ENGINEERING AND TEST DEVELOPMENT OF HEAT FLOW PROBE AND PNEUMATIC DRILL FOR LUNAR LANDER MISSION TO MARE CRISIUM.

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Introduction: In 2023, Firefly Aerospace, under NASA's Commercial Lunar Surface Payloads (CLPS) program will fly its Blue Ghost lander to the surface of the Moon with government and commercial payloads. Here we describe the pneumatic drill for deployment of the Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity (LISTER), which is one of ten NASA-supported payloads for this mission.

The LISTER heat flow probe design meets the following top-level requirements:
- ❑ Measure heat flux at landing site to 10% accuracy
- ❑ Make at least 3 measurements between 1-m and 2-m depth
- ❑ Complete the mission before lander-induced thermal noise affects subsurface regolith
- ❑ Conform to constraints of Total Mass < 15 kg; Power < 33 W (average during quiescent periods), 88 W (average during drilling)
- ❑ Meet Do No Harm requirements to ensure compatibility with operations of the lander and other payloads

The design, which has passed its critical design review, has been developed through extensive testing to inform both drilling performance and instrument measurement performance.

Heat Flow Probe Architecture and Concept of Operations: Heat flow is obtained as the product of the thermal gradient and the thermal conductivity of the regolith depth interval penetrated by a probe. LISTER is targeting a 2-m threshold depth, with a baseline objective of 3 m depth as recommended to avoid the influence of thermal waves associated with insolation cycles [1].

LISTER's drilling and sensor mechanism ("Mechanism") weighs less than 9 kg and fits within a 32 x 33 x 43 cm volume. LISTER Mechanism is a lander-agnostic system, designed to attach to a downward-facing surface, such as a lander underbelly (Fig. 1)

LISTER uses a pneumatic excavation system in quickly penetrating into lunar regolith [2]. Its deployment mechanism spools out a coiled tubing boom made of stainless steel (Fig. 2). On the way out of the mechanism, the coiled tubing is yielded and straightened to become a stiff drilling boom. The probe tip at the leading edge of the boom advances by the combination of the deployment motion and a nitrogen gas jet,

fed through the boom and emitted from the probe tip nozzle, blowing away regolith particles.
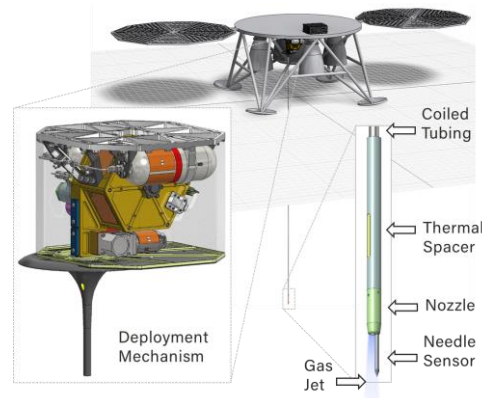
**Figure 1.** LISTER Mechanism on a generic lander.

A short (2.8-cm length), thin (2.8-mm diameter) needle sensor is mounted at the end of the probe tip (Fig. 1). The probe makes stops at pre-targeted depths on the way deeper into the regolith. At each stop, the gas jet shuts off, the needle sensor is pushed into the yet-to-be-excavated, undisturbed regolith at the bottom of the hole, and it makes temperature and thermal conductivity measurements. A platinum resistance temperature detector is used as the temperature sensor. After insertion to the regolith, the needle sensor passively monitors the temperature for 60 minutes as it thermally equilibrates with the surrounding. Afterwards, the needle heats up for 30 minutes and monitors the temperature rise over time. Thermal conductivity is determined from the rate of warming [3].

Five sets of such thermal measurements with ~0.5-m depth intervals will be obtained down to 2-m depth in one earth day. The stretch goal includes additional measurements to 3-m depth.

Laboratory Testing and Design Refinement: The difficulty of pneumatic drilling will clearly be affected by rocks, but lunar subsurface data is insufficient to precisely predict the nature and likelihood of rock encounters. In addition, drilling performance cannot be analyzed in high fidelity and must be verified empirically. Thus, LISTER hardware has been tested as early and often as practicable, with realistically-conservative conditions to characterize risk and verify design and operations concept.

Factors that drive how challenging a sample will be for LISTER – size and frequency of rocks, and level of compaction – have been determined from available data. Conservatism has been added to determine LISTER's design performance envelope; in particular, the concentration of small rocks is significant (typically ~33%vol) to ensure that rock encounter frequency is adequate in testing to avoid "lucky" successes (Fig 3.) Testing in 1-G gravity with rocks (rather than, e.g., lightweight aircrete simulants) is also conservative.

Testing has successfully demonstrated the full drilling and measurement ConOps, including drilling to 1.35-m depth in conservative rocky simulant, and to a 2.2-m target depth in an ideal fines-only simulant (Fig. 4 and 5). Furthermore, a mitigation strategy against rocks referred to as "dithering" has been tested and shown to be effective in aiding penetration.
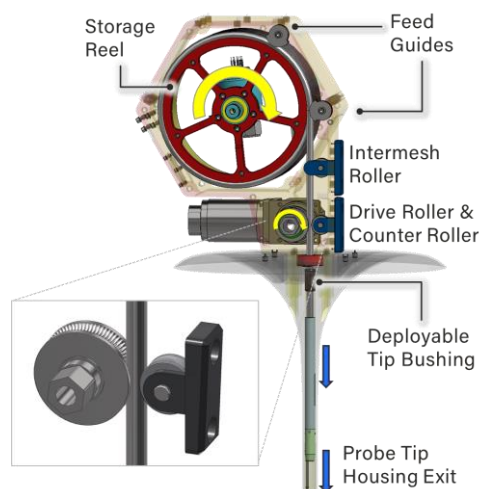
Figure 2. LISTER Mechanism cutaway view, showing deployment schematic

Figure 3. Borehole following vacuum drilling test in conservative rocky simulant, showing ~33%vol sample rock distribution with depth
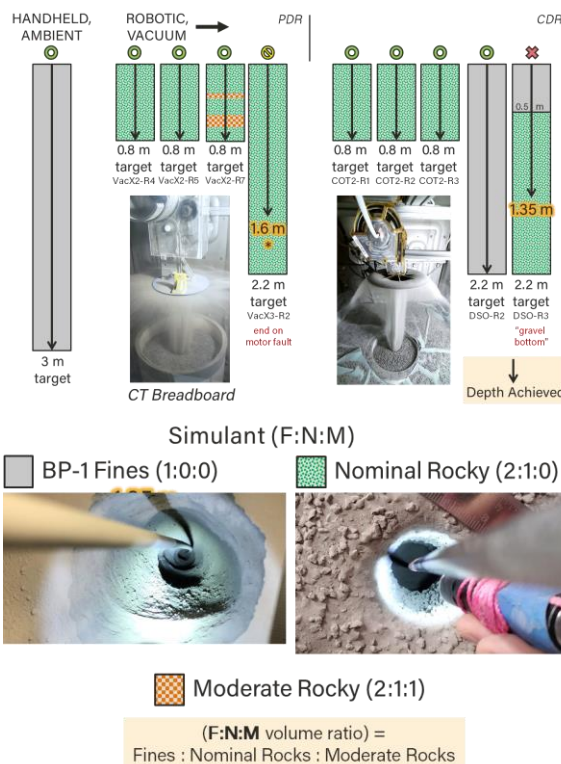
Figure 4. Summary of LISTER drilling test results. Simulant types are highlighted in the bottom legend.

Figure 5. Time-lapse image collage showing the start of pneumatic drilling into lunar simulant inside a vacuum chamber.

References: [1] Cohen, B. A., et al. (2009) *ILN Final Report*, 45 p. [2] Zacny, K. et al. (2013) *Earth, Moon, Planets, 111*, 47-77. [3] Nagihara et al. (2012) *International Workshop on Instr. for Planet. Missions,* Abstract#1014.