Reflections on the Lunar Proving Ground Workshop

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This essay presents an independent assessment of the Lunar Proving Ground (LPG) Workshop hosted by the Lunar Surface Innovation Consortium at the Johns Hopkins University Advanced Physics Lab (JHU-APL) in August, 2023. It reviews the various needs and desires that the participants presented. It concludes that the majority of these researchers expressed a need and a desire for real lunar dust and regolith to pursue their experiments. Therefore, the LPG needs to include a large "dirty" thermo-vacuum chamber in which to conduct tests with real lunar dust and regolith.

FIGURE 1. Existing Dusty Thermal Vacuum Chamber at Michigan Technological University's Planetary Surface Technology Development Lab. Credit: Paul Van Susante.

Key Words: lunar regolith, lunar dust, thermal-vacuum chamber, centralized, decentralized, network of facilities, consortium, virtual institute, nanophase iron inclusions, glass shards

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Nomenclature

Artemis	NASA's program to return to the Moon
DTRV	Dump Truck Retrieval Vehicle
DTVAC	"Dirty" Thermal Vacuum Chamber
EPSCoR	Established Program to Stimulate Competitive Research
GCR	Galactic Cosmic Ray
HEPA	High-efficiency particulate arrestance
HQ	Headquarters
IP	Intellectual Property
ISRU	In-situ resource utilization
JSC	NASA's Johnson Space Center
LPG	Lunar Proving Ground
LSIC	Lunar Surface Innovations Consortium
LuDuRR	Lunar Dust and Regolith Retrieval mission
MSFC	NASA's Marshall Space Flight Center
MTU	Michigan Technological University
NASA	National Aeronautics and Space Administration
PSTDL	Planetary Surface Technology Development Laboratory
PSR	Permanently Shadowed Region
RCN	Research Coordination Network
SEP	Solar Energetic Particle
SME	Subject Matter Expert
SPE	Solar Particle Event
Thermo-vac	Thermal Vacuum Chamber
TRL	Technology Readiness Level (from NASA)

I. Introduction

THE Lunar Proving Ground (LPG) Workshop addressed the need to test equipment and hardware under lunar-like conditions on Earth before deploying it to the Moon. The Workshop's script asked broad questions of the participants, such as:

What is an LPG?

What are the LPG's capabilities?

Is it centrally located or decentralized to several locations?

Is it located on the Earth or on the Moon or both?

This essay conveys observations, perceptions, and thoughts about these questions and more. A recurrent theme concerns what efforts it will take to design, build, and operate the LPG. This essay also connects the LPG to the technology development process.

A. The Workshop

This essay presents a "minority report" of the LPG proceedings by two attendees. The Lunar Proving Ground Workshop was successful insofar as it was very well organized and ran smoothly. However, the proof of true success will be whether the Workshop leaders can put together a coherent story explaining it. They must also explain why an LPG will be essential to enable future lunar exploration and development.

B. Context

The context encompasses the hundreds of specialized testing facilities available throughout the science and space communities. Many of these facilities might be suitable for testing various aspects of spaceflight and lunar surface hardware plus their digital accoutrements and counterparts. However, for some (large-scale) lunar surface testing needs, the necessary facilities do not yet exist. The question stands on whether to build such bespoke facilities as part of one or more LPGs or an LPG consortium. Or, shall we leave them to the technology developers to build what they need for individual projects? Given that these ambiguities will persist for years into the Artemis program, it becomes even more important to "put stakes in the ground" for a testing facility or facilities.

II. Data, Data, Everywhere

The Workshop collected a large amount of "data" in the form of sticky notes with comments written on them. The LSIC has also been collecting information about existing test facilities to share with the community that may be relevant or useful to a LPG, very broadly characterized.

A. Sticky Notes as Intelligence

These contents consist predominantly of the participants' conjectures, opinions, and speculations. So, the idea of proceeding via guesswork by subject matter experts (SMEs) may not appear promising as a starting place. However, these comments can prove valuable at framing many of the important questions — What is the LPG? Where should it be built? Should it be a consortium? Who would lead and fund an LPG? — that emerged in the workshop. Answering these questions should help articulate the arguments for the LPG. The answers can shape the reasoning that drives it.

B. Directory of Test Facilities

A parallel effort at data collection consists of compiling a directory of relevant test facilities throughout the USA and perhaps eventually the World. While this effort deserves commendation, it elides the fact that the people in each discipline already know where their preferred test facilities are located. For instance, the people in radiation research know where all the particle accelerators are and their capabilities (e.g. Brookhaven, Fermi Lab, Loma Linda, MSFC, Kibo Japan, etc.). Like-wise with wind tunnels, flight simulators, and habitat analogs, etc. It could provide a directory for government and private funding. Although this directory may not be useful for people in a field of research to find the facilities they already know, it can be beneficial for a more general readership. This audience includes the plethora of commercial "NewSpace" companies. It can help them to appreciate the scope and breadth as well as availability of existing facilities. The directory may also help persuade NASA and Congress that LSIC has done its homework for LPG. It will help explain why none of the existing test facilities offer sufficient capability or capacity for the necessary large-scale lunar environment testing.

III. Real Lunar Dust and Real Regolith

The most frequently mentioned test facility that most researchers want in an LPG is a "dirty thermal-vacuum chamber." The key term is "dirty," which means that lunar regolith simulant is present in the thermal vacuum chamber to simulate the lunar surface conditions. The lunar simulants currently available on Earth are good for certain types of testing such as geotechnical, abrasiveness, and construction testing. However, certain characteristics of actual lunar regolith are poorly simulated such as the presence of agglutinates, or the nanophase iron inclusions, and the impact glass shards. Real lunar dust may be the most widely and frequently cited need because of its damaging effects on equipment and its harmful effects on human health. The nanophase iron particles and glass shards cause many of the problematic properties of lunar dust. So far, nobody has figured out how to synthesize nanophase iron particles or impact glass shards at a meaningful scale for lunar simulant. The Moon is the only place to collect them in sufficiently large quantities.

A. Nanophase Iron Particles – The problematic behaviors of dust particles that are affected by presence of nanophase iron include:

1. *Static cling (to space suits and vehicles),*
2. *Static charging, and*
3. *Dust Lofting comprises three basic phenomena* (Orger et al, 2018; Stubbs, Vondrak, Farrell, 2006)[3,6]:
   a. When an astronaut or vehicle passes nearby, dust can loft from 1s to 10s of meters.
   b. When the solar day/night terminator passes, dust can loft 100s of meters (or more).
   c. When the Earth's magneto-tail passes, dust can loft 1000s of meters.
4. *Microwave and electromagnetic susceptibility*

B. Impact Glass Shards

The problematic behaviors of sub-micron size impact glass shards include abrasion, erosion of surface materials, and health effects, especially respiratory and skin irritation and inflammation. The glass shards add traction to the static cling as the sharp edges of the glass can cut into aluminum, fabrics, plastic, “rubber,” and other softer material. The glass shards, or agglutinates, are also very frangible, which means they easily break into smaller particles.

C. Static Charging

Static charging presents a threat to safe and reliable operations on the lunar surface. Static charging from the lunar dust can lead to electrical arcing in a spacesuit or a vehicle. Arcing between unlike materials with different electrical potentials could short-out or damage electrical and data systems. Also, it could possibly trigger ignition and fire in an internal oxygen-rich atmosphere. Learning how to handle safely the electrostatically clinging dust, the effect of variable mineral compositions, presence or lack of nano-phase iron, plus potential arcing and lofting will emerge as a key envisioned use of the “dirty” thermal-vacuum chambers.

D. Lunar Sample Laboratory Facility at JSC

Nearly all the regolith and lunar dust (380 kg) that was returned to Earth from the lunar surface during the Apollo missions resides in the extraterrestrial materials lab at JSC (Office of the Chief Engineer, 2021).[2] These materials are available for external research only in very small quantities. These meager samples are insufficient to supply a large scale thermal-vacuum chamber testing program that requires many thousands of kilograms. NASA is reluctant to release regolith for technology testing— especially destructive testing — rather than for science.

E. Regolith Processing

In other technology domains such as sintering regolith, researchers have shown success at forming bricks or pavers from lunar simulant (e.g. Workshop participant Sam Ximenes and Astroport). Do we know how real regolith will behave under the sintering process? Will the nanophase iron inclusions or glass shards interfere in some way?

IV. Earth-Based LPG versus Moon-Based LPG

At the LPG Workshop, a subset of participants advocated most vocally for an LPG on the Moon. My perception was that they argued this position because the only place to collect enough regolith or dust is on the Moon. They despaired of finding enough lunar material on Earth to conduct meaningful testing.

A. Earth-Based LPG

An Earth-based LPG could offer the most critical tests for dust and temperature extremes. It would be attractive to system developers, especially if it offered a menu of testing services or packages. The purpose of the Earth-Based LPG is to reduce as much engineering and operational risk as possible of the full-size systems and systems of systems for relatively low costs. This approach allows for quick iterations and failing early and often to get to the best performing system quicker.

B. Earth-First LPG

A Moon-based LPG could offer, in principle, all possible tests under lunar conditions. This option becomes available after answering two questions:

1. *Earth first? Would it be preferable or necessary to conduct system testing in an Earth-based LPG first, before taking the system test to a Moon-based LPG?*
2. *Can the Earth-based LPG become sufficiently comprehensive to defeat the arguments for a separate and tremendously expensive lunar surface LPG?*

To address *Question 1*: From one point of view, it may be difficult to envision a program that enables lunar surface testing before Earth-based testing. On the other technology flow path, it might be faster to go directly to the Moon without stopping along the way to perform duplicative testing. Cost and time will emerge as crucial variables in making these decisions, regardless of the actual capabilities.

To address *Question 2*: If an Earth-based LPG can be designed to offer a sufficiently comprehensive testing capability, might it obviate the need to build a lunar surface LPG? One could argue that the expenses saved would make affordable the Dump Truck Mission that supplies the magic sauce — Lunar Regolith — for the Earth-based LPG.

V. The Dump Truck Mission

The central problem for Earth-based lunar materials research is the unavailability of real lunar regolith and dust in sufficient available quantities. We face two options:

A. Bring the lunar materials to Earth in sufficient quantity to use at a bespoke LPG

This preference would be to bring a sufficient quantity of lunar material back to Earth for destructive and non-destructive testing in LPG facilities. Without making any judgement about location, centralization, or decentralization, availability on the Earth would pose a huge economic advantage over an LPG on the Moon. The economics dictate that it will be much less expensive to deliver a few tons of lunar regolith and dust to a LPG on Earth than to bring all the technology development experiments, facilities, and testing to a human-staffed LPG on the Moon.

While an Earth-based LPG could not recreate or simulate all the lunar dust effects encountered on the Moon, it may be able to reproduce the priority effects that are critical for lunar hardware system testing. These reproducible effects would include: impact glass shard adhesion and abrasion plus nanophase iron effects, static charging, and perhaps dust lofting up to about 10 meters.

Therefore, one part of the LPG could include a mission to the Moon to retrieve a large quantity of regolith and dust to be kept under vacuum conditions at all times to maintain any specific lunar properties related to the regolith forming in absence of an atmosphere. This *Dump Truck Mission* would send a robotic spacecraft with an excavator and a "Dump Truck Return Vehicle" that of course acquires the instant acronym *DTRV*.

B. Bring the entire LPG testing facility on the Moon.

At the LPG Workshop, there was a sizable contingent of engineers and scientists who were interested primarily — if not exclusively — in building the LPG on the lunar surface. They were frustrated by the limits of simulation and done with artificial simulants. They wanted the true partial gravity effects. And real lunar regolith and dust. These advocates argued that going straight to the Moon to build the LPG was more realistic than bringing lunar materials back to Earth. They argued that it would at best be a "crater half-empty" to experiment with lunar dust without the 1/6-g. This partial-g allows the dust to loft so easily hundreds of meters high.. They were also concerned about the law that dictates that JSC is the custodian of all asteroidal, lunar ,and planetary returned samples, at least if they are acquired with federal funding.

VI. The Technology Readiness Level (TRL) Perspective

The Workshop was blissfully free of NASA Technology Readiness Level (TRL) jargon. Yet now, it may *prove* more valuable to start from an examination of the technology development process itself and what it implies for developing highly specialized facilities for an LPG. Now would be an appropriate window to introduce the TRLs as a way to demonstrate various technology development paths.. One relevant resource for dust exposure testing is NASA STD-1008 (Office of the Chief Engineer, 2021).[2] TABLE 1 shows the key decision points to choose among the LPG testing options. They are presented here as separate elements to show that each of these major decisions and accomplishments must stand on its own, in addition to representing a milestone in a larger process.

The following sections refer to FIGURE 2.

A. TRL-5 Subsystem Test in a Relevant Environment

Testing in a dirty thermo-vac would be useful for components and subsystems and small Commercial Lunar Payload Systems (CLPS) size full systems. Because of the limited size of most thermo-vac chambers, it would be helpful to be able to test smaller portions of any system headed to the Moon. That would help leave the larger chambers free to test larger items.

B. TRL-6 System Test in a Relevant Environment

Let us assume that a technologist has successfully developed a lunar system to TRL-6*, System Test in a Relevant Environment*. The underpinning of this "relevant environment" is that it provides one or more pertinent aspects of the space environment.

This TRL rubric means that all components and subsystems have been tested to at least TRL-5, *Component or Subsystem Test in a Relevant Environment*, and have been integrated into the larger system for TRL-6 testing. If one component has only passed TRL-4, *Benchtop or Breadboard Test in a Laboratory Environment*, then the entire system is still only TRL-4, not TRL-6. That said, what comes next after an *Integrated System* successfully completes conventional, *non-lunar* TRL-6 testing?

But does it complete TRL-6 without actual lunar dust in the mix? How can it? The existing lunar simulants are formulated primarily to provide a semi-realistic material for geotechnical and construction purposes as well as other ISRU processes like to extract oxygen. It lacks the crucial nanophase iron particles and impact glass shards that will be critical for some TRL-6 system tests.

TABLE 1. Lunar Proving Ground Testing Decision Tree Elements

TRL-6 (A) System Test in a *Relevant* Environment

LPG Testing Decision

No LPG Test

1. No LPG testing. Conventional TRL-6(A). Go directly to space.

LPG Test on Earth

2. Test in a LPG on Earth

LPG Test on Moon

3. Test in a LPG on the Moon. This option comes with a secondary decision point:

    a. To test in an LPG on the Earth first and then do supplementary testing in an LPG on the Moon, or

    b. Go directly to the Moon to test the system, bypassing lunar-specific test capabilities on Earth.

TRL-6 (B) Earth-LPG System Test in *Special Lunar Sim. Environment*

LPG TRL-7 (C) System Test *On the Moon*

C. TRL-7 Space Test in Operational Environment

In traditional TRL advancement, once a system cleared TRL-6, it became de facto cleared as a space system. It could be launched, thereby beginning TRL-7, *Operated in a Space Environment* or *Spaceflight Demonstration*. Deep space probes — that are one of a kind — might spend their entire career at TRL-7. For spaceflight hardware that becomes part of a series of launch successes, it may achieve TRL-8, *Spaceflight Qualified* without any further actual "testing.'

VII. Testing Decisions

FIGURE 2 presents the "front end" of the LGP decisions flow chart. It is enlarged to make the key initial boxes readable.

A. Test Decision Logic Flow Chart

FIGURE 2 Presents an initial concept for how the research might proceed through the process of deciding where (and how) to test new technology systems. This chart assumes that the technology system will have completed a conventional TRL-6 and be ready for exposure to the Lunar Environment. The LPG test facility can create a resemblance to the space environment EXCEPT for the peculiar conditions of the lunar surface. The LPG on Earth provides these peculiar conditions of dust, regolith, and thermal extremes to enable a *comprehensive completion* of TRL-6. The paradox is that some TRL-6 tests can be conducted only on the Moon, implying a de facto, paradoxical TRL-7 arrangement on the Moon.

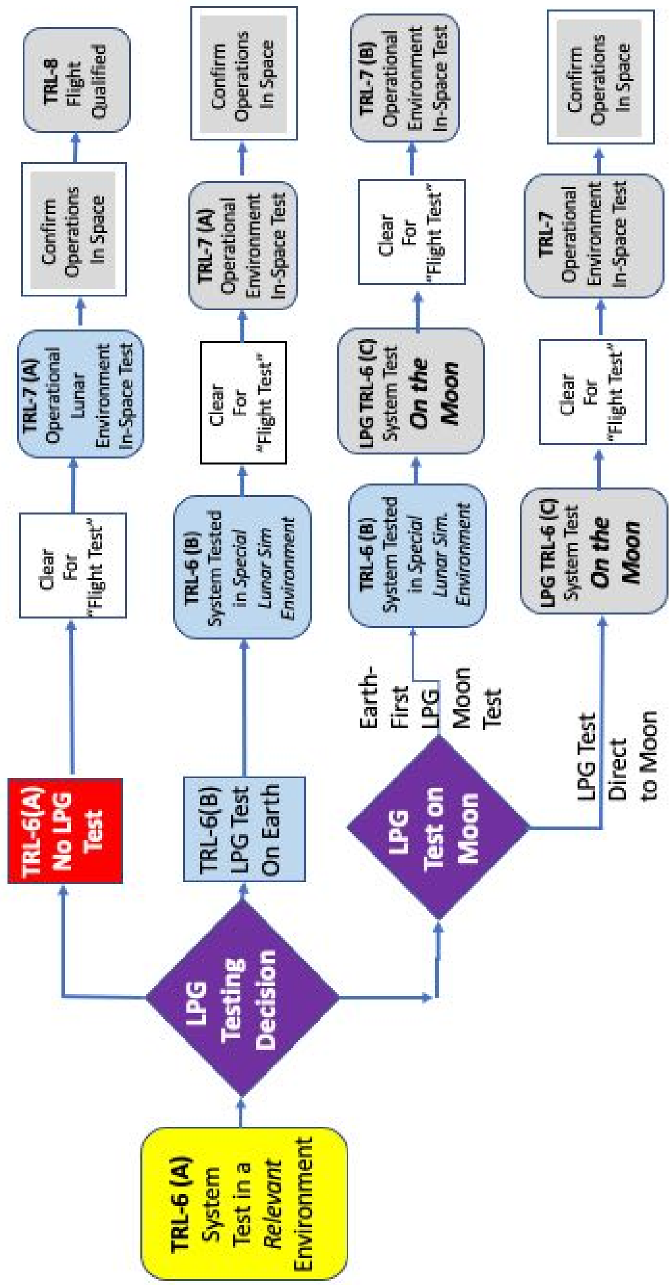

FIG. 2 Logic flow chart for the LPG Earth, Moon, and No LPG Test options.

B. Flow Chart Decisions

The flow chart decisions should be based on the relevant properties affecting the test and thus how good the fidelity of the earth based DTVAC testing is. The relevant environment may be 95% good, except for the agglutinates., The question is how much risk remains and if can the mission be designed to handle the expected differences? Is it mission-critical to know and test the behavior including agglutinates and nano-phase iron or not? Not all systems will require those particular properties in order to be successful.

VIII. Lunar Environment Effects We Cannot Reproduce on Earth

An Earth-based LPG will never truly replicate all environments in which scientists or technologists may want to test instruments or systems. Here are some further considerations about the lunar environment for environmental effects for which it will be necessary to go to the Moon. So, eventually, a unique need for an LPG on the Moon may arise. Examples of these environments and phenomena include:

A. Partial Gravity

The Moon has 1/6-g gravity. One of the panelists at the Workshop mentioned 1/6-g parabolic flights, but in the "open discussions,", no one spoke about it. It is possible to simulate lunar gravity to a limited extent in a neutral buoyancy test facility and in a parabolic flight aircraft. It may be possible to create a sub-scale experiment using a small "dirty" thermo-vac on a parabolic flight aircraft to replicate lunar dust effects under partial-g. This experiment could attempt to replicate dust electrostatic cling and lofting on a very small-scale during seconds of 1/6-g, among other effects. *Real lunar dust would be required to conduct these experiments.* For most of the systems testing, parabolic flights do not provide reduced gravity for sufficiently long timescales, nor can they accommodate testing full scale systems that will be needed in the future.

3 4. One of the two regolith boxes with a lunar rover prototype being loaded in the Dusty Thermal Vacuum Chamber at MTU-PSTDL. Credit: Paul van Susante.

B. High Dust Lofting

Although an Earth-LPG may accommodate lofting from the passage of space-suited astronauts and lunar roving vehicles up to about 10 m, it cannot replicate lofting to hundreds or thousands of meters.

C. Solar Wind

The solar wind consists of a steady stream of particles that over the eons have deposited hydrogen-bearing molecules in the permanently shadowed regions (PSRs). According to Alan Binder, the PI for the Lunar Prospector mission, over 2 to 3 billion years, the solar wind has deposited up to 2 meters of hydrogen-rich material in the PSR craters.[7]

D. Ambient Radiation

Although it is possible to replicate a single particle stream in an accelerator at one time, and by replicating a variety of particles in a piece-wise fashion, it is not possible to reproduce the full particle flux of the violent solar particle events (SPEs) and their solar energetic particles (SEPs). Ambient radiation includes thermal neutron radiating from the regolith.

F. Galactic Cosmic Rays

Likewise, although it is possible to replicate single particles from the Galactic Cosmic Rays (GCRs), and replicate a variety in piecewise fashion, it is not possible to reproduce the full spectrum in the lab. That is available only in deep space, i.e., on the Moon.

G. Micrometeoroid Flux

Micrometeoroids burn up in the Earth's atmosphere as meteors and land as micrometeorites. To emplace an instrument that monitors and measures the flux over a wide field the testing facility must be emplaced on the Moon.

IX. The "Dirty" Chamber

At the workshop, a number of people bandied about the term "dirty chamber" as if making one would be a piece of cake — lunar dust cake. In fact, designing and operating a thermo-vac with dust or regolith in it poses big challenges.

FIGURE 1 on the first page shows the custom designed and built DTVAC at Michigan Technological University (MTU). The dimensions inside the thermal shroud are 127x127x178 cm. It can be cooled with liquid nitrogen (LN_2) and heated using electric heaters for a thermal shroud temperature range of -196°C and 150°C. The MTU lab team achieved 10E-7 Torr of vacuum level with (icy) lunar simulant in the DTVAC.

FIGURE 3 shows a robotic vehicle on a bed of regolith simulant in as box being slid into the DTVAC chamber. The MTU DTVAC experiments show that it is not necessary to use real lunar regolith for the testing to be useful. Many aspects related to traction, excavation, wear, operations, sensing, etc. can be tested just fine with lunar simulant even though it is not perfect (Van Sustante, 2022; 2023; Van Sustante, Alger, 2019).[8,9,10].

Even if you bring lunar regolith back from the Moon for testing on Earth, it would have to be maintained under vacuum conditions at all times to not lose some of the electrostatic properties. This constraint includes transport vessels and contact with any conductive surfaces. An additional challenge with regolith (simulant) is that after a certain time of use the particles change (agglutinates are very frangible and would break etc.) and result in rounded particles no longer representative of the fresh lunar material. Mechanical interaction testing changes the regolith and simulant over time. Any simulant or regolith would have a finite lifetime of being a good representative material. The type of tests that can and need to be performed are related to the properties that the simulant/regolith needs to represent properly. FIGURE 5 shows a schematic plan drawing of a prototype "Dirty" Thermal Vacuum Chamber Test Facility.

A. Clean Room / Dirty Chamber

A unique feature of a terrestrial LPG where the returned lunar regolith will reside, will be a thermal vacuum chamber that is integrated into a complex of clean rooms. It would not be sufficient to place the thermo-vac in a single clean room. The big vacuum pump or pumps will need to be in a clean room, too. In addition, both of these clean rooms need clean ante rooms to help protect them from outside contamination and to help them contain errant dust particles. Ante rooms that step-up protection to higher classes of clean rooms are well established in the industry.

B. Clean Room Metrics and Standards

Lunar dust is composed of diverse particles of varying sizes. For example, impact glass shards commonly run in the neighborhood of 0.3 μm. Clean room standards address the minimum (as in smallest) size that will be permitted to pass through the filtration system. So, to reliably "arrest" these glass shards, a minimum filtration of ≥ 0.2 μm might be appropriate. Under Clean Room Standard ISO 4 (for a Class 100 facility), that filtration would incorporate 240 to 360 air changes per hour (ISO Standard 14644-4:2022en).[1] Filtration at that level would allow only 2,370 maximum particles/m^3. So, this design problem and the operations that follow are far from trivial.

C. Chamber Operations

Operating a thermo-vac suffused with lunar dust will be a complicated and challenging job. It involves continuous pumpdown during operations to filter and manage the dust ,and enforce adherence to clean room standards.

1. Continuous Pumping

Operating a vacuum chamber means continuously pumping it down through a vacuum pump. All the equipment that involves pumping air and the rooms that house them will need to contain, control, and recover the dust from the chamber and any dust that may escape. This dust must be retrieved from the HEPA filters and wherever it strays.

2. Pump Protection

The pump turbine blades will be vulnerable to damage from lunar particles. The dust has sharp edges with erosive properties. And, where does the dust go? We cannot just blow it out into the atmosphere like the air in a conventional thermos-vac. That is why the dust filters go BEFORE the pumps so any particles get caught before the pumps. Even so, in a vacuum, the particles fly ballistically. In MTU's DTVAC it is rare that the particles reach the pump inlet. There are various ways to protect the inlet from entering dust. The dust load is not very high if you do things appropriately. The Co-Author has operated the DTVAC for 3 years and has not needed to replace the filter once.

3. Filtering the Dust

Therefore, it will be necessary to filter and/or prefilter the dust before it enters the vacuum pump and then capture and collect whatever particles pass through it. Filtering will require a more powerful pump than would normally be indicated for a volume of the chamber's size. That indicates more power, more pump cooling, and more maintenance.

4. Saving the Dust

Collecting the dust and other particles and returning then to the chamber could be a delicate and tricky operation. The dust will need to be protected from earthly contaminants — including air and humidity. It will need to be measured, weighed, and accounted before and after each use. Ideally, the dirty thermo-vac should be able to recycle and reuse the dust, provided it remains free from Earth contaminants. However, the cost of recovering most or all of the dust to be reusable could be prohibitive. Alternatively, the LPG could give the used filters to scientists to study. Then the LPG could install new filters.

5. Time Factor

FIGURE 4 presents the complete flow chart that begins in FIGURE 2. FIGURE 4 culminates with the completion of TRL-6 (A, B, or C). FIGURE 2 shows full extension into TRL-8 Space- Qualified and TRL-9 Space-Proven. One aspect that emerges is that an important time factor is involved. Deciding to test in a LPG will incur time penalties in the development process. This time factor may induce a developer to want to skip LPG testing and go right into operation on the Moon. On the other hand, many system developers will want to undergo LPG testing in order to reduce risk quickly and comparatively inexpensively to assure better performance, reliability, and safety on the Moon.

6. Another Time-Factor

Some Workshop attendees fretted that there might be a “five-year wait” to use the desired “dirty chamber” on Earth. The answer is:

a. To bring enough dust and regolith back from the Moon, and

b. To build enough dirty thermo-vac chambers to use the dust and regolith to serve the researchers’ needs.

c. To vet the researchers to make sure the level of fidelity is actually required or if regolith simulants are sufficient.

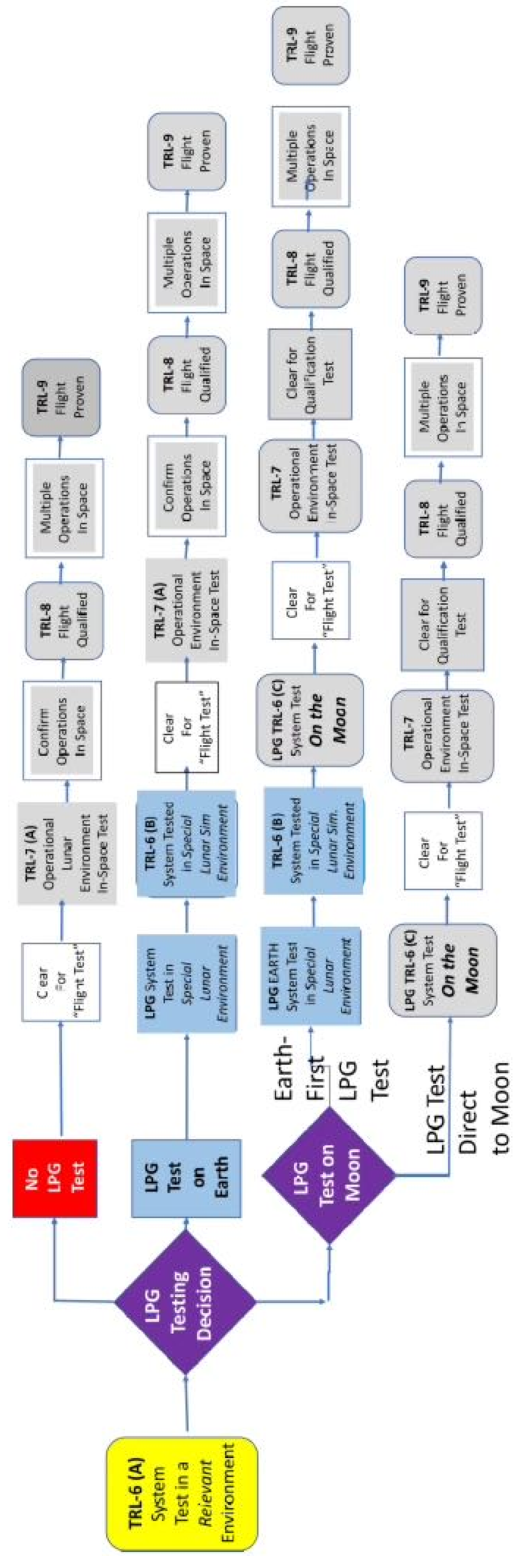

FIG. 4 The complete Technologist-Experimenter’s LPG decision flow chart.

X. Centralization, Decentralization, Institution, and Location

The idea of a LPG *network or consortium* begs the question of centralization versus decentralization. What is the difference between a decentralized facility or a network or a consortium of facilities? To a certain extent, it is mostly a matter of semantics. However, the network idea involves existing facilities that may be coordinated with the LPG mission or recruited to join it. This prospect raises the matter of whether these existing facilities could handle lunar dust and regolith to operate a "dirty" facility (absent a clean room system). This question applies whether it is a thermal-vacuum chamber or something else. In all probability, no existing chambers could handle the lunar dust; they will need to be designed, built, and operated on a new foundation. The purpose of a consortium would be also an exchange of information and lessons learned between all partners from academia, government and industry

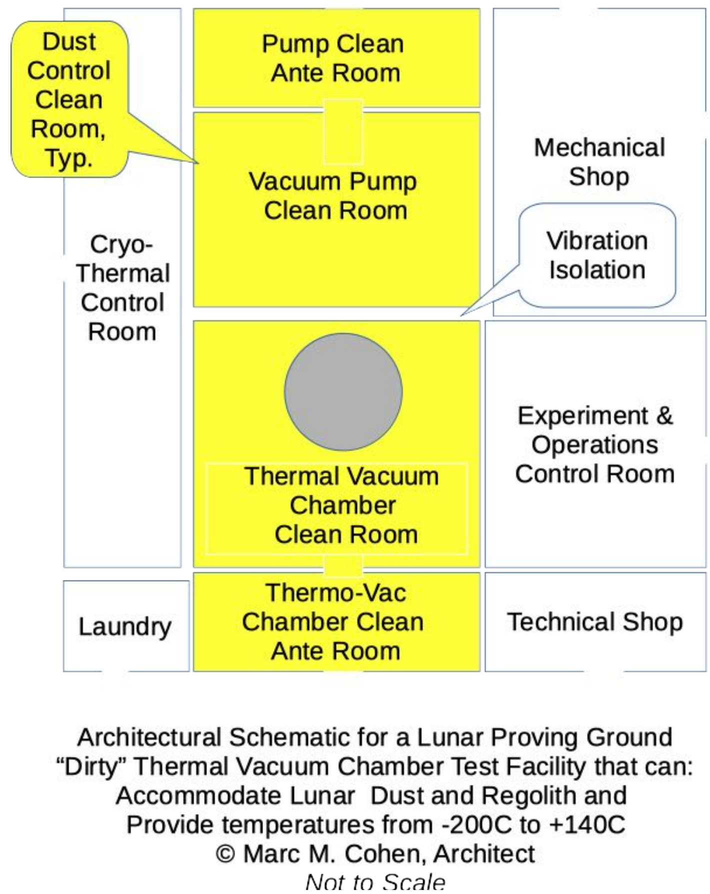

FIG 5. Schematic Drawing of a Custom-Designed "Dirty" Thermal Vacuum Chamber for an LPG.

A. Decentralization or Network?

If existing chambers are not adequate to manage lunar dust and regolith, then what is the meaning of the network? It probably means that institutions participating in the network will need to offer alternative resources instead: expertise, funding, instruments, land, personnel, and supporting technical services. If cobbling together such a network means building highly specialized test facilities on widely dispersed campuses, that may show a viable path to decentralization. There would be a political advantage to such a decentralized, newly-built network. It would increase the base of support for collaborative lunar research and development. It would put students at universities at closer touch with this lunar engineering and science research. It could greatly strengthen STEM education. Another advantage of this decentralized approach might arise if participation was offered through the NASA or NSF Space Grant programs. These facilities could be built on the campuses of public universities. Public (state) universities generally have more land available for such development, especially rural campuses, compared to urban public and private universities. They are entitled to receive NASA Space Grant and EPSCoR funding.

B. Centralization

Centralization takes a converse approach, not so much because it co-locates everything in the same vicinity, but because it takes advantage of concentrated resources. These resources may include: adjacency, economy of agglomeration, economy of scale, a larger pool of talent, the law of propinquity, shared science labs and technical shops, and presumably a unified security structure. Each of these resources signifies a major cost center but also may confer financial advantage. If there is a decision to make a single LPG campus, a battle royal will ensue among states, universities, and major corporations to win it. Thus, centralization may prove to be as much of a political disincentive as asking Congress to pay for a LPG on the Moon.

C. Centralized and Decentralized Together?

In all likelihood the LPG will combine dimensions of centralization and decentralization. The facilities, whether they involve "dirty chambers," chemistry labs, flight simulators, particle accelerators, or something else, will be distributed to more than one location. The primary reason is the expertise — the SMEs work and often live at widely dispersed institutions and thus a consortium approach appears prudent.

D. LPG Headquarters

Conversely, it may be advantageous to emplace the headquarters functions in one location. There are many reasons in favor of a centralized HQ. These reasons include: a unified interface with NASA, other space agencies, and major industry partners. The HQ would house the design and engineering office that oversees the design and construction and perhaps scheduling of testing facilities in coordination with the local institutions. Lunar materials are highly irritating and toxic and it will be vital that the LPG exercises a uniform oversight to ensure health and safety standards including no release of toxic materials. A further centralized function would be to ensure the quality control and assurance for the testing facility instruments and data collections systems. It would also facilitate knowledge exchange, lessons learned, and best practices/standardization of testing.

E. Location? Location? Location?

So, where should we put our Earth-based LPG facilities? At first, it may appear as a question of population geography; locating it close to the technologists and scientists who would use it makes a strong argument. But geography is only part of the equation. Each locational decision will be competitive, complex, financial, geographical, and political. In the end the availability of expertise may drive the location. Existing Earth proving grounds could form a basis for co-location since they have many decades of expertise in creating repeatable test courses and environments (e.g. the Keweenaw Research Center at Michigan Technological University). MTU offers a 900-acre proving ground facility for Earth vehicle and robotics testing under extreme conditions and includes many outdoor and indoor test facilities where dozens of outside customers come test their vehicles.

F. Culture of the Institution

What may be more important is whether at a candidate institution there exists a culture of serving outside customers. Companies are all about serving customers. NASA centers accommodate and serve customers in wind tunnels, flight simulators, analog habitats, and super computers, to name but a few such facilities. Universities are leaders in many aspects of innovation, science, and technology. However, serving outside customers is not usually one of academia's strengths. Choosing the institutions and locations for LPG facilities will pose a complex multivariate problem.

XI. The Network as a Virtual Institute

Regardless of whether the LPG is built in centralized or decentralized form, it can still operate as a Virtual Institute or consortium, with or without bricks and mortar. Conceived as an "institute without bricks and mortar," a highly successful example of such a Virtual Institute is the NASA Astrobiology Institute (NAI)[4] or the Solar System Exploration Virtual Institute (SSERVI).[5] The small headquarters office is located at NASA Ames Research Center, but the members are far-flung all over the world. They employ highly sophisticated video conferencing and data sharing technologies to bring the Institute members close together. Just this year, NASA is moving the NAI towards a series of Research Coordination Networks that will ultimately replace the Institute. In a similar manner, the LPG could integrate a virtual institute, network structure, and distributed testing facilities.

XII. Closing Conjectures

In closing, here are the takeaway points about a possible LPG. It discusses what steps would be necessary to start it. For certain lunar testing capabilities, the most pivotal will be the *Dump Truck Mission* (aka LuDuRR, The Lunar Dust and Regolith Retrieval Mission).

C. The Dump Truck Mission

Some workshop attendees advocated for a Moon-based LPG because of the unavailability of lunar dust and regolith on Earth. The solution could be to fly a mission to the Moon, scoop up say, three tonnes of dust and regolith, and return it hermetically sealed under vacuum conditions to the Earth. Then a unique part of the Earth-based LPG test facilities will be in business! However, even with one or more Dump Truck missions, the dust will be expensive and of finite quantity.

D. Real Lunar Regolith and Real Lunar Dust

The crucial ingredient in a LPG testbed or facility is real lunar regolith and real dust. These lunar materials are special because they contain nanophase iron particle inclusions, which give it electrostatic and magnetic properties. Impact glass that gives it key physical properties and cannot be created in lunar simulant. The only place to obtain these materials is from real regolith and dust on the Moon.

E. Networks of Testing Facilities

Among the hundreds of testing facilities that may be relevant to LPG, very few have the capability to incorporate lunar dust simulant testing. None can do actual lunar regolith testing at scale. Very few—if any—can achieve and sustain 40K temperature. Few — if any— are integrated with a system of clean rooms, [8,9,10].

F. Networks are Nice, but . . .

It is possible to identify existing test facilities that currently can participate in a distributed lunar testing network that can test many aspects of lunar technology, subsystems and small systems. With the possible exception of the giant thermos-vacs at MSFC and JSC, none can test at the required large scales needed in the near future and none are equipped to facilitate actual lunar regolith testing at larger scale. Until we can provide sufficiently large quantities of real lunar dust and regolith to them, we will not be able to test all aspects of operations on the lunar surface like a true Lunar Proving Ground.

G. Extreme Temperature Range

The ability to provide the lunar extremes of temperature (-233C to +140C) will be a vital concomitant for the LPG. Finding materials that can withstand the 40K (-233C) while retaining the desired mechanical and structural properties turns out to be quite challenging.

H. Cling, Charging, and Lofting

With sufficient quantities of lunar dust and regolith, it may be possible to simulate these phenomena in an Earth-based LPG. It may also be possible to simulate dust lofting up to 5 or 10 m in a sufficiently high vacuum chamber. It is conceivable that the chamber may take the form of a silo, either above ground like a grain silo or below ground like a missile silo. *It may also be possible to experiment in 1/6-g on a parabolic flight aircraft to evaluate the degree to which this partial-g enables dust lofting.*

H. Dirty Thermo-vacs in Clean Rooms

Having a "dirty chamber" in a "clean room" may seem like a contradiction in terms. However, that contradiction is exactly the central challenge of designing and operating the Earth based real lunar regolith LPG facility. An essential element for success in the LPG testing regimes will be to install thermo-vac chambers and their supporting mechanical equipment (e.g. vacuum pumps, air dryers, etc.) in clean rooms that can control and recover lunar dust.

I. Intellectual Property

The question of data sharing and intellectual property protection conveys the complexity of how to operate the LPG facilities. What share of data collection, generic or bespoke, could be shared with other researchers in the network? What are the protections for intellectual property (IP). What are the standards for test materials or devices that the LPG provides? How are these responsibilities divided among centralized and decentralized authorities? The implication may be that the test facilities must provide "private" cells in which customers can do their research with physical security for their work area. Existing consortia where industry, academia and government collaborate to tackle difficult challenges could function as an example for organization, collaboration and IP protection and sharing.

J. Mission Timeline Factors

NASA announced plans to return astronauts on Artemis III to the lunar surface by December 2025 and Artemis IV by September 2028. Many more crewed landings should follow. When will robots and rovers need testing? When will crews need equipment tested in LPG? How does the potential timelines for LPG interact with the NASA lunar mission timelines?

K. LPG Development Temporal Factors

Time factors may become dispositive in the creation and operation of LPG facilities.

1. Smaller and less expensive LPG facilities are likely to be candidates for funding and completion sooner than very large facilities which may take many years to design, fund and build. Existing DTVAC facilities at NASA and at universities such as Michigan Technological University have limited capacity for the growing need for high fidelity TRL-5 and TRL-6 testing.
2. Earth-based LPG facilities will receive funding much earlier than Moon-based LPG facilities. Launch funding may take even longer.
3. "Moose on the Moon, or what makes Luna tick?" *from Rocky and Bullwinkle.*

XIII. Conclusion

Regolith simulant is suitable for many investigations in a "dirty" thermal vacuum chamber. The DTVAC system at Michigan Tech shows that the technology is here today to conduct a wide range of experiments. These experiments using simulant could be highly cost-effective compared to waiting for real lunar regolith and dust and then taking special care not to lose any of it.

Larger than currently existing lunar proving ground facilities are needed in the near future to test systems at full scale for expected distances and volumes of regolith to move and process.

The main type of investigation that requires real lunar regolith and dust concerns electrostatics. A specialized chamber design would be required for real lunar samples. The lunar material would need to be kept in a vacuum so as not to degrade its electrostatic properties by exposure to air and water vapor in the Earth's atmosphere. Also, an effort to capture and recover all the lunar dust used in a test would be very expensive in terms of specialized filtration systems and settling chambers.

Future directions may include development of additional medium size dusty thermal vacuum chambers to allow for increased near-term demand in testing with lunar simulant in relevant conditions. Development of one or more much larger size lunar proving ground facilities will allow for testing of full-size lunar terrain and human rover vehicles and operational testing of construction and In-Situ Resource Utilization systems. These capabilities include long distance driving, long duration testing for purposes of wear and dealing with dust over time (months to years of continuous use). When additional lunar samples start being returned to Earth, special tests can be conducted and larger quantities of it can be made available for testing in the community. An additional question that will need answering is how long regolith simulant can be (re-)used in tests that can mechanically change the particles over time (e.g. driving over them),.Any other process that would lead to particles becoming rounder over time changes its mechanical properties. Large scale test beds will require thousands of metric tons of lunar simulant to create the scales required.

Future directions may include these steps:

1. Survey the relevant test facilities in the USA, then internationally. Publish a directory.
2. Collect experiment proposals and their requirements. Evaluate which existing facilities — if any — meet those requirements.
3. Identify the requirements for which no existing facility will serve.
4. Distill those requirements into discrete and unique capabilities that would be needed to meet them.
5. Define what new facilities and capabilities will be needed to conduct these experiments.
6. Evaluate which existing research centers or facilities offer as commonality with the new requirements in terms of subject matter experts, operating experience, utilities (e.g., electrical substations), supporting equipment, etc.
7. Propose the creation new terrestrial LPG facilities. Once funding is possible, open these opportunities to competition.
8. Define the scope of need for regolith and dust to be returned from the Moon to make certain experiments possible.
9. Identify the capabilities and facilities that can perform their necessary tasks only on the Moon.
10. Propose new lunar LPG facilities. Evaluate the crew and logistical requirements to operate these facilities.

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