MODULAR HEAT FLOW PROBE FOR SMALL LUNAR LANDERS. S. Nagihara[1], K. Zacny[2], M. Hedlund[2], and P. T. Taylor[3], [1]Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), [2]Honeybee Robotics, Pasadena, CA 91103, [3]Goddard Space Flight Center, Greenbelt, MD 20711.

Introduction: Heat flow measurement is considered a top priority for future lunar-landing missions by the latest Decadal Survey by the National Research Council [1]. The Survey recommends a *New Frontiers*-class, *Lunar Geophysical Network* (LGN) mission, which would deploy a 'global, long-lived network of geophysical instruments on the surface of the Moon' and that heat flow measurement would be a part of it. Besides LGN, a number of robotic and human lunar-landing missions are proposed by government agencies and private organizations such as *Resource Prospector*, *SELENE-2*, *Luna-Glob*, *Golden Spike*, and the missions competing for the Google Lunar X Prize.

Heat flow is obtained as a product of two separate measurements: the thermal gradient and the thermal conductivity of the depth interval of the regolith penetrated by a probe. A panel of scientists [2] recommend that a heat flow probe on a future lunar mission should penetrate to a minimum of 3 m into the lunar regolith, ~0.7 m deeper than the depth reached by the Apollo 17 heat flow experiments [3].

The enhancement in excavation capability is necessary for high-quality data, while a light-weight, compact system is desired for relatively small landers considered for the aforementioned missions. Here we report our progress in designing and testing prototypes of such low-mass, low-power lunar heat flow probes for possible use in future lunar robotic missions.

System Description: Our heat flow probe utilizes a pneumatic excavation system in deploying thermal sensors into the subsurface. The deployment mechanism (~28-cm tall, Fig. 1) of the probe spools out a glass fiber composite stem downward. The stem then forms a hollow cylinder of ~1.5-cm diameter (Fig. 2). It pushes the penetrating cone into the regolith, while gas jets, emitted from the cone tip, blow away loosened material. Removing material from the bottom of the excavated hole allows the stem to advance deeper with minimal thrust. A short (~1.5 cm), thin (~2-mm diameter) thermal probe attached to the cone tip measures temperatures and thermal conductivities of the regolith by stopping for 30 minutes at different depths on the way down. During each stop, to measure the thermal conductivity of undisturbed regolith, the probe shuts off the gas jet and pushes the needle probe into the bottom-hole regolith. After the stem reaches the targeted, 3-m depth, the temperature sensors embedded on the fully extended stem monitor long-term stability of the thermal gradient.

Figure 1. The latest prototype of the lunar heat flow probe with the stem stowed.

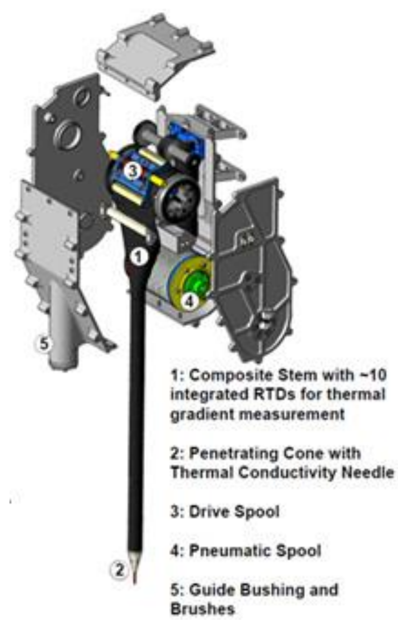

Figure 2. Schematics of the major components of the heat flow probe.

In its current design, the probe weighs 1.2 kg and can operate with a minimal power (< 10 W). The compressed gas required for excavation can be provided from a dedicated gas tank or from a pressurant tank which is part of the propulsion system (and in turn comes "free"). The gas excavation efficiency can reach 1:6000 (1 g of gas can loft 6000 grams of soil) in vacuum [4]. The use of the pneumatic excavation system enables more than 10 kg of saving in total mass, compared to a rotary-percussive drill such as the one used in the Apollo heat flow experiments [3].

Our heat flow probe is a modular system, and it can be accommodated into a variety of lander configurations. It only requires a stable platform for deployment on the lunar surface. It is also an ideal science payload for a human lunar-landing mission, because it is a set-it-and-forget-it system from the astronaut's point of view. All the astronauts need to do is to find a suitable location and set up the probe. Then, it can be remotely deployed from the earth [5].

Lab Tests: We have presented elsewhere the results from our thermal conductivity probe measurements on JSC-1A lunar regolith simulant in a vacuum chamber [6]. Here, we focus on our recent excavation tests using the latest prototype of the heat flow system (Fig. 1).

In our first test, the probe was deployed into well compacted JSC-1A lunar simulant filling a 1-m deep bin placed in a vacuum chamber set at 4 Torr. The penetrating cone reached the bottom of the bin in less than one minute, using 5 grams of nitrogen gas pressurized at 400 kPa, while weight on bit (WOB) was kept under 30 N most of the time (Fig. 3).

Next, we deployed the probe into NU-LHT-2M lunar highlands simulant filling a 3-m tall bin placed in a vacuum chamber. Using gas pressures and thrusting forces similar to our earlier penetration tests, we were able to advance the probe down 1.9-m depth into the simulant in ~2 minutes. The penetration stopped at that depth even at increased gas flow rates. Inspection after the test revealed that simulant particles were blown inside the hollow cylinder of the stem instead of being lofted between the stem and the borehole.

Finally, we carried out a stop-and-go operation test into NU-LHT-2M simulant in a vacuum chamber. The probe excavated down to 0.5-m depth, stopped for 30 minutes for a heating experiment for thermal conductivity measurement, resumed excavation down to 1-m depth, and carried out another heating experiment successfully. This demonstrated that it is possible to stop and re-start penetration, and in turn conduct thermal conductivity tests at various depths.

Discussion and Future Work: Our excavation test fell short of reaching the 3-m target depth because some regolith particles found their way into the interior of the hollow, cylindrical glass-fiber stem. The regolith particles inside the stem also made their way into the deployment mechanism and caused it to jam. We are now designing a new stem that can prevent regolith particles from entering its interior. We believe that would enable us to reach the targeted 3-m depth. On a separate test, we have already confirmed that a 3.5-m long, hollow aluminum tube can penetrate to 3-m depth into NU-LHT-2M just by blowing gas down the tube and its nose cone. The 3-m depth was reached in 3 minutes.

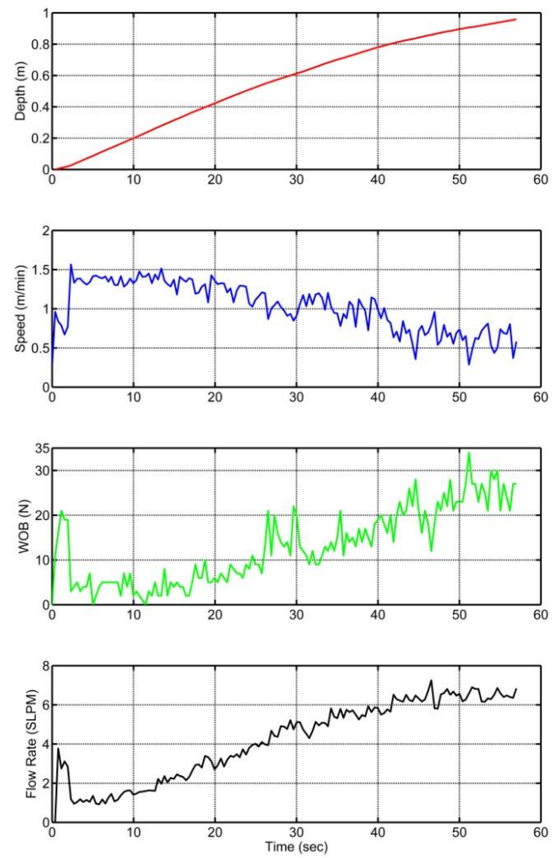

Figure 3. Instrument readouts from the 1-m excavation test on JSC-1A lunar regolith simulant in vacuum chamber.

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