

HEAT FLOW PROBES FOR SMALL LUNAR LANDER. E. Mumm¹, K. Zacny¹, N. Kumar¹, M. Hedlund¹, S. Smrekar², P. Morgan³, S. Nagihara⁴, J. Shasho⁵, A. Pierides⁵, and B. Milam⁶, ¹Honeybee Robotics Spacecraft Mechanism Corp. (zacny@honeybeerobotics.com); ²NASA JPL, ³North Arizona University, ⁴Texas Tech University, ⁵The City University of New York, ⁶NASA GSFC.

Introduction: The heat-flow probe directly addresses the goal of the Lunar Geophysical Network, which is to understand the interior structure and composition of the Moon [1]. The International Lunar Network (ILN) is a near-term mission that requires a heat-flow probe. ILN is a set of four small landers, scheduled for launch in the 2016-2018 time frame that will deploy up to four instruments. The ILN payload is limited to ~25kg and its power will most likely be provided by a ASRGs.

To place 1kg on the surface of the Moon costs ~\$50k to \$100k. Thus, any scientific instruments must be efficient with respect to limited spacecraft resources such as mass, power, and volume without compromising on quality scientific measurements.

A key challenge for a heat-flow probe will be getting to a 3m depth at which the endogenic thermal gradient can be measured, i.e. below the depth of penetration of the annual thermal wave, within ILN Payload limitations. The Apollo 17 two heat flow probes reached 2.4m.

To accurately measure endogenic heat flow, two measurements need to be acquired: the thermal gradient and the thermal conductivity. The thermal gradient is determined from temperature measurements at different depths. The thermal conductivity can be measured at the same depths as the temperature measurements by inserting heaters. The thermal gradient is a differential measurement and must exhibit better than 0.05 K precision. The precision required can be achieved via thermocouples or RTDs, depending on the implementation architecture. There are two ways to measure thermal conductivity. The first one, used by Apollo 15-17, is the so-called 'continuous heating' technique and the second method (developed after Apollo missions) is called 'pulse heating' technique.

Heat-Flow Probe Concepts: We have been developing two highly innovative low mass and low power heat-flow probe systems (robotic, but can be also astronaut deployable). Each system consists of two parts: 1) a method of reaching 3m depth in lunar regolith, and 2) a method of deploying thermal sensors [2].

Percussive Heat Flow Probe: The first system uses a percussive (hammer-like) approach to drive a small diameter (20mm) cone penetrometer to >3 meter depth (Figure 1). Ring-like thermal sensors on the penetrometer rod (heaters and temperature sensors) are deployed into the regolith every 30 cm as the penetrometer goes down to 3 m. The system leaves only small sensors in the borehole. The deployment rod is removed once depth is reached, maximizing measurement sensitivity by eliminating thermal path to lander except for the electrical tether.

In addition, the penetration rate of the percussive penetrometer can be correlated to regolith bearing strength and density; this added measurement will help with thermal conductivity correlation.

There are two critical aspects of this system: 1) penetrating highly compacted regolith to the required depth and 2) deploying thermal sensors. We have demonstrated both aspects and in turn verified successful operation of this method.

Verifying Penetration into Lunar Soil Simulant: To verify penetration of the regolith, we devised an experiment whereby a rod with a cone at the end was driven into highly compacted JSC-1a lunar regolith simulant by a percussive hammer system. The density of the regolith was >1.9 g/cc which corresponds to a relative density, D_r , of >90%. This high compaction (consistent with densities of lunar soil on the Moon) was achieved using a vibrating table. The regolith was introduced in small batches and a dead load applied to ensure high relative density. All penetrometer designs reached 0.9 m depth, though with different speeds. The fastest, corresponding to 10mm diameter cone, reached the bottom in a few tens of seconds while the slowest, corresponding to a 25mm diameter cone, took 3 minutes. The tests thus showed an increase in the amount of time and energy required to penetrate the regolith with increasing cone diameter. Thus, it is important to keep the borehole as small as possible. The size of the borehole must be traded against the difficulty of packaging sensors within borehole clearance constraints.

Verifying sensors Deployment: A sensor deployment scheme was developed whereby sensors were placed on the outside of the penetrometer rod and were deployed in a "top-down" scheme (Figure 2). Once the penetrometer reached depth for a given sensor, the sensor was deployed via a burn wire and the penetrometer was lowered to a next position. For this 1m demonstration system, sensors were released from the penetrometer rod at 20 cm, 40 cm, 60 cm 80 cm, and 100 cm.

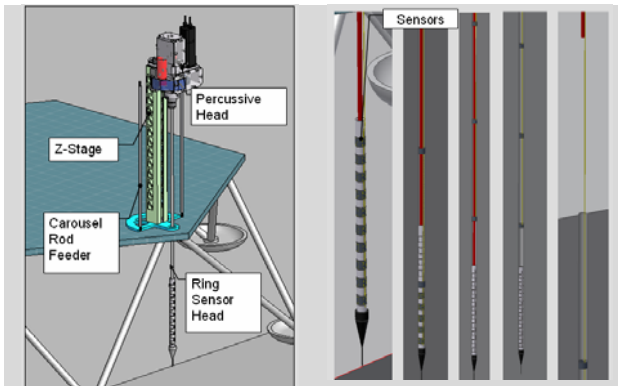


Figure 1. Percussive Penetrometer deployment of heat flow sensors. Upon reaching the depth, the rod is pulled out and sensors are left in a hole.

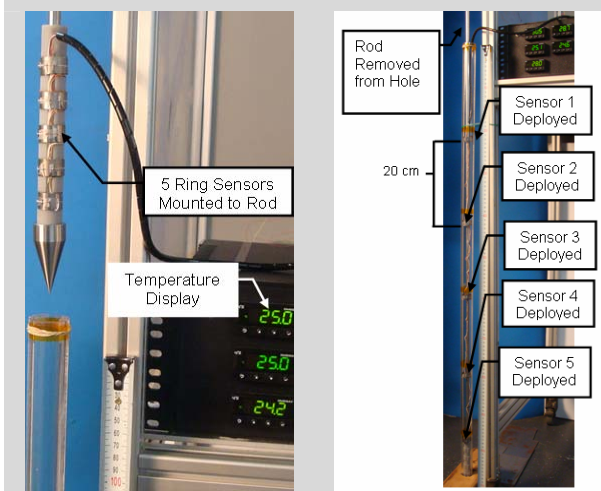


Figure 2. Prototype Sensor deployment. Left: Sensors mounted near percussive rod tip deployed into a hole (clear acrylic tube); Right: 5 ring sensors deployed every 20 cm to 1 meter depth.

Pneumatic-Proboscis System: The second system uses a pneumatic (gas) approach to lower the temperature and thermal conductivity sensors attached to a lenticular (bi-convex) tape to >3 meters (Figure 3). The system is a revolutionary innovation for ILN as it has extremely low mass, volume, and simple deployment. This system is dubbed the “Proboscis” because of its similarity to a butterfly proboscis.

The pneumatic heat flow architecture implements concave/convex tapes in a different manner to arrive at a bi-convex (lenticular) shape. A set of two tapes are arranged in a biconvex configuration and bound together, forming a rigid rod capable of pressing the needle tip into the soil. RTDs are integral to the tape. The tape is coiled around a deployment drum similar to how a tape measure functions. The full length of the heat flow probe can then be packaged in a small form factor around the drum. Compressed gas is

plumbed to the nozzle at the end of the tape which provides the mechanism for penetration into the regolith. A heating needle with an RTD protruding from below the cone measures the temperature and conductivity of undisturbed regolith ahead of the cone.

Helium gas, used for pressurizing liquid propellant and typically vented once on the surface, can be scavenged from the lander propulsion system, making the thermal probe system lighter. Should spacecraft helium not be available, a simple gas delivery system may be added specifically for the heat flow probe. Honeybee demonstrated that 1 gram of N₂ at 5 psia can lift 6000g of JSC-1a in lunar conditions (vacuum, 1/6g) [3]. Thus, only a small amount of gas would be required to penetrate to 3 m.

The pneumatic proboscis system has the potential to be a game-changer for the ILN mission. The extremely low mass and volume required to reach 3m, along with very simple penetration method allow the heat flow instrument to remain in a variety of payload architectures. The low mass and power cost of such a system may result in higher risk tolerance because it does not come at a large cost with respect to other payload elements.

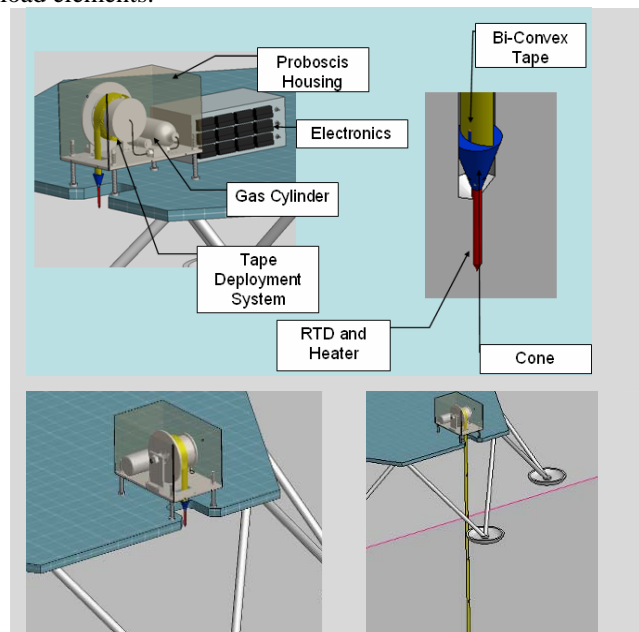


Figure 3. Pneumatic Proboscis deployment of heat flow probe uses compressed helium gas to advance below the regolith surface.

References: [1] Science Definition Team for the ILN Anchor Nodes, ILN Final Report (2009). [2] Zacny, K. Methods and Considerations for Heat Flow Probe Deployment, NLSI (2009). [3] Zacny, K. (2009) *LPS XXXX*, Abstract #1070.