Designing the PLANET Chamber for Lunar Environment Ground Testing

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The Planetary, Lunar, and Asteroid Natural Environments Testbed (PLANET) is a new 2m x 3m high-vacuum chamber facility currently being designed and built at NASA's Marshall Space Flight Center. When completed, it will be one of the highest-fidelity space/surface environment simulation chambers in existence. Instrumented with equipment to produce charged particle radiation, full spectrum ultraviolet, low-density plasma, and thermal extremes, PLANET can be configured to recreate the most challenging space environments. Additionally, a large regolith bed and distribution system will expose hardware to lunar regolith simulants and dust. This paper will describe the process of designing and optimizing PLANET and discuss some common considerations for performing ground-based environmental testing for lunar exploration.

I. Introduction

The lunar environment presents several unique challenges for hardware intended to explore the surface of the Moon. To have the best chance of ensuring mission success, ground-based environmental testing is a critical component of any technology development campaign. The Planetary, Lunar, and Asteroid Natural Environment Testbed (PLANET) is designed to meet this need by providing a high-fidelity lunar surface environment inside a well-equipped high-vacuum chamber at NASA's Marshall Space Flight Center (MSFC) in Huntsville, Alabama.

The Space Environmental Effects (SEE) team has decades of experience in simulating space environments, from low Earth orbit (LEO) to deep space and near-Sun. The SEE laboratory houses several vacuum chambers of different sizes, with wide-ranging space simulation capabilities. One of these is the Lunar Environment Test System (LETS), a 76.2-cm (30-inch) diameter vacuum chamber, containing a regolith box, cryogenic shroud, 100 keV electron gun, and particle imaging velocimeter, which has been operational since 2008 and provides a base of experience for lunar surface environment simulation. However, with the significant development effort being put into NASA's Artemis program, there is a clear need for additional facilities that can test larger scale equipment. PLANET will leverage our team's experience with space environmental chambers and translate it into a new, state-of-the art facility for raising the Technology Readiness Level (TRL) of programs providing support to Artemis missions, including Gateway, the Human Landing System (HLS), and Commercial Lunar Payload Services (CLPS).

The PLANET vacuum system is currently in the procurement phase, with delivery of the vacuum vessel, pumps, and automated controls planned for late 2023. Outfitting with environments and instrumentation will proceed over the following several months, with specific capabilities being added incrementally as needed. Several potential early partners have been identified from programs throughout NASA for initial test campaigns. PLANET's testing capabilities will grow hand-in-hand with the defining and refining of requirements on lunar hardware as we experience ground truth during upcoming missions. We expect PLANET to be providing for testing services and partnerships to

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the community by mid-2024. A CAD mock-up of the PLANET vacuum chamber, depicting port locations and the large regolith tray, is shown in Figure 1.

In the next section, we describe the design considerations and trades involved in designing a chamber with PLANET's intended purpose. Specific natural environments are described, along with details on how they will be simulated in PLANET. These environments include high vacuum, plasmas, radiation, dust/regolith surface simulants, and thermal extremes. Next, other design elements are considered, including chamber sizing, port arrangement, and instrumentation.

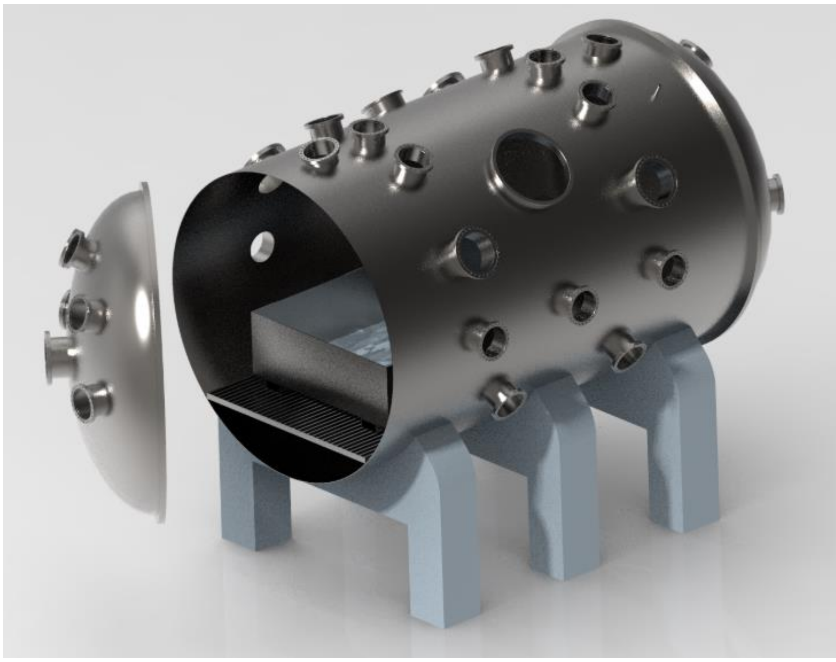

Fig. 1 Preliminary CAD rendering of the PLANET vacuum vessel showing notional port locations and a regolith simulant container.

II. Design Considerations and Planned Capabilities

There are many considerations and trades to make when designing a chamber like PLANET. Ultimately, the goal is to provide a functional, cost-effective testbed for the wide range of technologies that will go to planetary surfaces, including the Moon, Mars, and potentially other low-atmosphere bodies. PLANET is meant to be quickly reconfigurable, flexible, and modular to meet a variety of research and technology test goals. Fidelity must rank highly, so defining the environments that must be simulated to capture the most important effects is paramount.

The first focus (after acceptance and commissioning of the vacuum vessel) will be simulating the lunar surface. Artemis I has already successfully launched an Orion capsule to orbit the Moon, heralding the next generation of lunar surface exploration. NASA and multiple commercial partners are busily working out new technologies that will require environmental proving via test campaigns, and PLANET is intended to help fill this gap in available facilities.

A. Environments

PLANET is designed to have the ability to replicate several different aspects of in-space and planetary surface environments with great fidelity. These environments can be combined in simultaneous exposures to study synergistic effects with engineering implications or applied alone for gathering basic science data to inform models. Immediate efforts are focused on recreating aspects of the lunar surface. There is much we do not know about the true lunar surface environment – the last direct human reports from the lunar surface are from the 1970s, and technology has far advanced in the last 50 years. Multiple robotic missions have gathered valuable data since then (primarily from orbit, but also from landers), but ground-truth data from the lunar south pole, the target location for Artemis base camp, is still notably lacking. PLANET is designed to be extensible and will be calibrated and improved using data from upcoming surface expeditions. NASA's Cross-Platform Design Specification for Natural Environments (DSNE) [1] holds the environmental definitions that missions should plan to and that laboratories should plan tests around; the latest science is integrated in this document. As of this printing, Revision I is current. Below, several environmental factors that PLANET will be capable of replicating are described.

1. High Vacuum and Low Atmosphere

Vacuum forms the basis for most space-environments testing. Low pressures can affect basic material properties such as conductivity and strength by causing atomistic compositional changes as water and other volatile compounds outgas. Contamination can occur when compounds that outgas or sublimate in vacuum redeposit on nearby surfaces, especially those that are in good line-of-sight and/or a colder surface. Sensitive optics are especially at risk. Thin layers of contamination may photo-fix in UV light, changing thermal and optical properties of a surface [2]. Components that rely on air for pressurization or heat rejection will suffer in vacuum unless appropriate precautions are taken (and tested). Many of the effects caused by other environmental factors are changed significantly in vacuum, so vacuum is an important contributor to combined effects.

Most space simulation chambers reach high vacuum (HV) levels, in the 10^{-5} to 10^{-8} Torr range. The General Environmental Verification Standard (GEVS) states that $1\text{x}10^{-5}$ Torr is sufficient to effectively eliminate thermal conduction [3], safely in the molecular flow regime. Tests that require extremely accurate surface energies or reactivity states will benefit from higher vacuum levels, but reaching ultra-high vacuum requires specialized pumping and sample preparation that is unrealistic and unnecessary for many technologies. Many factors affect pump down time – chamber surface area, conductance to pump inlet, and outgassing of test articles and instrumentation. PLANET is designed to reach at least the 10^{-7} Torr regime when empty with a combination of a scroll pump for roughing and a cryopump for reaching HV. For comparison, the lunar exosphere ranges from 10^{-9} Torr in the day to 10^{-12} Torr at night when gases condense on the surface.

PLANET will have some means of detecting and monitoring contamination and outgassing, although other MSFC chambers are dedicated to specialized particulate and molecular contamination testing for purposes of qualification. A Residual Gas Analyzer (RGA) Mass Spectrometer will be used to monitor specific chemical peaks real time. We are potentially outfitting PLANET with a TQCM (temperature-controlled quartz crystal microbalance).

In the future, planetary surfaces with low atmospheres will be simulated in PLANET. Mars is one example; a small, regulated amount of introduced carbon dioxide and other trace gases can mimic the Martian "air." This fidelity is important for heat transfer, chemistry, and materials properties evolution.

2. Plasma and Charging Environment

The solar wind consists mainly of a low-density plasma of protons and electrons, continuously streaming out of the Sun, following magnetic field lines. The average solar wind particle speed is in the range of ~400 km/s [4]. Complex plasma environments exist on planetary surfaces, driven by these particle streams interacting with local features, topography, and solar illumination conditions (photoemission), as well as the orbital relationships with their neighbors in the Solar System, such as the moon's periodic interaction with Earth's magnetotail [5]. Particles in the solar wind can act as both a source and a sink of charge. Electrons and protons deposit charge onto surfaces or deep inside bulk material (including spacecraft, equipment, and regolith). Depending on the conductive properties of the material, it will diffuse or accumulate the charge. When dissimilar materials build up different potentials, electrostatic discharge (ESD or "arcing") can occur between them, damaging components and potentially endangering crew. Internal arcing (IESD) can occur within a given dielectric material if it reaches its breakdown voltage. But plasma can also provide a mechanism for discharging spacecraft components, with interactions washing charge away and reducing floating potential differences. Lunar regolith is notoriously non-conductive, and it cannot be used as common charge sink as (wet) ground can on Earth. Illumination conditions also affect charging levels – photons knock electrons from their orbits when in direct sunlight, but electrons can build up in shadow; strong negative charging is more likely to be a problem in the dark [6]. The electrostatic environment on the Moon is severe, and the problem is compounded by the abundant loose, powdery regolith that is easy to charge. Tribocharging is expected to be a significantly larger problem for ambulatory assets on the lunar surface than is charge build up from natural phenomena.

The SEE Team operates several charged particle and plasma sources to address the wide range of in-space and planetary surface environments that spacecraft, landers, and rovers might encounter. While in some cases the goal of a test may be to recreate the space conditions as close as possible, there are multiple scenarios where it is advantageous to tune the conditions to accelerate testing, or to eliminate conditions that have no significant impact on the system under test, thereby reducing the test matrix. Applying a higher flux than encountered in space, for example, offers a means to accelerate charging tests to quickly determine the materials or interfaces that pose a threat to generate electrostatic discharges. In the case of plasma testing, a key figure of merit is the Debye length, which represents the dimension over which the plasma will screen out electric fields. In solar wind conditions the Debye length can extend into the 100s of meters. For ground-based test systems like PLANET, the practical solution for looking at plasma effects on spacecraft materials or systems is to adjust the plasma source parameters to yield a Debye length of a few centimeters to a meter.

The electron sources range in energy from 50 eV to 100 keV and include commercially built flood guns designed for large coverage areas to custom in-house designs that are compact and rated for high-flux applications. Using electron transport modeling, SEE Team personnel can design scattering foil solutions that allow the generation of highly uniform beams as well as beams with an energy distribution that can extend into the low-energy surface charging regime appropriate for solar wind simulation.

For plasma sources, three types of sources are routinely deployed: 1. Hollow Cathode, 2. Kaufman-style Gridded Ion, and 3. Magnetically Filtered. In all cases the plasma sources deliver a quasi-neutral plasma (i.e., electrons and ions). The Hollow Cathode and Magnetically Filtered sources are often used for low Earth orbit plasma simulation. However, each source can be modified to operate in different regimes, allowing operation beyond the LEO conditions. One of the key features of the Magnetically Filtered system is the production of very low temperature plasma electrons, which can be difficult to obtain in other plasma sources. The Kaufman-style sources provide great flexibility in the ion energy range, and since they utilize a neutralizer filament, they provide an ion beam with directed energy that carries low temperature electrons along with the beam of ions. In 2016 - 2017 the SEE Team successfully used a modified Kaufman-style source to provide solar wind ions for the flight qualification test of the Parker Solar Probe instrument known as the Solar Probe Cup [7].

Three commercial proton sources are currently available for application to PLANET. The sources range in energy from 200 eV to 30 keV. Each source utilizes a different plasma generation system which has its respective advantages including long-term stability, high-flux, and easy maintenance. The three types are: duoplasmatron, RF discharge, and simple cathode-anode. Each of the systems employs a mass filter or bending magnet to eliminate H_2^+ ions and yield only protons. To create a large coverage area, the proton sources all employ a raster scanner. The SEE team is reviewing options to acquire a new proton source that utilizes a very compact Electron Cyclotron Resonance (ECR) discharge system. This flange-mounted proton system offers new options for deployment on top of PLANET or on any of the angled ports.

The existing inventory of charged-particle and plasma sources that can be applied for use in the PLANET system is key to ensuring the broadest range of customer requirements and mission scenarios can be realized. Each spacecraft system has a different sensitivity and susceptibility to electrostatic charging and discharging. The application of targeted charged particle beams or plasma environments allows investigation of charging on materials including polymers, composites, coatings, thermal control paints, multi-layer insulation, thin-film coatings, anodization layers, and solar cell coverglass. Most frequently application of a low-energy (<100 keV) electron beam provides information on worst-case charging levels and the generation of discharges (arcs). Solar array ESD testing is frequently conducted with electron beams to explore the establishment of so-called inverted gradient states. However, some porous materials or woven fabrics (with openings) may not charge under electron illumination, instead they may be more sensitive to proton/ion beam charging. The use of electric propulsion systems on spacecraft for station-keeping, or primary propulsion, provides a scenario where an ion beam plasma source is required to simulate charging due to plume impingement. For tests with small rovers and landers, the full complement of charged particle and plasma sources may be needed to generate the complex regolith charging scenarios that are extremely difficult to model [8]. Finally, combined operation of sources may also be needed to explore the integrated charging of a complete system where multiple boundaries exist between materials and coatings – leading to differential charging across interfaces.

3. *Ultraviolet Radiation*

The ultraviolet spectrum spans the wavelengths ~100 nm to 400 nm. It is roughly 8% of the total Solar constant (1388 W/m2). In the space environmental effects community, ultraviolet is broken up into two ranges, which are tested with different sources. Vacuum ultraviolet (VUV) ranges from about 100 to 200 nm. The higher energy VUV photons are absorbed in Earth's atmosphere but are present in space and on some planetary surfaces. Even though they make up a small fraction of the total solar constant, they can potentially cause significant damage to polymers, composites, acrylics, and other materials. 200 to 400 nm is called near ultraviolet (NUV). The spectrum here is typically replicated by a xenon arc lamp with filters to remove infrared contributions.

UV damage commonly manifests as yellowing to surfaces and tensile strength reduction. Polymers and composites are likely to be vulnerable as crosslinking and chain scission affect their bonds, which can have relatively low energy barriers to transformation. Ultraviolet photons are generally stopped within the surface layers of material, concentrating damage to a thin volume, but this can still affect characteristics like ultimate tensile strength. Yellowing changes thermal and optical properties (absorptance and emissivity, transmittance), both functional and aesthetic qualities.

Testing for UV exposure is often accelerated by some amount, otherwise the test takes as long as the real expected lifetime. But accelerating too much risks causing unrealistic stress and damage to materials through secondary effects (raising the temperature, excess yellowing). The SEE lab typically accelerates NUV exposure by no more than twice, running lamp output at up to 2 Suns (where 1 Sun is the radiance experienced at 1 AU), often less. VUV exposures have extremely low flux, and the intensity is controllable only with geometrical reconfiguration, so more acceleration is usually performed. Testing campaigns with three levels of equivalent Sun hour (ESH) exposure can yield curves predicting performance closer to end of life (EOL) – 500, 1000, and 2000 ESH are commonly recommended. If required, sample temperatures can be controlled with cold plates to partially mitigate the effects of acceleration. In addition to material changes and degradation, UV exposure is associated with photoemission of electrons resulting in positive charging and creating a differential charging scenario with portions of the spacecraft that are shadowed.

PLANET will have a flange mounted deuterium lamp for vacuum UV exposures and a filtered xenon lamp to provide the NUV spectrum through a window. The sample exposure area through the entire UV spectrum will be approximately 20” diameter, though mounting the lamps to different ports allows for a variety of potential exposure geometries.

4. Ionizing Radiation

Charged particle radiation from the Sun and deep space causes damage to materials and sensors, degrading mechanical properties over time. Laboratory total ionizing dose (TID) testing can replicate the effects of spending time in a high radiation environment on an accelerated schedule by depositing an equivalent amount of energy to a volume using a different spectrum of particle types and energies than would be present in the true environment. PLANET will be directly equipped with low energy electron and proton charged particle sources as discussed in the earlier section on charging, but these sources can only provide ionizing doses to extremely thin materials and surfaces. For most tests requiring radiation exposure, the SEE team’s complementary Pelletron or x-ray facilities will be used to first irradiate a material before it is transferred into the PLANET chamber for follow-up testing in the other available environments. MSFC’s Pelletron is a unique dual-beamline facility that can deliver electrons up to 2.5 MeV and protons up to 800 keV simultaneously into a single target at high vacuum. The beams are monoenergetic for any single exposure, but multiple exposures at different energies can be run in sequence to produce the desired depth-dose profile. The x-ray facility exposes samples in air to a maximum of 320 kV photons and can penetrate to greater depths than the Pelletron. TID testing is particularly important for technologies with long expected lifetimes on the lunar surface – perhaps 10 to 15 years or more.

5. Regolith and Dust

The soil of a planetary body is known as regolith – on the Moon, billions of years of meteorite strikes have cratered the surface and broken larger rocks and minerals into fine powers and sharp fragments. Dust and regolith interactions are expected to be among the most compelling technical challenges we will face as we return to the Moon. NASA now has an excellent standard to guide dust testing – NASA-STD-1008 [9]. It describes many tests that could be conducted to advance dust robustness and thus mission success. It does not mandate that any specific test be performed but provides guidance to plan test campaigns. PLANET is being designed to cater to some of the suggested tests, often with improvements in fidelity provided by additional space environments.

The large regolith simulant “sandbox” will have an area of 1.2 x 2.4 m and a depth of ~0.2 m. Different simulants can be used for different tests and planetary surface regions (in the same sandbox or in an interchangeable system of containment boxes). This amount of regolith simulant is expected to weigh around 800 kg. Combined with the weight of the sandbox itself, the chamber floor will need to support a weight of roughly 1200 kg. PLANET’s design includes welded angle brackets along the chamber length to support the floor. Depending on the goal of the test, particular simulant characteristics will be important – geotechnical, chemical, thermal, etc. Lunar mare simulants based on Apollo samples are most readily available, but Artemis basecamp is planned for the lunar south pole – a highlands region. Doing the same tests with multiple lunar simulants will allow the community to provide better error bounds on results and increase understanding of simulant differences. Ultimately (but perhaps not immediately), this can bring down cost. The facility chosen to house PLANET has a large roll-up door aligned with the chamber’s long axis, which means that regolith simulant beds can be moved in and out relatively easily. It also gives flexibility where bakeout procedures are conducted (in situ vs in small batches or at the neighboring Environmental Test Facility). There are still open questions about regolith compaction and reusability of simulant across multiple test campaigns. In the future, Mars simulants will be explored.

Additional equipment will be needed to enable specific types of dirty testing, i.e., with regolith simulant. A regolith application/distribution system will be implemented to meter out known quantities of simulant from above a test article; this will allow deposition of thin layers of particulate onto surfaces for subsequent exposures and tests which required periodic regolith introduction from a hopper (for example, for wear testing or additive manufacturing). This problem is non-trivial – some of the most relevant and damaging particles are 10-20 μm diameter, invisible to the human eye, so precision is important, and detection and verification of distributed particles is challenging. Mechanism and seal testing (including wear, abrasion, and leak resistance) is also envisioned, as dust contamination in mechanisms is expected to be a significant challenge for lunar surface equipment based on Apollo astronaut testimony [10]. Equipment needed for this testing, including motion stages, load cells, and sample fixturing equipment is being designed.

The idea of having regolith simulant and dust in a test chamber is anathema to traditional thermal vacuum chamber operators, who attempt to keep chambers as clean as possible. However, vacuum is an essential environment to combine with dust if the true behavior of a system is to be revealed. Best practices, which evolved from early simulant work in vacuum chambers across NASA, include performing a thorough bakeout of the simulant before attempting to pump to high vacuum. High temperatures (above 100 C) help drive out adsorbed water that would otherwise boil off as pressure is reduced; even more extreme temperatures can drive out structural water but may also affect other chemical properties. Tortuous paths, filters, and gravity (using placement at the top of a chamber) can reduce exposure of pumps to the dusty environment but can also decrease pumping speed in the molecular flow regime. MSFC's SEE team prefers cryopumps in the high vacuum regime to decrease the chance of catastrophic mechanical failure from regolith particulate entering turbomachinery. In LETS, we also placed a non-sealed lid over the simulant box to reduce the effects of viscous/turbulent flow during the rough pumping stages; similar precautions will be taken with PLANET.

From the safety perspective, lunar regolith simulants present potential health hazards to scientists, engineers, and technicians when handled. Many formulations have high calcium and silicate content, with inhalation risk potentially leading to silicosis. There are efforts underway to develop highlands simulants with lower toxicological risks, but cost and availability are still concerns for the simulant shopper. Occupational safety/hygiene should be considered when undertaking a dirty chamber project; masks and respirators may be recommended or required when working with certain simulants. Particles under 20 microns can have significant effects on electrical and thermal performance but are unresolvable to the human eye. The V20 chamber at MSFC chose to have a large clean tent around the entrance, but drifting regolith has not been an issue during operations so far. PLANET will take similar precautions to ensure the safety of personnel working with simulants.

6. Thermal Extremes

Thermal variation in space is clearly a significant issue, and technologies must be able to withstand and perform at both hot and cold extremes. Thermal vacuum testing is a well-established practice when qualifying spacecraft and PLANET will be equipped to provide cryogenic and hot environments for thermal cycling, soaking, and balance tests.

A cryogenic shroud is often employed in space simulation chambers. Shrouds provide a "deep space"-like view for radiative cooling of units under test. However, PLANET has a large number of penetrations (see Section C), which would necessarily correspond to openings in the shroud. This complicates the design and could result in non-uniform temperatures across the shroud surface. Instead of a full shroud, a modular panel system is being considered. This would allow for easier port access, be fully customizable for unique test setups, and minimize coolant waste. Cold plates (which can quickly cool articles conductively to target temperatures) will also be utilized as needed. Liquid nitrogen is the baseline cooling fluid, allowing for temperatures as low as -180 C inside the chamber. In the future, a helium cooling system is envisioned for testing at even colder temperatures, such as those found in Permanently Shadowed Regions (PSRs) on the Moon.

Radiant heating will be provided via quartz infrared lamps. Contact heating (e.g. Kapton strip heaters) are effective for conductive heating and useful for mimicking other payload/spacecraft instrumentation. Resistive heaters such as these are generally quick acting and easy to control with a DC power supply.

7. Combined Environments

The ability to expose materials/instruments to multiple environmental factors at once can give more realistic results, as synergies can exist between phenomena. For example, dust particles in a vacuum environment will have different adhesion properties than in air and will certainly also be affected by the charging environment. Impinging charged particle radiation may cause greater or lesser damage to a target material depending on that materials temperature (and thus, affecting what repair mechanism energy pathways may be accessible).

Some effects are accelerated at different rates, so sometimes environments may be applied sequentially. In PLANET, this can be done without breaking vacuum and exposing the sample to recovery factors like the water vapor and oxygen in air.

B. Chamber Size

The core of PLANET is a 2 m diameter by 3 m long cylindrical high-vacuum chamber with domed doors on either end. Inside, a 1.22 m *x* 2.44 m regolith simulant bed (with 0.2 m depth) holds test articles while environmental exposures are conducted. This size was chosen to optimize across several factors described below.

First, the chamber must be large enough to accommodate common technologies that customers want to test; examples include deployment mechanisms, sealing mechanisms, dust removal technologies, and small payloads, rovers, and drills. Although PLANET will not be large enough to test all full-size systems, we anticipate that subsystems and components of interest can be isolated for dedicated testing in many cases. Second, the chamber should be small enough that environments can be applied relatively uniformly and consistently to the article under test. For example, due to limitations of chamber geometry and source placement, environment sources such as electron beams or UV light can only expose a limited area to their effects. This spot size tends to be in the 0.2 to 0.5 m range; above this size the uniformity and intensity- sharply drops off. Finally, we see PLANET's role primarily as a research-and-development testbed (though it can also act as a qualification and verification facility as needed). Thus, it should be cost-effective for the customer to run multiple iterative tests within a limited time. PLANET's size means that material, supply, and labor costs are low compared to a larger chamber, and pump-down from atmosphere to high-vacuum and back can be accomplished quickly.

Luckily, the facility we are building PLANET in can accommodate its size without significant modification, although relocation of other equipment is needed. The laboratory space has adequate electrical power, cooling water loops, liquid and gaseous nitrogen lines, and HVAC. The ceiling height is the most limiting factor; thus PLANET will be built on relatively short legs. A cart system to load and unload regolith beds and provide a comfortable working area for instrumenting test articles is planned. See Figure 2 for a mockup image of the facility that will house PLANET.

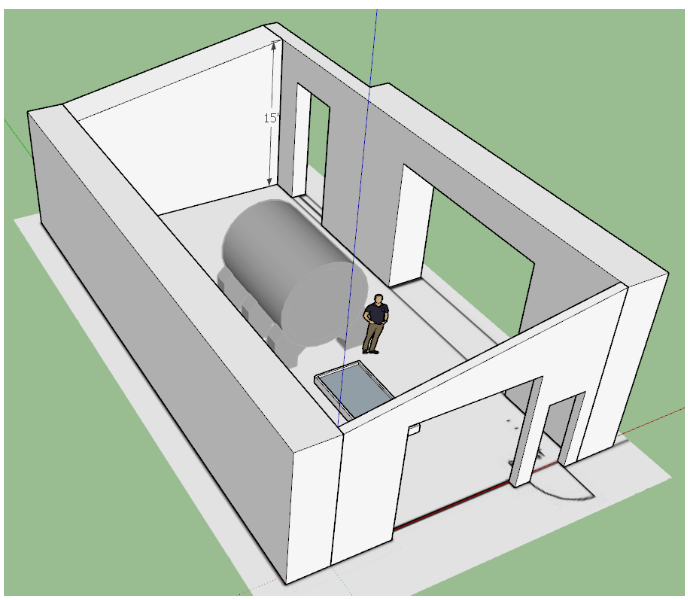

Fig. 2 Basic mockup of PLANET chamber placement in existing laboratory space; view from the southwest.

As a part of Marshall's lunar testing ecosystem, PLANET will complement two other "dirty" vacuum chamber facilities at MSFC – LETS and V20, pictured in Figure 3. The Lunar Environment Test System (LETS) is a smaller space environments chamber, housed in the same building that will house PLANET. There is a small simulant tray within the 76 cm (30-inch) diameter chamber (equipped with cryogenic shroud), which has been tested with JSC-1A. The tray has a non-airtight cover, designed to minimize turbulent flow around the surface material during initial pump down. LETS has been used for regolith charging and lofting studies, and material coupons can be exposed here to study basic properties.

V20 is a 6 meter (20-foot) diameter by 8.5 meter (28-foot) long thermal vacuum chamber that has recently been converted to handle regolith and dust (DTVAC). It has a large bed that can hold full-scale hardware. It is outfitted with a cryogenic shroud and radiant heating, but no other space environments. PLANET is sized to address hardware that is too large for LETS, but requires specialized space environments beyond DTVAC, or desires iterative testing. From early materials development work in LETS to payload/system level exposures in PLANET, to integrated qualification in V20, technology readiness level (TRL) can be raised by testing in these three chambers as a concept matures.

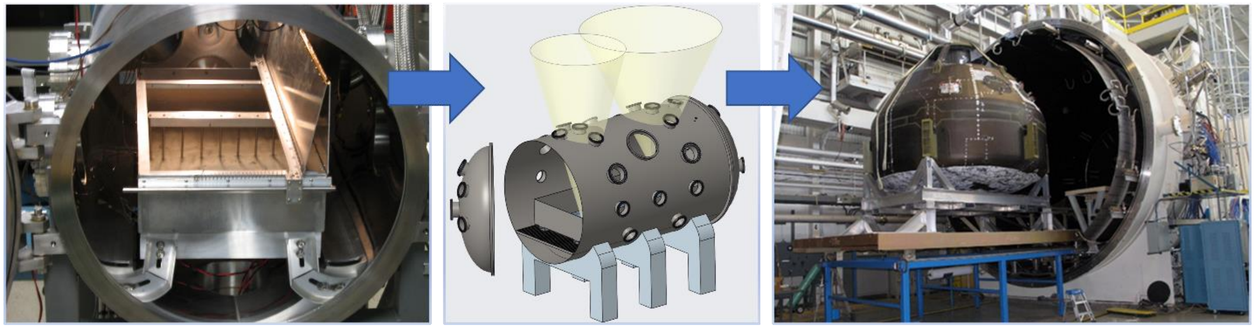

Fig. 3 Marshall Space Flight Center's lunar surface environmental testing ecosystem includes multiple facilities for different technology development levels and hardware sizes. From left to right: LETS, PLANET, V20.

C. Port Arrangement

Ports are essential for bringing both environments and instrumentation into the chamber. Both ends of the chamber can be opened as access doors, with several ports on their rounded domes. Ports along the sides of the vessel and on the doors are versatile, serving as viewports, feedthroughs for power and data cables, and plumbing access points. PLANET is designed with two main zones along the length of the chamber. In each zone, four large overhead ports (CF 10-inch) are angled to focus on a plane where the test article will be situated. To accommodate articles of different sizes, each zone has a slightly different focus height. The zones can also be used to create two environments in a single chamber – for example, the terminator (the region between day and night) can be emulated by a hot bright zone next to a cold dark zone. A view showing the ports on top of the chamber Figure 4.

Additionally, a large port is planned for the bottom of the chamber. In the case that a piece of hardware (such as a drill or sampling system) requires a deeper regolith bed, PLANET will be able to provide it.

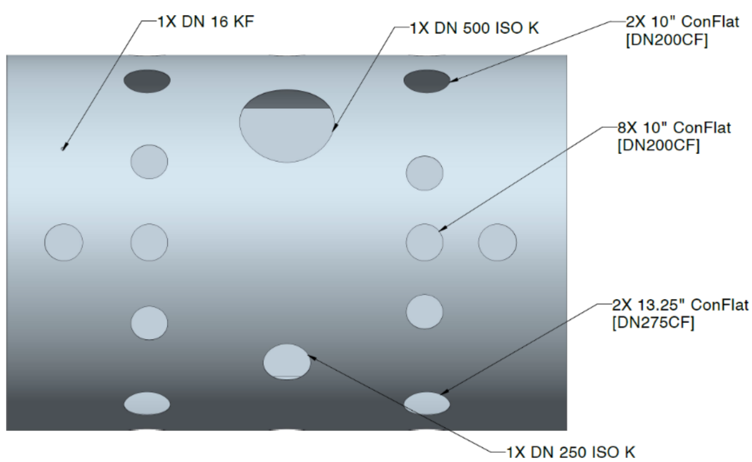

Fig. 4 View from the top of the PLANET vacuum vessel model. The large central port will be connected to a cryopump, and the primary environments will be delivered to two zones through the groupings of four 10-inch ConFlat ports on either side. Additional ports are abundantly available for instrumentation and viewing.

III. Conclusion

When completed, PLANET will expose spacecraft materials, subsystems, and instrumentation to high-fidelity space environments, including lunar and Martian surface environments, with an immediate focus on the lunar surface environment in support of Artemis missions. The vacuum vessel at PLANET's heart will be instrumented with equipment to replicate plasma and solar wind, ultraviolet radiation, low-energy charged particle radiation, thermal extremes, and exposure to regolith simulant and dust. Many trades were considered early in the design process to optimize customer utilization, test effectiveness, and cost effectiveness of the unique facility. The facility will close gaps in NASA's testing ability and provide scientists and engineers the opportunity to raise their Technology Readiness Level to 6, Demonstration in a Relevant Environment.

Designs for PLANET have been generated by MSFC's internal team, and the procurement process to have the PLANET chamber built and installed is underway. Delivery to MSFC is expected in late 2023, at which point the chamber will be instrumented with environments and checked out. Customer access is planned to start in mid-2024.

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