campaigns can be effectively designed.

Proposals must include a detailed development plan for advancing the state of the art in terms of performance of cold-tolerant analog ICs, while improving the 3-year reliability matrix, as defined above. This plan must include milestones wherein comparisons are made between the key performance parameters of the proposed technology and more traditional methods (e.g., heated Si electronics). For example, for ADCs, the comparison table should include SNR, sampling rate, dynamic range, gain, non-linearity performance, and effective number of bits.

Proposers are required to include testing and validation plans in a relevant environment (70 K) as part of their research plan. The proposal must articulate a clear plan for advancing the TRL.

In addition, proposers are encouraged to include physics-based modeling detailing the ultimate performance limitation of their proposed technology.

References:

[1] Leahy, F., *SLS-SPEC-159 - Cross-Program Design Specification for Natural Environments (DSNE) Revision H, 2020,* https://ntrs.nasa.gov/citations/20205007447

[2] Lawrence, D., A tale of two poles: *Toward understanding the presence, distribution, and origin of volatiles at the polar regions of the Moon and Mercury*, *Journal of Geophysical Research: Planets*, Volume 122, Issue 1, p. 21-52, 2016, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016JE005167

[3] Cressler, J., *Low temperature electronics*, 6th International Planetary Probe workshop, Atlanta, GA, 2008.

[4] Ying, H., J. W. Teng, U. S. Raghunathan, J. P. Moody and J. D. Cressler, *Variability of p-n Junctions and SiGe HBTs at Cryogenic Temperatures*, IEEE Transactions on Electron Devices, vol. 68, no. 3, pp. 987-993, 2021, doi: 10.1109/TED.2021.3054358

[5] Bolotin, G., Sheldon, D., Lias, M., Stell, C., Suh, J., and Hunter, D., *Compact Low Power Avionics for the Europa Lander Concept and Other Missions to Ocean Worlds*, In Proc. IEEE 68th Electronic Components and Technology Conference (ECTC), pp. 1813-1823, 2018, doi: 10.1109/ECTC.2018.00272

[6] Diestelhorst, R., et al., *A new approach to designing electronic systems for operation in extreme environments: Part 1 – the SiGe Remote Sensor Interface,* IEEE Aerospace and Electronic Systems Magazine, Vol. 27, Issue 7, 2012.

Please refer to Section 7 – Points of Contact for Further Information of this Appendix if you have technical questions pertaining to this topic. Please note that NASA is unable to comment on whether a proposed area of research is responsive to this topic.

Topic 4 – Novel Heat Transfer Fluids

The goal of this topic is to develop and/or characterize novel heat transfer fluids that may provide significant mass and performance improvements in thermal control systems for lunar surface applications.

Single-phase (liquid) heat transfer fluids have been successfully used in a variety of applications for human and robotic spacecraft [1-4]. For future lunar applications, vehicles and surface assets will be required to survive and operate through the extreme temperatures experienced on the lunar surface. Thermal conditions can range from the 70 - 100 K during the lunar night to 400 K near the subsolar point at lunar noon. In addition, some lunar vehicles will be expected to function after significant dormant and low-power periods where crew are not present or the asset is not in use, thus minimizing the amount of heat that will need to be rejected.

Human spacecraft have historically used single-phase fluids (liquid) in either a one-fluid (Apollo) or two-fluid (Shuttle, ISS, Orion) architecture configuration. Two-fluid systems have typically been driven by the need to minimize the risk of the crew exposure to hazardous fluids while within the vehicle, and simultaneously providing design robustness to varying heat loads and thermal environments external to the vehicle. While these two-fluid systems increase mission flexibility and decrease risk to crew, they require additional system mass to accommodate support hardware associated with having multiple fluid loops. Novel fluids may allow systems to achieve increased operational flexibility, reduce system mass, and minimize hazards to the crew [5-8].

While several candidates have been explored and implemented for single-fluid human spacecraft thermal control systems in low Earth orbit, lunar thermal systems would benefit from improved fluids that are more capable of handling the extreme lunar thermal environments.

This solicitation topic specifically seeks proposals for novel fluids that enable single-fluid, single-phase (liquid), thermal control loop architectures for crewed vehicles. Candidate fluids must offer thermophysical properties better than those currently provided by state-of-the-art external fluids (such as HFE 7200), reduce the pour point to preclude freezing during lunar night/low power periods, and minimize risks associated to potential crew exposure. Solutions must focus on novel fluids/mixtures development and demonstration, not design mitigations for existing fluid candidates (heaters, etc.). Since the combination of a fluid’s various thermal properties have a complex effect at the system level, it is difficult to define a specific set of quantitative requirements. However, desired threshold performance metrics of the novel fluid for crewed vehicles are provided below:

- Liquid temperature range: 100 K – 373 K:
    - Operational exposure limits are expected in the range of 150 K to 323 K;
    - Stability over 1000s of temperature cycles;
    - Changes in liquid density over the temperature range must be characterized; however, no specific design metric is offered in this regard.
- Threshold thermophysical properties:

- Specific heat ≥ 2000 J/kgK at 293 K;
- Thermal conductivity ≥ 0.1 W/mK;
- Viscosity considerations:
  - Provide viscosity low enough to maintain turbulent flow in key heat transfer sections such as radiator tubing;
  - Result in viscosity increase ≤ 2.3x at 243 K (50 K below reference temperature);
  - Result in viscosity increase ≤ 5.5x at 193 K (100 K below reference temperature);
  - Result in viscosity increase ≤ 65x at 153 K (140 K below reference temperature).
- Vapor pressure considerations (for crewed applications) [8]:
  - Minimize toxicology hazards to crew (Tox 3 or lower) [9,10] – the fluid vapors must be non-reactive and breathable at its saturation pressure;
  - Minimize risks associated with oxygen displacement.
- Compatibility with typical system materials, components, and operational pressures:
  - Materials include but are not limited to aluminum alloys, stainless steels, titanium, and common soft goods and seal materials (Teflon, silicone, Viton, etc.);
  - Minimize risk to tight tolerance components, such as positive displacement or centrifugal fluid pumps;
  - Operational life > 10 years.
- Provide microbial growth inhibition (if applicable).

Offerors must demonstrate that the proposed activities will provide the desired improvements in performance and demonstrate an understanding of system-level implications of the investigated heat transfer fluid(s) and their potential benefit. For example, nanofluids may be considered due to their increased thermal conductivity and improved heat transfer performance; however, an investigation into system-level effects for a previous spacecraft active thermal control system revealed that the inclusion of nanoparticles resulted in a heavier system or used more pump power than the baseline system due to the larger density and viscosity of the nanofluid [2]. In addition, while analytical techniques may be leveraged early in the program, the proposed work must, at a minimum, include a series of empirical tests that demonstrate the ability to provide the desired thermophysical properties and characteristics of any fluid/mixture investigated.

References:

[1] Birur, G., et al, *From Concept to Flight: An Active Fluid Loop Based Thermal Control System for Mars Science Laboratory Rover*, AIAA International Conference on

Environmental Systems, San Diego, CA, 2012, https://trs.jpl.nasa.gov/bitstream/handle/2014/42754/12-2473_A1b.pdf;jsessionid=82FB35BC1549374676BEFBCD127714A1?sequence=1

[2] Ungar, E., and Erickson, L., *Assessment of the Use of Nanofluids in Spacecraft Active Thermal Control Systems*, In Proc. AIAA Space 2011 Conference & Exposition, 2011.

[3] van Gerner, H., et al., *Fluid selection for space thermal control systems*, International Conference on Environmental Systems, Tucson, AZ, 2014, https://ttu-ir.tdl.org/bitstream/handle/2346/59591/ICES-2014-136.pdf?sequence=1

[4] Westheimer, D.T. and Tuan, G.C., *Active Thermal Control System Considerations for the Next Generation of Human Rated Space Vehicles*, In Proc. AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 2005.

[5] Cutbirth, J., *Designer Fluids for use in a Single Loop Variable Heat Rejection Thermal Control System*, NASA SBIR/STTR Report, Mainstream Engineering Corporation, FL, 2015 https://ehb8.gsfc.nasa.gov/sbir/public/documentDownload;jsessionid=3LbKXKzsl9Lm9dmPKt5P872gU6IgCcanjTBBfDLjTGfUBMfzQahz!787867708?severFile=briefchart.pdf&proposalId=SBIR_15_P1_154921&docType=BRIEFCHART

[6] Stephan, R., *Overview of the Altair Lunar Lander Thermal Control System Design*, In Proc. 40th International Conference on Environmental Systems, Barcelona, Spain, 2010.

[7] Ungar, E. K., *Spacecraft Radiator Freeze Protection Using a Regenerative Heat Exchanger with Bypass Setpoint Temperature Control*, In Proc. SAE International Conference on Environmental Systems, San Francisco, California, 2008.

[8] Perry, J.L., *Case Studies in Crewed Spacecraft Environmental Control and Life Support System Process Compatibility and Cabin Environmental Impact*, NASA/TP-2017-219846, 2017, https://ntrs.nasa.gov/api/citations/20180002400/downloads/20180002400.pdf

[9] Garcia, H., Lam, C., Langford, S., and Ramanathan, R., *Guidelines for Assessing the Toxic Hazard of Spacecraft Chemical and Test Materials*, JSC 26895, NASA Johnson Space Center, 2014, https://www.nasa.gov/sites/default/files/atoms/files/jsc_26895_rev1_final.pdf

[10] *NASA-STD-3001 Technical Brief, Spaceflight Toxicology Chemical Contaminants*, NASA Johnson Space Center, Office of the Chief Health & Medical Officer, 2020, https://www.nasa.gov/sites/default/files/atoms/files/spaceflight_toxicology_technical_brief_ochmo_12112020.pdf

[11] Lee, S.H., Mudawar, I., and Hasan, M.H., *Thermal analysis of hybrid single-phase, two=phase and heat pump thermal control system (TCS) for future spacecraft*, Journal of Applied Thermal Engineering, vol. 100, pp 190-214, 2016, https://www.sciencedirect.com/science/article/abs/pii/S1359431116000739

[12] Minea, A., *Overview of Ionic Liquids as Candidates for New Heat Transfer Fluids*, International Journal of Thermophysics, vol. 41, 2020.

[13] Kazakov, A., Magee, J.W., Chirico, R.D., Paulechka, E., Diky, V., Muzny, C.D., Kroenlein, K., Frenkel, M., *NIST Standard Reference Database 147: NIST Ionic Liquids Database - (ILThermo)*, National Institute of Standards and Technology, Gaithersburg MD, 2017, https://www.nist.gov/mml/acmd/trc/ionic-liquids-database

Please refer to Section 7 – Points of Contact for Further Information of this Appendix if you have technical questions pertaining to this topic. Please note that NASA is unable to comment on whether a proposed area of research is responsive to this topic.

2.0 AWARD INFORMATION

As noted in 2.0 of the NRA, awards are authorized by The National Aeronautics and Space Act of 1958, 51 U.S.C. § 20113(e).

2.1 Funding and Period of Performance Information

NASA plans to make up to 4 awards as a result of this Appendix. NASA reserves the right to make no awards under this Appendix, or exceed 4, subject to the receipt of meritorious proposals and the availability of funds. It is possible that the Selection Official may decide to defer selection decisions on some proposals while making selection decisions on others. If the Selection Official exercises this option, proposals will be categorized as "selected," "declined," or "deferred". Proposals receiving deferred decisions may be considered for supplemental selection at a later date. Offerors who receive a deferred selection decision will be notified of the timeline for supplemental selection decisions.

The LuSTR Appendix requests proposals for new awards; continuations of awards will be handled separately.

Proposals of 1-2 years in duration are invited. Total budgets are expected to range between $1M and $2M per award, depending on the scope of the proposed project. Annual budget requests between $500K and $1M would be considered typical. The budget request for a single year may not exceed $1.2M and the total budget may not exceed $2M. In addition, actual budget usage by the awardees is monitored by NASA; proposed budgets must account for ramp-ups within the team (i.e., slower initial costing due to staffing considerations). All amounts must be justified.

Initial funding is anticipated to be for the first year of the award, and subsequent funding will be contingent on the availability of funds, technical progress, and continued relevance to NASA goals. A continuation review at the end of the first year – to assess technical progress and continued relevance – is required.

The anticipated type of award instruments will be grants, subject to the provisions of the 2 CFR (Code of Federal Regulations) 200, 2 CFR 1800, and the NASA Grant and Cooperative Agreement Manual (GCAM). Contracts will not be awarded as a result of this Appendix.

3.0 ELIGIBILITY INFORMATION

3.1 Limitation on Number of Proposals per Organization

Only accredited U.S. universities (i.e., postsecondary institutions that offer both undergraduate and graduate degree programs) are eligible to submit proposals to this solicitation. Teaming is permitted, subject to the eligibility of offerors (see 3.2 of this Appendix). There is no limit on the number of proposals which may be submitted by an accredited U.S. university.

3.2 Eligibility of Offerors and Limitation on Number of Proposals Per PI/Co-I

In general, faculty and research staff may serve as PIs on proposals submitted to this Appendix, provided they hold a full-time, continuing appointment at the submitting university and have a doctoral degree. The following may not serve as PIs: adjunct faculty, visiting faculty, affiliate faculty, and postdoctoral scholars. Teaming is permitted, subject to the following restrictions:

- In order to facilitate broad, nationwide participation in this program, a PI or Co-I may participate in no more than two proposals in response to this Appendix. Participation in more than two submissions may result in all being deemed non-compliant. Note: when more than one proposal is submitted on behalf of a PI or Co-I, each proposal must be a separate, stand-alone, complete document for evaluation purposes;
- The university submitting the proposal may partner with other universities and colleges. Partnering with industry and/or non-profit entities is encouraged;
- At least 60% of the proposed budget must go to accredited U.S. universities;
- Other government agencies and non-NASA FFRDCs are permitted to collaborate only (i.e., not funded through the proposed effort - see additional information on *collaboration/collaborators* below);
- NASA centers and JPL are *not* permitted to participate on proposals submitted to this Appendix.

Proposals that fail to meet the above eligibility criteria may be rejected without review.

NASA especially encourages proposals submitted on behalf of women, members of underrepresented minority groups, and persons with disabilities.

Other Proposal Personnel

Co-Investigators (Co-Is), postdoctoral associates, consultants, and collaborators are permitted, subject to restrictions listed above and further explained below.

As specified in Appendix B of the *2020 NASA Guidebook for Proposers,* a collaborator is not critical to the proposal but is committed to providing a focused but **unfunded** contribution for a specific task. The Scientific/Technical/Management Section of the proposal (see 4.3.5 of this Appendix for additional information) should document the nature and need for all collaborations. If research collaborators are participating in the proposal, it is presumed that the collaborator(s) have their own means of research support; that is, a LuSTR proposed budget may not include any expenses for the collaborating organization.

This LuSTR Appendix is seeking to fund the best research proposed to the solicited topics from *outside* of NASA. NASA civil servants and JPL employees may not appear on submitted proposals, and there can be no solicitation-related communications with NASA (including JPL) employees from the time this Appendix is released until proposal selections are final. The proposer is permitted to identify potential specific fruitful collaborations with agency experts; however, these collaborations may not be discussed with agency personnel *a priori*. Potential collaborations will not be a factor in proposal evaluation, and letters of commitment from NASA (including JPL) are not permitted. If a proposal is selected, any potential NASA collaborations identified will be addressed at that time.

3.3 Proposals Involving Non-U.S. Organizations

Collaboration by non-U.S. organizations in proposed efforts is permitted as specified in 3.3 of the NRA.

3.6 Cost Sharing

Cost sharing is not required and is not considered as part of the evaluation.

4.0 PROPOSAL SUBMISSION INFORMATION

4.1 Introduction

The following supplements the information provided in 4.0 of the NRA. Note that in instances where this Appendix and the NRA or Guidebook differ, the Appendix takes precedence.

Proposals submitted in response to this Appendix will be evaluated and selected through a one-step process.

4.2 NSPIRES Registration

In order to submit a proposal, all team members and their institutions must be registered in the NASA Solicitation and Proposal Integrated Review and Evaluation System (NSPIRES). Therefore, every organization (including Co-I and collaborator organizations) that intends to submit or be a named participant on a proposal to NASA in response to this solicitation, whether submitting through Grants.gov or the NSPIRES system, must also be registered in NSPIRES. See 4.2 of the NRA for NSPIRES registration requirements.

4.3 Proposal Content and Submission

4.3.1 Electronic Proposal Submission

Offerors may submit proposals via NSPIRES or Grants.gov. See 4.3.1 of the NRA for details.

The electronic proposal must be submitted in its entirety by an Authorized Organizational Representative (AOR) no later than 5 PM Eastern (2 PM Pacific) on September 17, 2021. Proposals submitted after the proposal deadline will be considered late and may be rejected without review.

4.3.2 Notice of Intent to Propose

NOIs are strongly encouraged by August 20, 2021. The NOI is submitted via NSPIRES. See 4.3.2 of the NRA for details of the information to be included in the NOI. The information contained in the NOIs is used to prepare for the proposal review process and is, therefore, of value to both NASA and the offeror; the NOI is not a factor in the proposal evaluation process.

The restriction on number of proposals described in 3.2 of this Appendix – a maximum of two per PI or Co-I – does not apply to NOIs. However, prospective offerors are encouraged to consider this restriction as early in the proposal window as possible, ideally prior to the NOI submission due date.

NASA is unable to provide feedback on NOIs.

4.3.4 Proposal Cover Page

The Proposal Cover Page shall include the proposal team, the proposal summary (abstract), responses to program specific data questions, and the budget. Instructions for completing the Proposal Cover Page are specific to the electronic proposal submission system used by the offeror (NSPIRES or Grants.gov).

See 4.3.4 of the NRA for NSPIRES and Grants.gov instructions.

4.3.5 Proposal

The proposals must include the following sections in the order listed. Please note frequent references to 3 - Proposal Preparation and Organization - of the *2020 NASA Guidebook for Proposers*. Proposals that fail to meet the requirements specified herein may be rejected without review.

NASA Guide-book Section	***Proposal Section***	***Maximum Page Length***
	Title Page (optional)	1
3.12	1. Table of Contents	1
N/A	2. Overview Chart	1
3.13	3. Scientific/Technical/Management Section	15
3.11	4. Data Management Plan	2
3.14	5. References and Citations	As needed
3.15	6. Biographical Sketches	As needed. Maximum of 2 pages per PI/ Co-I.
3.16	7. Current and Pending Support	As needed
3.17	8. Statements of Commitment and Letters of Resource Support	1 page each, if needed
3.18	9. Proposal Budget with Budget Narrative and Budget Details	As needed (Note: facility descriptions, if needed, may not exceed 4 pages total)
3.20	10. Special Notifications and/or Certifications	As needed

Note: A Title Page that states the name of the proposal and the proposing organizations may be included in the proposal but is not required.

Proposals must be formatted as a single, unlocked pdf file containing the elements enumerated in the above table. Failure to submit a single, unlocked pdf file may result in the proposal being deemed non-compliant.

Reviewers will not consider any content in excess of the page limits specified in the table above.

Section 1: Table of Contents

See 3.12 of the *2020 NASA Guidebook for Proposers*.

Section 2: Proposal Summary Chart

The proposal summary chart is intended to provide a quick sense of the proposed effort and should stand alone (i.e., not require the full proposal to be understood). As noted in 4.3.4.1 of the NRA, the summary chart should not include any proprietary or sensitive data as NASA intends to make it available to the public after selections are announced.

The chart must include the following information:

- A representative graphic with caption;
- The proposal title, the PI's name, the PI's institution and information (name and affiliation) of other key team members;
- The objectives of the technology development, a comparison to the state of the art (SOA), a discussion of key challenges, and start and projected end TRL;
- A high-level summary of the approach, including methods, testing, and validation to be employed;
- The potential impact and potential for infusion of the effort (i.e., benefits and outcomes as they relate to LSII and Artemis).

The proposal summary chart should be organized as illustrated in Figure 1 – Template for Required Proposal Summary Chart – and must be oriented as shown (i.e., landscape mode). Font size 10 or above must be used.

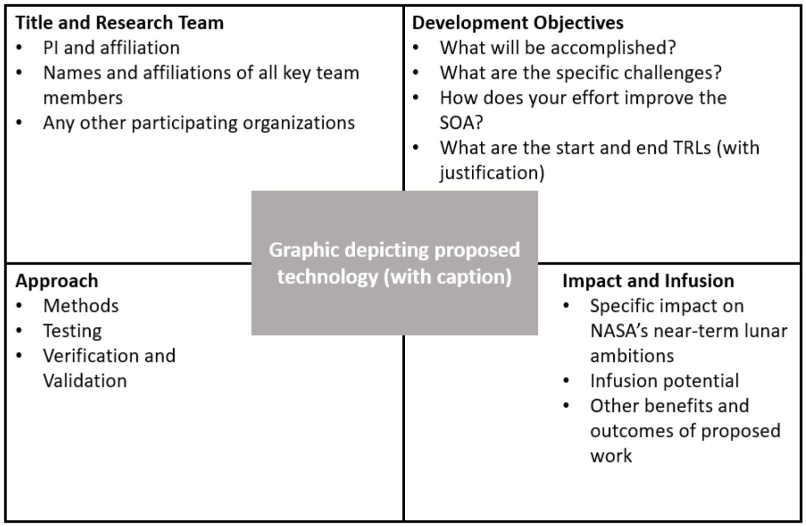

Figure 1 - Template for Required Proposal Summary Chart

Section 3: Scientific/Technical/Management Section

This is the main body of the proposal and must cover the following subsections in the order given. The Scientific/Technical/Management Section is limited to 15 pages with standard (12 point) font, and the text must have one-inch margins. This page limit includes illustrations, tables, figures, and all subsections.

a) The **relevance** of the proposed work to the specific LuSTR Appendix goals, objectives, and topics, as described in 1.2 and 1.3.
  i. Please note that the NRA and this Appendix describe the relevance of LuSTR to the NASA Strategic Plan; therefore, it is not necessary for individual proposals to show relevance to NASA's broader goals and objectives. The proposal should instead focus on demonstrating responsiveness and relevance by discussing how the proposed research and technology development directly addresses one of the topics;
  ii. A comparison between the proposed effort and the SOA, including a discussion of existing limitations and what capabilities the proposed research and development will enable;
  iii. A clear statement on the impact and timeliness of the proposed work as it relates to the LuSTR objectives detailed in 1.2 and 1.3 of this Appendix;
  iv. A technology infusion plan; specifically, the proposal should identify and discuss a path for further development and infusion – within a five-year horizon – post-LuSTR, including the potential challenges for scaling up the proposed technology;

b) The **technical approach** and methodologies (types of analyses, testing, validation, and other research and development activities) to be employed while conducting the proposed work. Target performance goals must be articulated.

Include a description of any hardware to be built and the facilities and/or capabilities of the proposing organization(s) required to execute the approach. Access to NASA facilities should not be assumed during the course of the LuSTR effort, nor should NASA facilities be included in the proposal. Note: facilities and proposer capabilities will be evaluated under the third evaluation criterion as described in 5.2 of this Appendix;

c) A general **work plan**, including schedule and anticipated key milestones. Expected research and development products/outputs (databases and associated analysis tools, measured performance metrics, designs, fabrication and characterization methods, or other technical advancements) – with a schedule of completion – should also be described. The planned work for all years in which funding is sought should be identified and a discussion of the potential risks and mitigation strategies should be included;

d) A discussion of the current **TRL** of the proposed technology (see Attachment 2 of the NRA) as well as the projected TRL at the end of the research. The proposal should justify the proposed starting TRL. In addition, the proposal should provide a clear and substantiated description of how the exit TRL will be accomplished under the proposed funding profile;

e) The **management structure** for the proposal personnel (PIs, Co-Is, etc.), any substantial collaboration(s) and/or use of consultant(s) that is (are) proposed to complete the investigation, and a description of the expected contribution to the proposed effort by the PI and all proposal personnel, regardless of whether or not they derive support from the proposed budget. See section 3.2 of this Appendix for restrictions. The relationship between strongly related and/or leveraged current support involving any PI or Co-I and the proposed research must be described in this section. The qualifications, capabilities and experience of the proposal personnel should be submitted under Section 6: Biographical Sketches (see below).

Section 4: Data Management Plan

One of NASA's missions is to provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof. Therefore, it is NASA's intent that all knowledge developed under this Appendix be shared broadly through publication of the results.

All proposals are required to submit a **data management plan** (DMP), in accordance with the *NASA Plan for Increasing Access to the Results of Scientific Research*. Award recipients are subject to reporting requirements under this plan, including submitting peer-reviewed manuscripts and metadata to a designated repository and reporting publications with progress reports. As of this Appendix release the designated repository is PubSpace; however, note that NASA will be releasing a new portal for NASA-funded submissions in the coming months. More information on the new portal and details on the above-mentioned plan can be found here.

The DMP applies to any data needed to validate the conclusions of peer-reviewed publications, including data that underlie figures, maps, and tables. Other data, models, software, and hardware designs that would enable future research must also be addressed in the DMP. The DMP must discuss how research products will be made available to NASA and the public and include evidence (if any) of past research product sharing practices. Sound rationale must be provided for any open access limitations.

The DMP must include information on how the proposer/team plans to archive research products, including details on types of products, where products will be archived, schedule for archiving products, how the DMP will enable long-term preservation, and roles/responsibilities of team members to accomplish the DMP.

For information about data rights, and other aspects of intellectual property such as invention rights resulting from awards, see 2.5 of the NRA and Appendix J of the *2020 NASA Guidebook for Proposers.*

Section 5: References and Citations

See 3.14 of the *2020 NASA Guidebook for Proposers*.

Section 6: Biographical Sketches

The PI and all Co-Is must provide biographical sketches, regardless of whether or not they intend to derive support from the proposed budget. A biographical sketch (not to exceed 2 pages in length) should include professional experiences, positions, and a bibliography of recent publications, highlighting the publications relevant to the proposed investigation.

Section 7: Current and Pending Support

Information must be provided for all ongoing and pending projects and proposals that involve the proposing PI or Co-I, even if the PI or Co-I would receive no salary support from the project(s).

All current project support from any source (e.g., Federal, State, local, or foreign government agencies, public or private foundations, industrial or other commercial firms) must be listed. This information must also be provided for all pending proposals already submitted or submitted concurrently to other possible sponsors. Do not include the current proposal (i.e., the proposal in response to this Appendix) on the list of pending proposals unless it has also been submitted to another possible sponsor.

For pending research proposals involving substantially the same kind of research as that being proposed to NASA under this Appendix, the proposing PI must immediately notify the NASA Program Officer identified for this Appendix of any successful proposals that are awarded any time after the LuSTR proposal due date and until the time that NASA's selections are announced.

Also see 3.16 of the *2020 NASA Guidebook for Proposers*.

Section 8: Statements of Commitment and Letters of Resource Support (if needed)

Each team member identified as a participant on the Proposal's Cover Page and/or in the proposal's Scientific/Technical/Management Section must acknowledge their intended participation in the proposed effort.

- NSPIRES allows for participants named on the Proposal Cover Page to acknowledge a statement of commitment electronically; acknowledgement via NSPIRES is considered sufficient for this Appendix. In the event that a team member is unable to confirm participation through NSPIRES, the proposer should include a statement of commitment (one page maximum each) in the body of the proposal;
- Any proposal submitted via Grants.gov must include signed statements of commitment (one page maximum each) in the proposal.

In addition, a letter of support is required from the owner of any facility or resource that is not under a team member's direct control, acknowledging that the facility or resource is available for the proposed use during the period of performance. The letter(s) may not include statements of affirmation (that endorse the value or merit of a proposal). NASA neither solicits nor evaluates such endorsements for proposals. The value of a proposal is determined by peer review using the evaluation criteria defined in 5.0 of this Appendix. Statements of commitment and/or letters of support from NASA civil servants and JPL employees are not permitted.

Also see 3.17 of the *2020 NASA Guidebook for Proposers*.

Section 9: Proposal Budget with Budget Narrative and Budget Details

The budget justification must include details adequate to substantiate the requested funding; detailed information is **required** not only for the proposing institution but also for all proposed subawards. The proposal must provide planned budgets for all years in which funding is sought.

Proposal funding restrictions are detailed in 4.3.7 of the NRA. Additional restrictions for this LuSTR Appendix include:

- The maximum annual and total award values are detailed in 2.0 of this Appendix. All amounts must be justified;

- Funds may be used for student (undergraduate or graduate) and postdoctoral fellow support, provided these individuals are directly involved in the proposed research and any costs related to such individuals are allowable and allocable according to governing cost principles;
- Funds may be used for research expenses, such as costs incurred in experiments, purchase of equipment and/or supplies, computing, and travel;
- If collaborators are included in the proposal, it is presumed that the collaborators have their own means of research support; that is, a LuSTR award may not include any expenses for the collaborating organization.

Please note that, if required, facility descriptions may be included in this section; however, they may not exceed four pages (total) in length.

Also see 3.18 of the *2020 NASA Guidebook for Proposers*.

4.3.7 Proposal Funding Restrictions

The funding restrictions and requirements given in 2 CFR 200, 2 CFR 1800, and 14 CFR 1274 and the GCAM are applicable to this Appendix and are detailed in 4.3.7 of the NRA.

Pre-award costs, expenses incurred within the 90-day period preceding the effective date of the award may be authorized but such expenses are made at the proposer's risk. NASA will not pay any pre-award costs incurred for unfunded proposals.

Section 10: Special Notifications and/or Certifications (if needed)

See Section 3.20 of the *2020 NASA Guidebook for Proposers*.

4.6 Collection of Demographic Information

See 4.6 of the NRA.

5.0 PROPOSAL REVIEW INFORMATION

5.2 Review Process

The review criteria used while evaluating proposals under this Appendix are given below. The questions associated with each criterion are provided to elaborate on their intended meaning. The three primary evaluation criteria – 1) Relevance, 2) Technical Approach, and 3) Qualifications and Management of Team, Resources, Data Management and Cost – are all equally weighted.

Relevance

Evaluation includes consideration of the following:

- Responsiveness to Topic: Does the proposed effort address a specific technology topic identified in this Appendix?
- State of the Art (SOA): How does the proposed effort compare to and advance the current SOA?
- Impact and Infusion: How might the proposed effort impact NASA's ability to fulfill its lunar plans? Does the proposal clearly articulate a strategy by which technologies developed under LuSTR can be infused into NASA's lunar exploration needs? Is the proposed effort timely and does it have potential for infusion within a five-year horizon?

Technical Approach

Evaluation includes consideration of the following:

- Technical Approach: Is the approach technically sound, logical, and feasible? Are target performance goals clearly articulated? Are the analyses, testing, validation, and other research and development methods sufficient and likely to lead to actionable conclusions?
- Work Plan: Is the work plan complete and appropriate to successfully accomplish the proposed technology development? Is the schedule, including key milestones, appropriate and realistic? Are the research products well-defined? Does the proposal recognize significant potential challenges and consider reasonable mitigation strategies?
- TRL: Is the proposed work at the appropriate entry TRL (2-4) as stated in 1.2 of this Appendix and is it well-justified? Will the proposed work plan, if successful, achieve TRL advancement?

Qualifications and Management of Team, Resources, Data Management and Cost

Evaluation includes consideration of the following:

- Qualifications of PI/Team and Management Structure: Does the proposal team possess sufficient technical knowledge and capabilities to complete the proposed research? Are the staffing levels adequate? Are all roles, including those of any collaborators, clearly defined? (Note: potential NASA collaborations identified will not be evaluated.) Is the management structure appropriate?
- Facilities: Are the proposed facilities appropriate to complete the planned research and development? Does the proposal team have access to (commitment from) the appropriate facility owners?
- Data Management Plan: Does the data management plan maximize the data and research products that will be publicly available as a result of the funded effort, with sound rationale for any open-access limitations?
- Budget: Is the proposed budget reasonable and justifiable given the scope and complexity of the effort? Is the budget of sufficient fidelity? Are the assumptions and components of the proposed budget well-defined?

Both Government (NASA and non-NASA) and non-Government reviewers may be used, and submission of a proposal constitutes agreement that this is acceptable to the investigator(s) and the submitting institution. Peer reviewers are selected with regard to both their scientific expertise and the absence of conflicts of interest.

The Selection Official for this Appendix will be the NASA Space Technology Mission Directorate Associate Administrator or designee. The Selection Official may take portfolio balance and other programmatic considerations into account when making final selections.

5.3 Selection Announcement and Award Dates

Selection notifications are anticipated in or about February 2022. PIs and university AORs will receive notification via NSPIRES.

Feedback to PIs will be provided upon written request; requests for feedback should be submitted as instructed in the notification letter and within 30 days of notification.

5.6 Risk Analysis

See 5.6 of the NRA.

6.0 FEDERAL AWARD ADMINISTRATION INFORMATION

All awards are subject to the terms and conditions, cost principles, and other considerations described in 2 CFR 200, 2 CFR 1800, and the GCAM. This Appendix does not invoke any special administrative or national policy requirements.

6.1 Federal Award Notices

For those proposals being recommended for an award, the notification should not be regarded as an authorization to commit or expend funds. Research grants are expected to be awarded as a result of this announcement. Assuming the availability of appropriated funds, a May 2022 award date is expected. If selected, NASA expects the grantee to commence with the proposed research on the award start date; deferrals will not be permitted.

Research Terms and Conditions

Awards from this funding announcement are subject to the Federal Research Terms and Conditions (RTC) located at https://www.nsf.gov/awards/managing/rtc.jsp. In addition to the RTC and NASA-specific guidance, three companion resources can also be found on the website: Appendix A— Prior Approval Matrix, Appendix B—Subaward Requirements Matrix, and Appendix C— National Policy Requirements Matrix.

Environmental Impact

All awards made in response to proposals to this Appendix must comply with the National Environmental Policy Act (NEPA). The majority of grant-related activities are categorically excluded (from specific NEPA review) as research and development projects that do not pose any adverse environmental impact. A blanket NASA Grants Record of Environmental Consideration (REC) provides NEPA coverage for these anticipated activities and it is expected that all awards resulting from this Appendix will be covered by this REC. Please see 3.20 of the *2020 NASA Guidebook for Proposers* for more information.

6.2 Award Reporting Requirements

The reporting requirements will be consistent with 2 CFR 1800.902 "Technical Publications and Reports" and Appendix F - Required Publications and Reports of the NASA Grant and Cooperative Agreement Manual.

The following requirements will also be incorporated into the LuSTR awards:

Quarterly Progress Reports. The Principal Investigator (PI) shall submit progress reports every 90 days, with the first one due 90 days from the grant start date. The reports will provide a summary of progress against the work plan, discussion of upcoming activities, student information, and any issues or concerns. In addition, information related to publications, presentations, conferences, inventions, follow-on funding, and press received – referred to as grant visibility and impact data – must be provided. Electronic copies of publications and presentations should be submitted along with progress reports. The fourth progress report will also require an annual summary of research chart.

Year 1 PI Meeting. LuSTR PIs will be expected to participate in the annual PI meeting near the end of the first year of the award; this meeting will fulfill the continuation review requirement (see 2.1); research team members are also welcome. Proposed budgets should therefore account for a 3-day trip to the Washington, D.C., area in the April timeframe. These meetings will highlight technology development progress under all first-year LuSTR grant awards and will provide a forum for researchers to engage with each other and with NASA and other government agency personnel.

Year 2 LSIC Seminar. The PI shall present at a Lunar Surface Innovation Consortium (LSIC – please see http://lsic.jhuapl.edu/ for more information) meeting during the second year of the grant award. LSIC seminar travel must be included in the submitted budget; meetings will be held at the Johns Hopkins University Applied Physics Laboratory and LSIC member organizations within the continental U.S. The purpose of this presentation is to raise awareness of the space technology development being conducted under the award, create opportunities for technical interaction and collaboration, and further elucidate infusion opportunities.

LSIC Focus Groups. The PI will be invited, but not required, to participate in the LSIC focus group corresponding to their project and have the opportunity to periodically report on the status of their project. The focus group meetings will showcase ongoing activities in the area and offer industry perspective. Virtual participation is possible.

Closeout Reports. The PI shall submit closeout report documentation (final technical report, final grant visibility and impact data, and final research summary slide) at the end of the final grant year. The Program will also schedule a virtual closeout briefing.

7.0 POINTS OF CONTACT FOR FURTHER INFORMATION

Questions (technical, programmatic, grants management, etc.) or comments about this Appendix may be directed to:

Claudia Meyer
Space Technology Research Grants Program Executive
Space Technology Mission Directorate, NASA Headquarters
hq-LuSTR@mail.nasa.gov

Questions to the manager of the NRA associated with this Appendix may be directed to:

Kimberly Cone
SpaceTech-REDDI NRA Manager
Office of Procurement, NASA LaRC
hq-LuSTR@mail.nasa.gov

Questions of a general nature may be added to the Frequently Asked Questions (FAQs) for this Appendix. The FAQs document will be located under “Other Documents” on the NSPIRES page for this Appendix.

All technical questions will be incorporated into one of the topic-specific Questions and Answers (Q&A) documents, also located under “Other Documents” on the NSPIRES page for this Appendix. When submitting a technical question, proposers are agreeing to have the question, and associated response, published in one of the Topic Q&A documents. Questions will be accepted through September 10, 2021; no technical questions will be accepted after this date. Please note that NASA is unable to comment on whether a proposed area of research is responsive to a topic described in 1.3.