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Terrestrial Proving Ground Capabilities Needed for Lunar *In Situ* Resource Utilization (ISRU) & Construction Concepts of Operation

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Abstract

Incorporating any new technology or system into a human exploration mission or architecture requires development well in advance of the mission to eliminate technology, cost, and schedule risk concerns. It is often stated that technologies need to be at a Technology Readiness Level (TRL) of 6, i.e. 'system/subsystem model or prototype demonstration in a relevant environment (ground or space)', by Authority To Proceed (ATP) or by the Preliminary Design Review (PDR) for the mission at the latest. There are two game changing capabilities for sustained human exploration of space that can have a significant effect on the overall exploration architecture and the technologies and systems included in the architecture. The first game changing capability, known as In Situ Resource Utilization (ISRU), involves the search for, acquisition, and processing of resources on the Moon and Mars into mission consumables and usable products, and the second is the ability to utilize space resources in the construction of roads, structures, and surface infrastructure.

ISRU and surface construction capabilities have the potential to greatly reduce the cost and risk of human exploration while enabling sustained lunar surface and commercial operations. However, ISRU and surface construction systems are complex and must operate in extremely harsh environments, with abrasive regolith and pervasive dust, for long-periods of time, with potentially limited opportunities for maintenance and repair by humans. The complexity of these capabilities and operations also means that there are a limited number of companies that can design, build, and operate end-to-end systems on their own. The majority of the technologies being developed for these systems are by small companies and at the component or subsystem level. With the overarching strategy of the United States National Aeronautics and Space Administration (NASA) Space Technology Mission Directorate (STMD) to enable industry to implement ISRU and surface infrastructure for Artemis and space commercialization, it is therefore important to establish processes and capabilities to promote and foster collaborations among large and small companies involved in ISRU and surface infrastructure development. For ISRU and infrastructure systems and capabilities to be used in Artemis missions and future commercial lunar surface operations, a coordinated framework with virtual/physical integration and testing locations, or 'Proving Grounds', needs to be established and operated on a regular basis and open to all. This paper will discuss the ISRU and surface construction near and long-term concepts of operations, and review operations and lessons-learned from the previous ISRU analog field tests. From this information, requirements and capabilities will be proposed to support and enable the integration and testing of ISRU and construction systems with industry, academia, and international agencies, as well as what facilities and organizations could help establish these Proving Grounds.
Keywords: ISRU, Construction, Test Facilities, Proving Grounds, Analog Testing, Environmental Testing

Acronyms/Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
ASCEND	Accelerating Space Commerce, Exploration and New Discovery
ATP	Authority To Proceed
CDR	Critical Design Review
CFM	Cryogenic Fluid Management
Comm	Communication
ConOps	Concepts of Operation
COTS	Commercial Off The Shelf
CSA	Canadian Space Agency
CSM	Colorado School of Mines
DARPA	Défense Advanced Research Projects Agency
Desert RATS	Desert Research and Technology Studies
DOD	US Department of Défense
DOE	US Department of Energy
ESRIC	European Space Resources Innovation Centre
FDR	Flight Delivery Review
FE	Foundational Exploration
FFRDC	Federally Funded Research and Development Center
g	Gravity
GRC	Glenn Research Center

H_2	Hydrogen
H_2O	Water
He	Helium
ILSO	International Lunar Surface Operations
ISRU	In Situ Resource Utilization
ITAR	International Traffic in Arms Regulation
JHU APL	John Hopkins University Applied Physics Laboratory
KSC	Kennedy Space Center
LEAG	Lunar Exploration and Analysis Group
LOGIC	Lunar Operating Guidelines for Infrastructure Consortium
LN_2	Liquid nitrogen
LRU	Line Replaceable Unit
LSIC	Lunar Surface Innovation Consortium
MCR	Mission Concept Review
NASA	National Aeronautics and Space Administration
Nav	Navigation
NH_3,	Ammonia
O_2	Oxygen
PDR	Preliminary Design Review
PNT	Position, Navigation, and Timing
SLE	Sustainable Lunar Evolution
SLOPE	Simulated Lunar OPErations
SSERVI	Solar System Exploration Research Virtual Institute
STMD	Space Technology Mission Directorate
TBD	To Be Determined
TLPG	Terrestrial Lunar Proving Ground
TRL	Technology Readiness Level
TRR	Test Readiness Review
US	United States

1. Introduction

The ability to locate, extract, and processes space resources into mission consumables, propellants, and manufacturing/construction feedstocks (known as ISRU), and the ability to modify local terrains and utilize locally produced feedstocks for construction requires the coordination and interaction of multiple surface elements and supporting infrastructure for power, communications, navigation, thermal management, control, product storage and distribution, and maintenance, repair, and logistics management. It is not anticipated that a single government agency or company can design, build, test, deploy, and operate all of the surface elements and infrastructure required to achieve large-scale ISRU and surface construction operations on the lunar surface. Instead, it is expected that just like terrestrial construction, mining, and processing operations on Earth, large-scale commercial lunar ISRU and surface construction hardware and software will be obtained from multiple companies, government agencies, and countries, and that these assets will be eventually operated and coordinated by a commercial company or consortium.

Unlike previously flown space missions where mission hardware is often tested on their own in very controlled environments, these complex lunar surface operations involving hardware from multiple companies and organizations will require a much different integration and testing approach than has been previously used in the development, verification, and certification of flight systems. The closest analogy to what may be required is a combination of traditional environment simulation chambers and facilities along with technology and mission field testing activities such as NASA's Desert Research and Technology Studies (Desert RATS) and the International Lunar Surface Operations (ILSO) and In-Situ Resource Utilization (ISRU) Field Tests [1]. The multi-day/week test campaigns performed in these programs were aimed at examining new lunar surface mission concepts of operation (ConOps) by utilizing 'realistic' mission hardware being operated under 'representative' mission surface conditions and terrains. These field tests and locations, sometimes referred to as 'analogs' mimicked aspects of the extraterrestrial exploration site of interest in terrain, materials, and minerals that were important to the technology and ConOps being evaluated. As will be discussed in this paper, what is considered 'realistic' and 'representative' are aspects that need to be considered during the development phases of new and complex mission operations and capabilities. Coordinated by NASA, these test campaigns often involved a significant number of personnel, US and foreign companies/organizations, and hardware assets that all needed to work with each other. While very successful, lessons-learned from these past test campaigns along with greater emphasis on industry involvement and establishing commercial operations requires a modified or new approach to the integration and testing of multi-element and multi-participant complex ISRU and surface construction operations. Over the last few years, the concept of establishing a 'Proving Ground' where these activities can occur has been discussed in forums and workshops. This paper will examine the concept, purpose/need, attributes, and management of a Terrestrial Lunar Proving Ground (TLPG) to advance lunar ISRU and surface construction, incorporating past considerations and new perspectives [1,2,3,4,5].

2. Purpose of Terrestrial Lunar Proving Ground (TLPG)

A Terrestrial Lunar Proving Ground (TLPG) is a coordinated network of test capabilities/facilities that will enable the evaluation and/or validation of one or more lunar surface elements as part of a greater system, surface infrastructure, and mission concept of operations. The primary purpose of the TLPG is to support the advancement of new and potentially complex *Concepts of Operations* (ConOps) with a focus on ISRU and surface construction systems and capabilities along with the *Interoperability* of critical technologies, modules., and supporting infrastructure. To achieve this purpose, the TLPG must:

- Provide location(s) where hardware (modules and functional blocks) can be virtually and/or physically integrated and tested under terrestrial analog and/or lunar environmental conditions for apples-to-apples performance and operational evaluations of individual hardware, integrated systems, and mission concepts.
- Focus on integration, validation, lifecycle testing, and operations involving human-in-the-loop and supervised autonomy.
- Include interoperable infrastructure representative of the capabilities that will be utilized during surface operations. It should be noted that the infrastructure itself (power, communication, navigation, etc.) may not just be provided by the TLPG facility but may be part of the surface elements participating in the test campaign.

When considering the TLPG, the particular focus on ISRU and surface construction systems is due to the fact that large scale/commercial ISRU and surface construction systems will be complex, multi-element operations that will need to be designed to operate for years under harsh conditions/environments with limited human involvement. Besides demonstrating that ISRU and surface construction products can be made to mission requirements, it is extremely important that NASA mission planners and external investors have confidence that i) the feasibility of the technology/ capability has reached an acceptable level, and 2) that a terrestrial and/or space market for the technology and/or product is within a reasonable timeframe. Therefore, developers will need to not just demonstrate that their hardware meets mission requirements but demonstrate how it operates in the larger system and ConOps.

3. Types of TLPG

There are three types of test conditions/capabilities that need to be considered for the TLPG, with respect to the roles they play in the evaluation and validation of ISRU elements and systems, as well as their integration, interoperability, and mission ConOps: Environmental Simulation, Analog Sites, and Digital Simulation

3.1 Environmental Simulation

The most familiar type of test capability is Environmental Simulation. This involves laboratory and environmental chambers that can replicate one or more mission environment that is critical to understanding and evaluating the performance of the hardware element and system. Capabilities needed for Environmental Simulation include:

- Vacuum ($<10^{-4}$ torr at a minimum/$<10^{-5}$ torr desired)
- Thermal Environment (hot and cold with liquid nitrogen (LN_2) temperatures as a minimum)
- Regolith simulant beds and feed/waste hoppers.
  - Access to large amounts and wide variety of simulants (physical and mineral)
  - Ability to prepare specific simulants (ex. icy regolith; solar wind implanted, etc.)
- Dust distribution; measured dust loading
- Solar/thermal, radiation, space environmental effects may be needed for certain tests.
  - Of regolith bed surfaces
  - Of hardware under operation
- Reduced gravity/offloading (Lunar-1/6th and Mars-3/8th g)
- Vibration: launch, landing, separation
- Data, power, and fluid feedthroughs; fluid storage and distribution for long-duration operations
- Hardware thermal management/heat rejection

3.2 Analog Sites

While Environmental Simulation capabilities can provide precise environments to evaluate and validate performance and environmental compatibility, they are typically limited in volume so that evaluation of mission concepts of operation are limited. Also the expense of operating an environmental simulation chamber may limit the ability to perform mission life testing at the complete system scale. Since ISRU and surface construction systems will operate over 100's if not 1000's of meters on the lunar surface and operate with limited human maintenance and repair for more than a year, it is critical to have locations where hardware and elements can be tested as part of a larger mission concept of operations and for extended periods of time. Whether enclosed or open to the environment, these mission 'Analog' simulation Site locations need to mimic important aspects of the extraterrestrial exploration site and operations of interest. Capabilities required to mimic 'representative' mission surface conditions for these test activities includes:

- Terrain features/slopes, rock distributions, surface/subsurface porosity, craters, etc. at traverse distances and mining areas
- Ability to modify terrain before and during testing
  - Before testing to meet mission concept of operation needs
  - During operations
  - Agreed upon post-test remediation of site or none required
- Distributed resources of interest (form, concentration, subsurface and areal). Lots of

regolith is needed. Mare and Highland. Possibly different mineral types.
- Lighting conditions (polar, equatorial, shadowed regions)
- Good weather or controlled environment
- Reduced gravity/offloading of one or more assets desired (Lunar-1/6th and Mars-3/8th g)
- Recognition of cultural and/or environmental impacts and approval for natural locations

To date, Analog simulation sites have fallen into three categories: Rock yards, Enclosed facilities, and Natural Terrains. Rock yards exist at several NASA centers and companies to allow for quick mobility and tool evaluation tests. These rock yards are typically limited in size and terrain features, and the materials used typically only mimic physical properties of extraterrestrial materials at best. Enclosed facilities provide weather control and the ability to better control of surface material properties and simulant types. Good examples of enclosed facilities used for ISRU, excavation, and surface mobility testing are the Swamp Works large regolith bin at the Kennedy Space Center (KSC) and the Simulated Lunar OPErations (SLOPE) laboratory at the Glenn Research Center (GRC) [6,7]. While these may be limited in size and therefore limit the size of the hardware and/or traverse/operation path that can be tested, new enclosed facilities under development will provide much greater surface area and testing support. Natural terrains provide large areas to operate with the potential for wide variations in terrain and mineral features. In many cases natural analog sites that have been used are tailored to specific mission concepts/resources. The negatives associated with using a natural analog site are the uncontrolled access, potential remoteness and limited nearby infrastructure, and potential cultural and environmental impact concerns.

3.3 Digital Simulation

The third type of TLPG testing and evaluation capability, Digital Simulation, has gained increased importance over the years and covers a broad spectrum of possible uses and approaches. One approach is the development of traditional sizing and physics-based computer models to better understand the operation and performance of hardware being developed and the impacts and implications to the system and upstream/downstream hardware. These models can lead to ‘Digital Twin’ models which can operated in real-time with actual hardware to compare and predict performance and failure trends. A second approach is to use these types of models (hardware emulators) in conjunction with other hardware elements to support system level tests and evaluations. This hybrid hardware-software model integrated testing is particularly useful when corresponding hardware is not available for testing or is at a lower fidelity than the main hardware elements in the test program. A third approach is the use of virtual environments to test hardware and mission concepts of operation. Using software and approaches similar to advanced video games, these virtual environments can emulate a wide range of terrains, environments, gravities, lighting conditions, etc. that might be difficult to emulate in Environmental Simulation or Analog Sites with minimum/no delay in testing or access once the virtual environment has been created.

3.4 TLPG Simulation Attributes

It should be noted that during development and validation of ISRU and surface construction technologies, elements, and systems, all three TLPG testing capability types will be needed, and that it is extremely unlikely that all of the capabilities will be accessible at a single location. Also, as will be discussed and highlighted in the next section, the wide variety of mission concepts and lunar locations of interest suggests that TLPG test locations may be tailored to address very specific mission operations and needs. Overarching to all three TLPG test capability types are three major attributes:

1. The Ability to Test **ISRU** and **Surface Construction** Technologies and Integrated Systems in relevant environments. To do this the TLPG will need to utilize environmental facilities for lunar performance and operation testing, esp. for regolith preparation and processing. It will also need to utilize analog facilities for concept of operations (ConOps) associated with regolith excavation, delivery, removal, and preparation with possibly adding processing when available, as well as utilize analog and environmental test operation software, control, procedures, etc.as the basis for future flight operation.
2. The Ability to Provide and Test **Infrastructure** and **Support Services** needed to support ISRU and Surface Construction testing. This is further divided into two sub-attributes: i) Infrastructure and Support Services to support ISRU and Surface Construction tests and operations. Incorporate other infrastructure/surface discipline technologies and capabilities; test and compare options. ii) Infrastructure and Support Services for the people and hardware supporting the tests and operations
3. Allow for both collaboration and competition with defined interfaces.

4. ISRU & Surface Construction Concepts of Operation (ConOps) for TLPG

As was stated previously, the primary purpose of the TLPG is to support the advancement of new and potentially complex *ConOps* with a focus on ISRU and surface construction systems and capabilities along with the *Interoperability* of critical technologies, modules, and supporting infrastructure. Recently three of the authors of this paper wrote and presented a paper at the AIAA ASCEND conference in Las Vegas, NV, titled "Using ISRU and Surface Construction to Define Long-Term Lunar Infrastructure Needs" [8]. In this paper, the authors defined the overarching architecture for a large-scale/commercial ISRU architecture, and identified the major steps and functions associated with finding, mapping, extracting, transporting, and processing lunar resources, delivering ISRU-derived products to customers, and defining the infrastructure needed to support these operations. Figure 1 from this paper depicts the full ISRU system cycle (green pentagons) with required infrastructure (blue hexagons), and overarching aspects (red diamonds) to ensure successful long-term operations. Primary ISRU operations occur at four distinct sites: Excavation, Processing, Product Storage, and Waste Storage sites. To support lunar ISRU operations, which will be performed primarily through remote and autonomous operations, an extensive communication and navigation system will be required, as well as an extensive power generation, storage, and distribution architecture. Because lunar ISRU operations will eventually occur around the clock in an extremely harsh environment (vacuum, temperature and sunlight extremes, abrasive regolith), a comprehensive maintenance and repair capability will also be required.

Due to time limitations at the time of writing the AIAA ASCEND paper, the authors were not able to delve as deeply into large-scale lunar surface civil engineering and construction activities as initially desired. However, it is important to stress at this time, that many of the design attributes, tasks, operations, and infrastructure needed for surface construction are similar to those that were discussed in #4. *Resource Extraction*, #5. *Resource Preparation*, #6. *Resource Transportation*, and even #7. Resource Processing in the paper. Figure 2 depicts notional surface civil engineering and horizontal construction activities that align with ISRU operations.

Based on ISRU mission concept studies and the architectures and operations examined in Ref. 8, it is expected that the TLPG will need to be able to support and test three main areas of interest with two or more ConOps associated with each area. It is these areas of interest and ConOps which will drive the requirements, interfaces, specifications, and eventual locations for TLPG facilities and test operations.

1. Mission Support
    a. Offloading, deployment, and assembly
    b. Maintenance and repair
2. ISRU
    a. Resource Exploration/Mapping missions: Type 1. Resource Reconnaissance, Type 2. Focused Resource Exploration, and Type 3 Reserve Mapping.
    b. Lunar regolith excavation, transportation (100 m minimum), and preparation (crushing, size sorting, mineral separation, blending)
    c. Lunar Regolith processing (O_2, water, metals, feedstocks) with product storage
    d. 2.b & 2.c combined
3. Surface Construction
    a. Site evaluation
    b. Civil Engineering: Area clearing, leveling, compaction, berm building.
    c. Horizontal Construction (Road construction; Launch/Landing Pad Construction)
    d. Shelter/Habitat Construction (Unpressurized and pressurized construction)
    e. Tower construction
    f. Rail construction

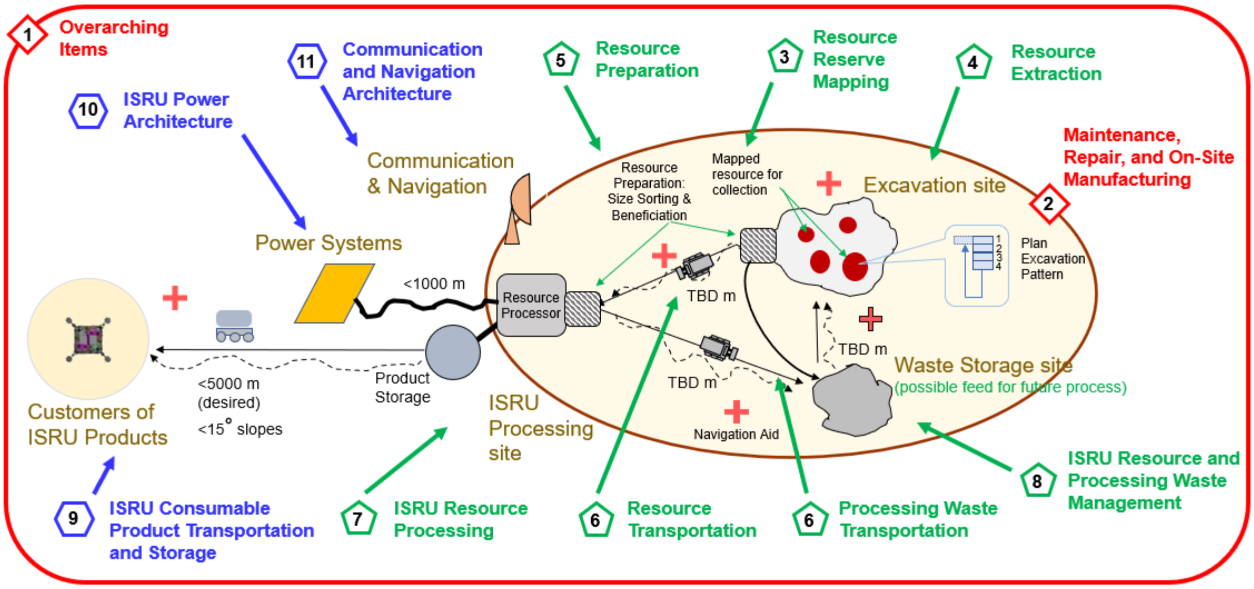

Figure 1. Lunar ISRU System and Concept of Operations

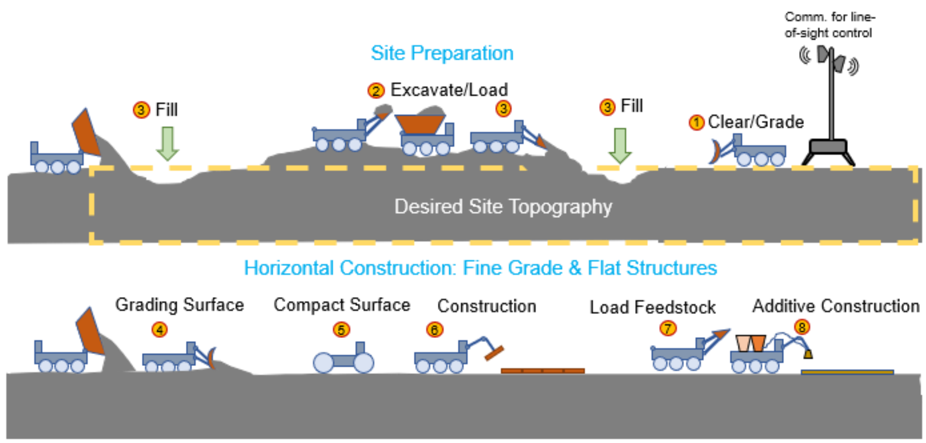

Figure 2. Notional Surface Civil Engineering and Horizontal Construction Operation

5. TLPG Test Capabilities and Attributes

Besides the test capabilities listed in the section *Types of TLPG*, there are a number of overarching capabilities and attributes that TLPG locations and facilities must also be able to provide to support test activities.

The TLPG must be able to provide <u>different levels of test complexity/capabilities</u> as a function of where the hardware and system are in the development/ certification cycle. Because of potential costs and schedule issues, it is expected that hardware elements to be tested in or as part of a larger ISRU or surface construction system will most likely be at Technology Readiness Level (TRL) 5, i.e. "component and/or breadboard validation tested in relevant environment" or higher, as well as potentially being the second or beyond generation of the element design. TRL 5/6 testing at a TLPG would involve development, life, and mission feasibility/ConOps testing. As hardware and systems mature toward flight applications, Pre-flight validation/certification and even qualification level tests may be performed. If costs can be kept low or subsidized, an interesting use of the TLPG could be to support feasibility testing of early generations of hardware associated with universities or NASA Challenges. For the recent Break the Ice Lunar Centennial Challenge, teams had to create their own traverse and simulated icy regolith (soft concrete) test capabilities, and a competition analog test-scape had to be temporarily created at an off-site facility of Alabama A&M University. Having an existing TLPG analog would have been beneficial to the teams and the competition, and possibly help in transition from competition to next generation designs.

The TLPG must provide <u>mission relevant infrastructure and mission support capabilities</u> such as communication, navigation, power, cryogenic fluid management (CFM), avionics/control/automation, thermal control/management for test hardware. For communications, the TLPG must provide secure communication/control capability for real-time on-site and remote control and oversight of test assets. For power, the TLPG will need to provide 10's of kilowatts (KWe) of power; nominally at 120 volts (V) and AC current but most likely will need to also provide power conversion capabilities to DC and other voltages as well. Because ISRU systems will utilize reactants and make mission consumables, the TLPG will need to have storage and distribution for several gas, liquid, and cryogenic fluids to initiate and/or support operations (examples include N_2, He, H_2. O_2, NH_3, H_2O). It should be noted that besides having the TLPG provide these capabilities, the TLPG should also invite or encourage companies wanting to provide lunar infrastructure services to provide their capabilities as part of TLPG test activities. The TLPG should help establish and provide realistic mission maintenance and repair capabilities for extended test operations based on established guidelines. Because it is expected that crew involvement in maintenance and repair will be limited, robotic operations are required. The TLPG should invite or encourage robotic arm and servicing companies to provide their capabilities as well. Figure 3, evolved from Ref. 8, depicts a potential two step maintenance and repair strategy (quick replacement of line replaceable units (LRUs) with offline LRU repair) tied to logistics, on-site manufacturing, and eventually ISRU provided feedstocks.

Because all hardware elements for a complete ISRU or surface construction system may not be available, the TLPG will need to be a to provide virtual emulators and/or commercial off the shelf (COTS) hardware to fill in gaps in capabilities until they can be provided by another developer. Also, the TLPG should provide mock-ups if real hardware is not available, esp. for landers, habitats, and potential 'customer' interfaces.

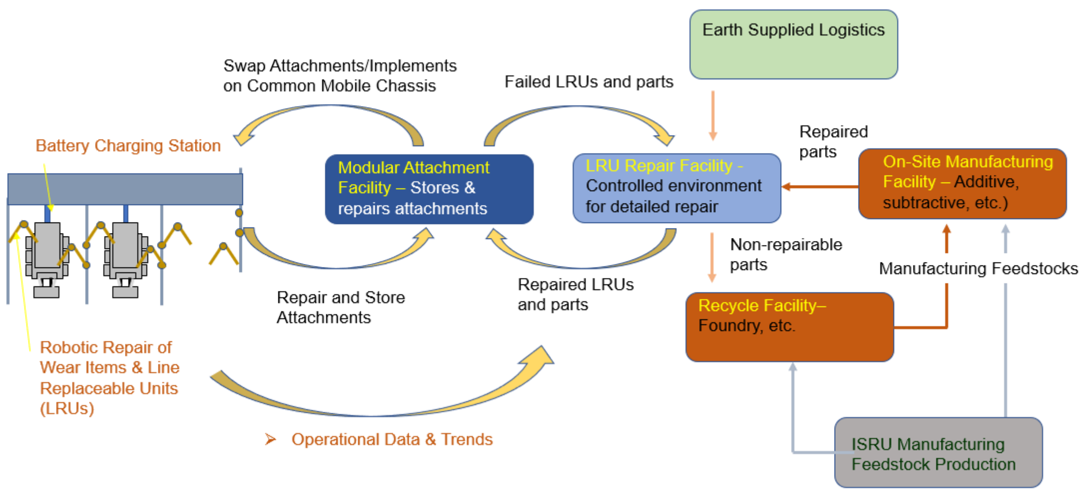

Figure 3. Two Step Maintenance & Repair Approach with Ties to Manufacturing

6. TLPG Test Support and Local Infrastructure Capabilities Needed

6.1 TLPG Test Support Capabilities Before Testing Begins

For tests to be run successfully at a TLPG location, a number of capabilities are required to support the test participants and test operations. The TLPG will need to provide hardware receiving, offloading, and private/secure locations for hardware assembly and checkout before the hardware elements can be tested. This may include the need for radioactive material safety storage and control. The TLPG should also provide repair locations and capabilities before and during test operations (if not part of the concept of operations), along with access to local stores and machine shop/additive manufacturing capabilities to minimize test schedule disruptions. Besides the hardware, the TLPG will need to provide on-site infrastructure for personnel, offices/meeting rooms, bathrooms, etc. To ensure smooth operations and provide support for small companies and university participants, it may be important for the TLPG to provide access to technicians and IT support personnel.

6.2 TLPG Test Operation Capabilities

To ensure safe operations as well as support and encourage responsible extraterrestrial extraction and processing techniques, the TLPG should provide environmental sensors and monitoring as part of test activities (in chambers and analog sites). To ensure correct operations and performance data, the TLPG should perform site 'pre-evaluation' before testing so that instruments and operation performance can be properly estimated. This may include the need to provide and/or operate regolith characterization instruments.

Once testing has been initiated, the TLPG will need to support around the clock operations for multiple days/weeks/months. These operations will need to include providing on-site control rooms and secure communication capabilities to support off-site real-time remote personnel involvement. The TLPG should also provide capabilities for public engagement (per agreements with participants) which could include on-site scheduled viewing times and locations and video/live streaming. If one of the responsibilities of the TLPG is to 'certify' the performance of the hardware elements tested at the TLPG, then data acquisition and performance data certification during and after testing may be required. This could include providing and/or operating instruments to verify and characterize products and wastes.

6.3 Local Capabilities Need for TLPG Activities

Large-scale and complex test operations may involve a large number of test assets and participants. From past experience with performing large analog test campaigns [1], it is important that there are capabilities within a 'reasonable' distance to support the delivery/removal or test hardware and the personnel involved in their operations. This includes assess to nearby airport and transportation capabilities for personnel and hardware shipping and delivery, as well as lodging/hotels and food/restaurants for the participants.

6.4 On-Site Safety

ISRU and surface construction operations can be very hazardous and can involve high voltages/currents, flammable/explosive materials and fluids, chemical/toxic reactants, radioactive sources, cryogenics and asphyxiants, etc. It is therefore critical that TLPG perform hazard identification and mitigation analyses before testing operations are allowed to proceed. Involvement during hardware development may be a service provided as well to customers of the TLPG. There will also need to be technician support and procedures for safety critical items and activities during testing, and access to both on-site medical and local hospitals in cases of injury and emergencies.

7. TLPG Oversight Management Attributes

Up to this point, the paper has primarily focused on what is at TLPG and what are the capabilities and attributes that TLPG will need to support testing of complex ISRU and surface construction hardware and systems within proscribed ConOps. However, just as critical as to WHAT a TLPG needs to do and provide, it is equally important to address HOW the TLPG will be managed and operated. As was previously discussed, due to the wide range of potential environments, ConOps, resources of interest, and levels of development, a Terrestrial Lunar Proving Ground will need to be a coordinated network of test capabilities/facilities that will enable the evaluation and/or validation of one or more lunar surface elements as part of a greater system, surface infrastructure, and mission concept of operations. Therefore, an overall management strategy and capability will need to be established to coordinate both the network of test capabilities as well as the participants and the ConOps that will be evaluated. The following section will expand upon the oversight management attributes needed to enable a TLPG to operate.

To begin with, the TLPG management must understand NASA/Artemis plans and on-going development of mission requirements, specifications, and capabilities associated with the Artemis campaign during the Foundational Exploration (FE) and Sustainable Lunar Evolution (SLE) segments. This includes expert knowledge on lunar locations and sites of interest, and the infrastructure expected during these segments and their evolution, esp. for power, communication, and position, navigation, and timing (PNT). This knowledge should also include international interests as well as commercial infrastructure capabilities not covered by NASA Artemis documents.

Because modularity, interoperability, and standardized interfaces will be critical for the implementation and evolution of commercial large-scale ISRU and surface construction operations, the TLPG management must understand, interact, and utilize existing consortiums and working groups that have been established to define standards, guidelines, interfaces, and engage communities of practice. Known consortiums that should be engaged include the Lunar Surface Innovation Consortium (LSIC), Consortium for Space Mobility and ISAM Capabilities (COSMIC), the Lunar Operating Guidelines for Infrastructure Consortium (LOGIC), and possibly the European Space Resources Innovation Centre (ESRIC).

A critical responsibility of the TLPG management will be to create the network of participating environmental, analog, and digital/virtual test capabilities and facilities, and update and expend these capabilities on a regular basis as needs grow and evolve over time. Partnerships and agreements will need to be established for operation, integration, and usage of these facilities on their own or in combinations to support test campaigns. This will involve providing and continuously updating documentation on facility capabilities (using the LSIC database as starting point), usage and safety rules and constraints, access specifications, costs, etc. It will also need to include establishing a secure communication network and protocols for remote operation and collaboration between facilities and remote users. When natural analog simulation sites are utilized, the TLPG management will need to perform permitting for analog site activities in advance of testing.

For the ISRU and surface construction analog field test campaigns performed during the Constellation Program, as documented in [1], NASA and the Canadian Space Agency (CSA) planned and managed the analog tests, identified and invited participants, and developed the ConOps that were evaluated. For the TLPG to be successful, the TLPG management will need to take on this responsibility and help match users/customers with the appropriate facility and/or test campaign. The authors of this paper have identified three possible user scenarios that the TLPG management will need to consider and address. One scenario is the individual user who wants to test their hardware in a relevant environment and supporting infrastructure. This type of user/test might include non-functional elements, mock-ups, and COTS hardware for interfaces if more realistic hardware is not available. The TLPG management should try to minimize the time between request and test for this user/test combination. The second scenario is a group of users have approached the TLPG management for testing. This scenario may involve a coordinated group of users/consortium that wants to test all of their hardware under realistic environments and/or ConOps with as much supporting infrastructure as possible, or potentially an uncoordinated group of users, that want to test their hardware and timing allows for multiple user involvement at the test location without planned interactions. The third scenario is the coordinated campaign, where the TLPG management invites users to be part of a large integrated test activity. This would most likely require the test campaign to be advertised in advance (TBD – 1 year) with specified involvement criteria and ConOps of interest. The third scenario might also include the TLPG working with a government agency or consortium to complete a particular ConOps of interest. In all cases, it will be critical for the TLPG management to help establish the ConOps, identify environment and test capabilities, and match these to facilities and test capabilities in the TLPG network. If the test capability doesn't exist and is critical for the test campaign to be successful, the TLPG management will need to advertise that need to grow the network.

It can be anticipated that multiple test activities may occur across the TLPG network. Therefore, the TLPG management will need to develop and advertise schedules and timelines for test campaigns/system-level tests on regular basis (unless the user/customer does not want to make the test public). Users/participants should be able to assess the TLPG network of facilities/capabilities on a regular basis, and potentially join planned tests if current participants agree and the new participant meets pre-defined acceptance criteria.

As stated in the previous section, the TLPG management and network partners will need to ensure that all operations are performed safely. This should include performing and/or reviewing hardware and operation safety reviews from the users before testing is allowed. Users must allow for insight into hardware designs to perform adequate safety reviews so there will need to be agreements for maintaining and protecting Intellectual Property (IP). Hazard analyses and assessments will also need to be performed on all the test assets and how they interact with each other. On-site safety will need to be involved before, during, and after all test operations. It should be noted that operations and procedures need to allow for hardware to fail (since part of the test activity may be to stress the hardware beyond normal operating conditions), but that failure will not cause hazards or damage other equipment.

In the *TLPG Test Capabilities and Attributes* section, the paper identifies that hardware tests and ConOps performed may be at different levels of test complexity/capability as a function of where the hardware and system are in the development/ certification cycle. The TLPG management will need to establish guidelines for involvement of multiple participants in system and campaign testing. With support and concurrence from NASA, they will need to define what is an 'acceptable' level of testing to be included in the Artemis FE and SLE segments. The TLPG management will also need to establish test inclusion and result expectations in advance for each test operation/campaign. For example, involvement in Dessert RATS analog field tests required significant testing and validation in advance, whereas involvement in the ISRU analog field test campaigns had much lower pre-deployment testing validation criteria. These expectations must be in line with the TRL and pedigree of hardware criteria for involvement. To ensure hardware integration and operation from multiple users and elements is successful, the TLPG management will establish 'Best Practices' documents and guidelines to all potential users and perform or review Test Readiness Reviews (TRRs) performed by the users before involvement in a test campaign/system-level test is allowed. The TLPG will need to perform an integrated TRR with all test participants as well before hardware shipment to the TLPG test location. Should international government agencies, industry, and/or organizations participate, the TLPG management will need to establish guidelines for their involvement including design information for safety reviews and IP management.

To be able to test large, complex, and multi-element ISRU and surface construction systems and perform viable mission ConOps, the TLPG management will need to either direct or support the connection of hardware/software from multiple organizations/ companies to create a complete end-to-end system. To do this, the TLPG management will work with NASA and the consortiums previously identified to establish and promote overarching requirements and common standards. They will than work with participants to establish appropriate tests and test procedures, while utilizing established test standards and guides to maximum extent possible. The standards, interfaces, and test procedures will need to include the ability to virtually link to other TLPG locations. In doing so, it may be advantageous to create modules/hardware that can be transferred/shared between multiple facilities/locations depending on test objectives.

With respect to interfaces between different system elements and hardware providers, the TLPG management will need to establish hardware/software interfaces based on the overall system-level test or mission concept. Working with NASA, the TLPG should encourage the use of the Modular Open System Approach (MOSA) and functional block diagrams to establish modules and interfaces to ensure hardware/software can be infused into a complete system with minimal issues. To minimize integration complexity/duration at the TLPG site, individual modules and interfaces should be pretested for functionality and performance before delivery and perform basic checkout testing after delivery. Any Ground Support Equipment (GSE) required for checkout and testing should be supplied by developer/test participant.

While it is expected that ISRU and surface construction operations will be performed autonomously or with remote human supervision/control, there may be operations that may require human involvement for safety and/or to fulfil test objectives (ex. repair). Under these circumstances, the TLPG management will need to establish guidelines for human and robotic interactions and interfaces.

A responsibility that was mentioned in several workshops was the desire to validate or certify test data and results so that they can be used in future solicitations or promote further investment. For this to be possible, the TLPG will need to establish test and performance data sharing and reporting guidelines and requirements, as well as ensure sensor calibration, and data management and collection capabilities are verified. They will also need to establish IP ownership and sharing rules on performance, operation information, and data with all parties involved in the test effort.

A major responsibility of the TLPG management will be the establishment of costs for services and operations across the TLPG network. This paper has identified a significant number of TLPG test capabilities, ConOps, and TLPG management attributes and responsibilities, but it is beyond the scope of the authors to address the possible costs that might be assigned to each of these items (see *Open Issues* section)

8. Past Experience and Lessons-Learned from Past Analog Field Test Activities

When lunar ISRU and surface construction development began before the official start of NASA's Constellation Program, the technologies that had been developed were sub-scale, proof-of-concept hardware operated and tested under laboratory conditions. Because of this, insertion of ISRU and surface construction capabilities into the NASA Constellation program lunar architecture was limited and considered a high risk until proven. It was recognized early by NASA ISRU development managers that these capabilities needed to be scaled up, tested in integrated system configurations, and must leave the laboratory to examine how these systems would be operate on the lunar surface (i.e. concepts of operation – ConOps). With extra funding provided by NASA and other government agency participants for testing, the ISRU project within NASA began to initiate a series of analog field test activities [1]. Before starting these test activities, NASA established overarching goals and objectives for the complete surface architecture (i.e. lunar mining cycle), integrated modular architecture and fluid/power connections and interfaces (Figure 4), and identification of the development/operation challenges that needed to be addressed. Then each analog field test performed was aimed at increasing the fidelity of the hardware, the breadth of the mining cycle, and the completeness of the integrated modular system architecture, all of which were tied to the development/operation challenges. This approach allowed technologies and systems to mature on a regular cadence and test results and lessons-learned to be able to influence subsequent hardware development and test activities. Figure 5 depicts the operations performed at the 2008 and 2010 ISLO/ISRU Analog Field Test campaigns and the extent of advancement achieved over the two years between test campaigns.

Besides achieving technology advancements, the ISRU Analog Field Test campaigns achieved a number of other important benefits and advancements.

Advancement of Partnerships and Collaborations. The test campaigns allowed for involvement of other government agencies, universities, and industry, with the list of participants growing with the expanded scope and breadth of technologies, systems, and ConOps evaluated. In many cases collaborations between government agencies and other participants as well as participant-to-participant collaborations occurred to ensure integrated operations and interfaces were achieved. The field tests also allowed for a NASA and CSA partnership to be created with International Traffic in Arms Regulation (ITAR) compliant technical interchanges and increased trust under non-flight conditions and pressures. This can be seen in both the increased scope of operations as well as the increased criticality of each partner in the success of the other partners objectives and the joint-integrated system operation (see government agency logos in Figure 5.)

Advancement of Personnel. Many of the participants involved in designing, building, and testing the hardware associated with the field tests were early in their career and had never been part of a flight mission. To advance their experience and careers, the analog field test campaigns were treated as a 'flight' program. Each major hardware element associated with the planned field test would follow the NASA system engineering and flight approach of performing a Mission Concept Review (MCR), Preliminary Design Review (PDR), Critical Design Review (CDR), Test Readiness Review (TRR), and deployment/Flight Delivery Review (FDR). The field test itself was treated as a 'mission' operation to the greatest extent possible based on the fidelity of the hardware and operations achieved.

Increased Stakeholder Understanding/Public Engagement. As mentioned, at the start of the NASA Constellation program, ISRU technologies were subscale and had never been integrated into a complete system or left the laboratory environment. Stakeholders and key mission and technology development decision-makers were invited to attend the field tests and see firsthand the hardware and operations being performed. This provided greater understanding of what ISRU systems would consist of, how they would be operated, and the advancements being made with each test campaign. The press was also invited to witness the field test activities, and public engagement activities were held during and after the field tests were completed.

It should be noted that many of the TLPG test and management attributes defined in this paper are based on the experience and lessons-learned in performing this series of analog field test campaigns. A significant lesson-learned not discussed so far in detail was the planning and logistics involved in shipping the hardware to the analog sites, supporting the travel of over 100 personnel, the delivery, integration, and checkout of all the hardware to the analog site, and the on-site and remote operations to manage and perform the test operations. After the testing was complete, the extensive disassembly, packing, and shipping of the hardware back to the participants locations, and the remediation of the site back to near its original state. All of this was performed in 2 to 3 weeks. From this experience, the TLPG should attempt to minimize the time and effort associated with all of these tasks while allowing for greater duration tests to be achieved with increased remote operation capability to minimize personnel travel.

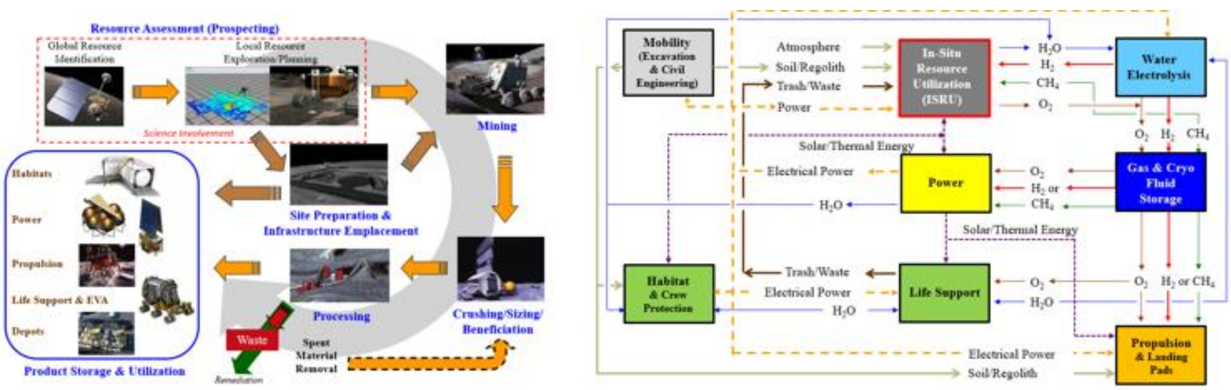

Figure 4. Space Mining Cycle (Left) and Integrated ISRU Modular Architecture (Right)

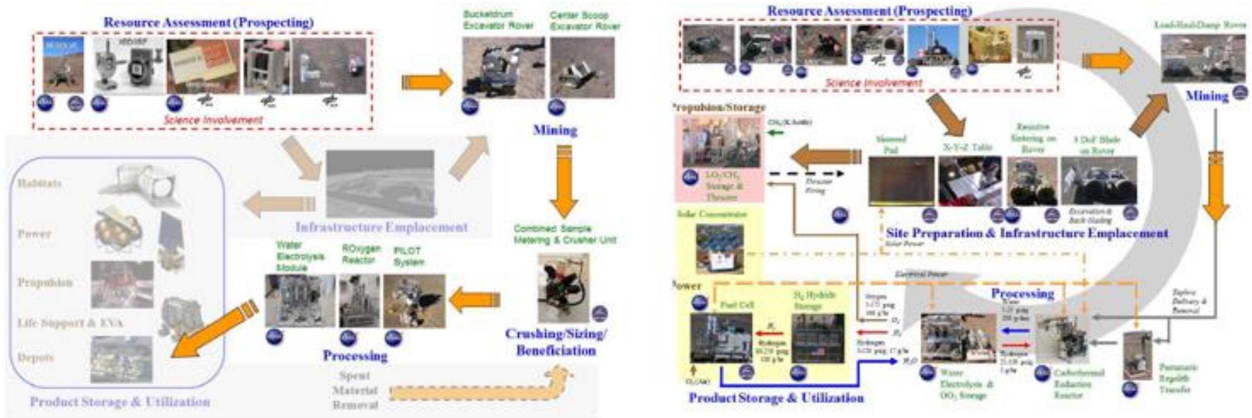

Figure 5. Scope of 2008 ISRU Analog Field Test (Left) and Scope of 2020 ISRU Analog Field Test (Right)

9. Why Begin to Establish a TLPG Now?

Incorporating any new technology or system into a human exploration mission or architecture requires development well in advance of the mission to eliminate technology, cost, and schedule risk concerns. ISRU is a critical capability for a sustainable future on the Moon as outlined in US government and NASA policies. While the current plan is to only demonstrate ISRU and surface construction capabilities in the Artemis campaign Foundational Exploration (FE) segment, it is important to understand and prepare for the evolution of these demonstrated capabilities into the large-scale, complex, and integrated systems discussed in the *ISRU & Surface Construction Concepts of Operation (ConOps) for TLPG section* of this paper and Ref/ 8. To date, several critical ISRU and surface construction technologies are approaching and achieving TRL 4 “component and/or breadboard validation in laboratory environment”, so guidance and the test capabilities to advance to TRL 5 and 6 (integration into systems and testing under relevant environments) is required to ensure smooth development and infusion. The first major projected mission for ISRU on the lunar surface is a ‘Pilot Plant’ in the mid 2030’s (depending on government funding and public-private partnership investments). The purpose of the Pilot Plant will be to demonstrate the end-to-end ISRU system and mission ConOps at a scale and duration that will eliminate the risk of scaling up to an initial full scale commercial operation during the Sustainable Lunar Evolution (SLE) segment of the Artemis program. To achieve these ISRU mission and capability objectives will require significant ground testing of integrate systems under lunar environmental conditions and evaluation and validation of mission ConOps in relevant terrains/materials with representee supporting infrastructure. While the objectives and capabilities associated with am ISRU Pilot Plant and initial commercial operation do not require all the test capabilities and management responsibilities addressed in this paper for a TLPG, they provide the basis and incentive to begin to establish an initial TLPG framework, organization, and test facility network.

10. TLPG Benefits

As in the case of performing a combination of environmental chamber and analog field mission ConOps tests during the NASA Constellation Program, establishing and utilizing a TLPG will provide several important benefits to the advancement of ISRU and surface construction capabilities and their future commercialization. A very visible benefit is validation that ISRU and construction system(s) are feasible and ready for flight development and lunar operations. The TLPG tests will help close NASA STMD shortfalls and gaps and help align multiple infrastructure related disciplines and elements. TLPG activities also visibly demonstrate advances in progress toward sustained human lunar missions and commercial operations. This will allow for increases in performance/capabilities of human lunar mission architectures, help advance modularity, scalability, and repair/maintainability attributes, and reduce the risk for flight hardware and operations. The TLPG will also promote and enable widespread involvement and partnerships. especially with international partners, in both a collaborative and competitive manner. The activities associated with a TLPG will also provide opportunities for sustained and evolving engagement with stakeholders, investors, and the public with visible accomplishments.

11. Approaches for Establishing TLPG

In the workshops and forums that have openly discussed the concept of a TLPG, no single approach to who and how the TLPG can be established was agreed upon. The overall consensus was that NASA needs to lead the definition and initial steps to initiating the TLPG along with the implementation plan for transition to industry/consortium management. While the anchor Business Plan will need to be tied to the Artemis campaign and Agency-level space commercialization plans, it also needs to accommodate non-governmental space commercial development as well. It has been suggested that utilizing an existing consortium(s) such as LSIC and ESRIC might facilitate and ease establishment of a TLPG since this could be considered a logical extension of their current responsibilities. If this is not acceptable or possible, then an alternative approach is to develop a new consortium. A third option is that the TLPG could be university, non-profit, and/or Federally Funded Research and Development Center (FFRDC)-led. It is expected that NASA/government agencies would fund some management and usage costs for any of these options and possible serve as an anchor tenant. Lastly, the TLPG could be NASA-led with International Agreements (similar to Desert RATS and the International ISRU Analog Field Tests) for international agency and company involvement. Usage could be proposal based with objectives, timing, and selections based on NASA/government agency priorities, development/mission timelines, and budgets.

No matter how the TLPG is formed and managed, it is expected that there would be a significant number of partners and collaborators. The list below should not be considered complete, but is a representation of the scope and breadth of potential involvement:

- Space/Government Agencies: NASA, ESA, DLR, LSA, KIGAM, KICT, …
- Other US Government Agencies: DOD, DARPA, DOE, …
- Space Resource Consortiums: JHU APL LSIC, ESRIC, …
- Lunar Exploration and Analysis Group (LEAG)
- Solar System Exploration Research Virtual Institute (SSERVI)
- Surface Infrastructure/Disciplines: Comm & Nav., Power, Thermal, Cryogenic Fluid Management, Autonomous Rendezvous & Docking/Satellite Servicing, Avionics/Control, Autonomy & Robotics, …
- Facilities: Government, Industry, and Academia analog sites and environmental test facilities.
- Simulant advisory groups: NASA, APL, SSERVI, UKSA, …
- Simulant providers: Off Planet Research, CSM, Exolith Lab/UCF, …
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12. Open Issues

While the authors of this paper attempted to be as comprehensive as possible in defining what a TLPG is, what it would support, and how it would be managed and established, there are still several issues that remain open and will require further consideration and resolution. The list below is just some of the items the authors recognized but were not able to address.

- *Insurance and liabilit*y. Who is responsible for damage and how will financial compensation be obtained
- *Media and Public Outreach*. Who is responsible, what level of involvement and information sharing is allowed.
- *Facility maintenance and improvement costs*: Who is responsible – TLPG management, network partners, service costs, …
- *Intellectual Property and Digital Twins*. How can digital twins from multiple elements owned by different participants be linked without transfer of intellectual property
- *Facilities not officially part of 'network'*. There may be cases where TLPG users want to link their facilities to on-going tests, or a campaign requires test capabilities not currently provided by the TLPG network.
- *How fast from request to testing*? An issue with all test facilities is how fast can a test be schedule in a facility. When organizing the ISRU Analog Field Test Campaigns, a significant amount of time was spent planning and organizing the campaigns with a 1 ½ to 2-year gap between test campaigns.
- *Geological and terrain variability at the site*. Is it useful/needed or are different sites allocated for each material required? For resource exploration tests, how much foreknowledge of the site is allowed?
- *How large of a test site footprint and site disturbance is allowed?* Do we return site to original state or leave results and construction efforts for next users? For the analog field site location on Mauna Kea for the ISRU Analog Field Test campaigns, the site had to be returned to its original state to the greatest extent possible (other than removing invasive plants)
- *Costs for TLPG*. It is expected that to achieve the full scope and breadth of the TLPG presented in this paper, that there will be significant costs associated with 1. Management, 2. Facility usage, 3. Facility upgrades/increased capabilities. How funding to cover these costs is obtained is left as an exercise to those that will lead the establishment of the TLPG network.

13. Conclusion

Based on discussions and workshops on the subject of system level testing for ISRU and surface construction, and the desire to have location(s) that foster partnerships/collaborations and integration and testing of hardware elements from multiple entities (governments, industry, academia), the authors believe that establishing a Terrestrial Lunar Proving Ground (TLPG) would be extremely beneficial to advancing these capabilities for sustained lunar human exploration and the commercialization of space activities. The timing to begin the establishment of the TLPG and network is now since ISRU and surface construction systems and capabilities under development the last several years are maturing to the point where integrated tests and examination of different concepts of operation (ConOps) will be needed soon. There is also growing interest in these communities for expanding the community of practice and interactions currently being provided by organizations such as the Lunar Surface Innovation Consortium (LSIC) and the European Space Resource Innovation Centre (ESRIC), as well as the yearly participants at the Space Resources Roundtable (SRR) and the Luxembourg Space Resources Week conferences. The NASA STMD and other government agencies are aiming more and more of their work and effort toward enabling ISRU and surface construction activities to be industry-led with increasing private investment to offset and enhance government budgets and investments. An established TLPG and network would significantly help achieve these objectives.

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