

B&P Project 25-3: Regolith Gas Permeability Tester Project (REGAPT2)

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NTR: KSC-14561: Regolith Gas Permeability Tester (REGAPT)

Start TRL: 3

End TRL: 5

Labor (FTE): 0.44

Procurement (\$k): \$78.4

Prime STMD Taxonomy:

TX09 Entry, Descent, and Landing

TX09.4 Vehicle Systems

TX09.4.5 Integrated Modeling and Simulation for EDL

Secondary STMD Taxonomy:

TX07 Exploration Destination Systems

TX07.1 In Situ Resource Use

TX07.1.3 Resource Processing for Production of Mission Consumables

TX07.2 Mission Infrastructure, Sustainability, and Supportability

TX07.2.3 Surface Construction and Assembly

Project Description: Regolith particles accelerated by gases from plume-surface interactions (PSI) during the descent and landing of a lander vehicle on the Moon represent a potential risk to the sustainable human exploration of the lunar surface. However, the nature of gas flow through granular materials also has broad implications across many fields. For example, gases escaping from the interior of comets permeate through regolith to create a coma around the nucleus and a tail of primordial dust; gas volatiles liberated from planetary surfaces for in situ resource utilization must diffuse through regolith; and gas has been used in touch-and-go sample acquisition maneuvers to excite asteroid regolith into collection pads. The permeability of regolith is additionally important when considering the construction of subterranean habitats. This FY25 Research and Technology (R&T) project at NASA KSC focused on measuring the gas permeability of granular lunar regolith simulant material in support of the Human Landing System (HLS) PSI project (see <https://ntrs.nasa.gov/citations/20230018215>). For each HLS PSI ground test case (or computational modeling of PSI effects), the gas permeability of lunar regolith is a fundamentally important parameter needed to understand the efficiency of gas flow in producing plume-surface interaction effects during a lunar landing.

Permeability depends on the media through which the gases pass and the nature of the gases themselves. Gases can easily pass through granular materials when the gaps between the particles are relatively large compared to the particles themselves. Such conditions exist in both monodispersed large and small spherical (or rounded) samples, as relatively large gaps result from the small particle-to-particle contact areas. Glass beads and sand, therefore, have a high permeability, for example. Gases do not easily pass through granular materials with a broad dispersion of irregularly shaped particles. Such samples have relatively smaller gaps due to larger contact areas and infilling by smaller particles. Lunar regolith, therefore, has a low permeability. Compaction of granular materials reduces gap sizes; therefore, density is also a parameter to consider. Porosity is used to quantify the volumetric fraction of these gaps (or voids) as compared to the total volume of a sample, and the void ratio quantifies the volume of the void spaces compared to the volume of the particles. Tortuosity can be described as the diffusivity in free space compared to the diffusivity through the media.

The flow of a fluid through a porous material can be described by its viscosity, flow rate, the pressure differential across the depth or height of the sample, and the permeability of the material - i.e. the resistance of the material to the fluid flow, where a high permeability means little resistance. In the simplest case, the flow is assumed to be viscous, unidirectional, single-phase, and laminar, and the fluid is assumed to be

incompressible. The nature of gas flow through a granular material also depends on the pressure of the gas itself. At high pressure, the dynamics of a gas are viscous, dominated by collisions between constituent molecules, and the average distance traveled by a molecule before a collision is described by the mean free path. At low pressure, gas dynamics are non-viscous and affected by molecular collisions with the granular particle surfaces.

For the gas permeability of lunar regolith under low-pressure conditions, the non-viscous case should be considered. This is referred to as the Knudsen regime, the slip regime, or molecular diffusion. However, the introduction of an engine plume significantly changes the pressure above the lunar regolith, where the gas flow can become viscous. This is referred to as the Darcy regime or bulk flow. Consequently, studies of the gas permeability of lunar regolith during PSI conditions must account for both flow regimes.

This project reports on efforts to experimentally determine the rarefied gas permeability of a lunar regolith simulant known as BP-1, which is sourced from the Black Point basalt flow outside Flagstaff, AZ. The geotechnical properties of BP-1 - such as morphology, particle size distribution, bulk density, and consequently, porosity - are consistent with natural lunar regolith, thus making BP-1 a relevant mechanical analog of lunar regolith for the HLS PSI ground test campaign that will be conducted at NASA LaRC in 2025-2026.

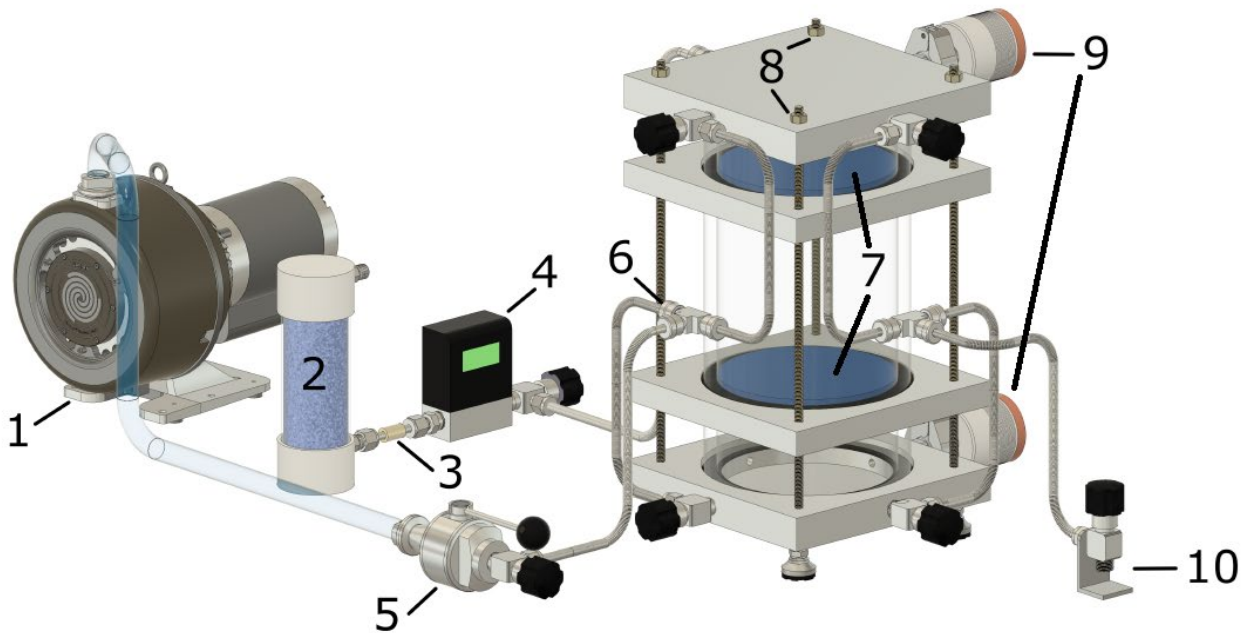


Figure 1. To scale REGAPT CAD rendering. The end plates and connecting plates are 8-inches square. **1)** Vacuum pump. **2)** DRIERITE® air and drying unit. **3)** 7-micron filter. **4)** Mass Flow Controller. **5)** Vacuum butterfly valve. **6)** Swagelok® fittings. **7)** Porous plate. **8)** Threaded rod and clamping nut. **9)** Pressure sensor. **10)** Needle valve.

The REGAPT (Figure 1) is an apparatus developed under this project to determine the gas permeability of a column of dried, granular material in response to the controlled flow of gas (dry air, in this case) under sub-atmospheric pressure conditions. The relevant measurements were the mass flow rate and temperature of the gas, as well as the gas pressure values above and below the layer of granular material, which was placed between two porous plates and compacted to a measured mass density. The Knudsen diffusion coefficient

and the dynamic viscosity were calculated, from which the permeability of the granular material was determined.

Table 1. Permeability and diffusion coefficient results from REGAPT measurements of BP-1.

Density (gcm^{-3})	Porosity	Moisture Content (%)	Permeability ($\times 10^{-13} m^2$)	Diffusion Coeff. ($\times 10^{-5}$)
1.65	0.43	0.87	1.9(0.1)	4.7(0.3)
1.65	0.43	0.52	1.7(0.1)	4.7(0.3)
1.65	0.43	0.07	1.1(0.1)	4.7(0.3)
1.65	0.43	0.03	1.2(0.1)	4.7(0.3)
1.82	0.37	0.04	0.50(0.05)	3.0(0.2)
1.90	0.18	0.04	0.38(0.05)	2.9(0.2)

The gas permeability of lunar regolith simulant BP-1 under sub-atmospheric pressures was measured using REGAPT and found to be on the order of $1 \times 10^{-13} m^2$ (Table 1). BP-1 samples were tested at three separate moisture content levels, and at three densities holding the moisture content constant. Permeability decreased for higher-density samples, but appeared to increase for higher-moisture-content samples. Outgassing of moisture adds a bias to the differential pressures that mimics a higher permeability. Higher-moisture-content BP-1 also adds significant overhead to testing procedures when attempting to bring it under low pressure. Outgassing increases the time to reach low pressure, and sudden outbursts disrupt the geotechnical conditions of the sample. Low pressures can be achieved faster and without eruptions if the BP-1 moisture content is below 0.1 percent.

Anticipated Benefits: The results of this FY25 R&T REGAPT2 project will inform NASA about the expected gas permeability of lunar regolith. This is a fundamentally important parameter needed to understand the efficiency of gas flow through regolith on the lunar surface. Such measurements will help predict PSI effects during a lunar landing, aid the development realistic computational models of PSI effects for lunar lander vendors designing vehicles that will enable sustainable lunar surface exploration missions, and support the use of lunar regolith for in situ resource utilization and lunar construction.

Project Closeout Summary: Motivated by the wide range of reported permeabilities in the literature, the range of regolith simulants used previously, and the dependence of permeability on density and moisture content, this FY25 R&T REGAPT2 project developed REGAPT to more accurately determine the gas permeability of the lunar regolith simulant BP-1. REGAPT has demonstrated the ability to measure the gas permeability under sub-atmospheric pressures using a broad range of differential pressures and gas flow rates. Granular materials representing all regolith simulants (e.g., lunar, Martian) can be tested at a range of densities and controlled for moisture content. The results of the REGAPT2 project are expected to influence future revisions of NASA's *Cross-Program Design Specification for Natural Environments* (DSNE)-specifically with regard to the permeability of lunar regolith found in Document No: SLS-SPEC-159.