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Thermal mapping and trends of Mars analog materials in sample acquisition operations using experimentation and models

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ABSTRACT

The effects of atmosphere, ambient temperature, and geologic material were studied experimentally and using a computer model to predict the heating undergone by Mars rocks during rover sampling operations. Tests were performed on five well-characterized and/or Mars analog materials: Indiana limestone, Saddleback basalt, kaolinite, travertine, and water ice. Eighteen tests were conducted to 55 mm depth using a Mars Sample Return prototype coring drill, with each sample containing six thermal sensors. A thermal simulation was written to predict the complete thermal profile within each sample during coring and this model was shown to be capable of predicting temperature increases with an average error of about 7%. This model may be used to schedule power levels and periods of rest during actual sample acquisition processes to avoid damaging samples or freezing the bit into icy formations. Maximum rock temperature increase is found to be modeled by a power law incorporating rock and operational parameters. Energy transmission efficiency in coring is found to increase linearly with rock hardness and decrease by 31% at Mars pressure.

1. Introduction

Drill-induced heating to a geologic sample on a planet or moon causes two substantial challenges. First, high temperatures may cause alteration to the sampled materials, for example, by baking clays or evolving volatile compounds of interest. Second, melting or sublimation of contained water ice could lead to an irrecoverable freeze-in of the bit inside the rock, soil, or ice formation.

Water ice on Mars has been detected by Mars Odyssey (Feldman et al., 2002) and touched by the Phoenix lander (Arvidson et al., 2009). Temperature changes caused by a sampling system are capable of creating phase change in ice (Zacny et al., 2004), which is due in part to the fact that the triple point of water is contained within the natural fluctuations of the Martian atmosphere. Should melted or sublimated water move from the hot cutting site at the bottom of a borehole to a cooler location near the rock surface, vapor could deposit onto the bit and freeze the bit in place. The adhesive strength of ice to steel below $-7\,^{\circ}$C is approximately 2 MPa (Raraty and Tabor, 1958), meaning that the force needed to pull a 2 cm OD, 5 cm long bit from a frozen borehole would be on the order of kilonewtons.

To minimize damage to the validity of scientific samples and risk to sampling hardware during rotary-percussive (RP) coring, it is necessary to carefully schedule sampling operations in order to prevent substantial temperature increases, for example, by scheduling pauses. A computer model, which predicts maximum temperatures according to known rock and drill properties, is essential in planning these operations. Monitoring feedback such as auger torque is not an acceptable approach for reasons listed in Szwarc et al. (2012).

2. Experimental testing

Experimental testing was performed at Honeybee Robotics Spacecraft Mechanisms Corporation's Pasadena, California office. The facilities at Honeybee include a 3.5 m^3 vacuum chamber capable of reaching Mars pressure in about 15 min; the Honeybee Subsystems for Automated Subsurface Sampling Instruments (SASSI), a Mars Sample Return (MSR) prototype drill capable of sampling with a variety of bits; computer support equipment to record temperature data from within rocks; and the rock saws and drills necessary to prepare samples for testing. The test setup is visible in Fig. 1. The 15.6 mm OD, 10.2 mm ID bit used was made from stainless steel and contains four tungsten carbide cutters.

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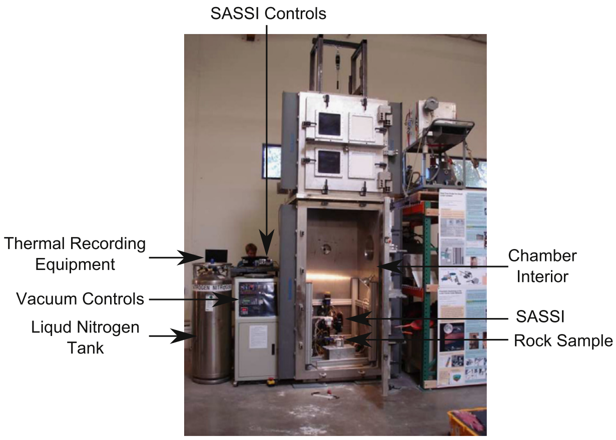

Fig. 1. The Honeybee Robotics vacuum chamber is shown along with the controls and data logging equipment used for the test suite.

2.1. Selected test materials

Five materials were selected for inclusion in the test suite.

Indiana limestone is a sedimentary rock with a typical unconfined compressive strength (UCS) of 45 MPa (Paulsen et al., 2010). It is generally consistent, homogeneous, well-characterized, and often used in drilling studies. For these reasons, it was selected for testing even though it is not an analog of a Martian or other planetary material.

Saddleback basalt, with a typical UCS of 115 MPa (Paulsen et al., 2010), is also a popular material for planetary sampling testing. Its origin in the Mojave Desert means it can be easily obtained for study in Pasadena. Saddleback basalt is fairly uniform in composition and a good analog for study of rocks of volcanic origin on Mars.

Kaolinite is a white, sedimentary, phyllosilicate clay. The UCS of kaolinite is highly variable. Soft forms may be crumbled by hand. The material obtained and studied in this investigation was of a much harder form. Kaolinite is a widely used Mars analog representing materials which could provide insight into Mars' watery past. Kaolinite is known for its ability to cause clogging in drill augers, sieves, and small passageways, making it a difficult material to sample and process regardless of its strength.

Travertine is an additional sedimentary rock composed of material often deposited by hot springs. Since hot springs have potential astrobiological relevance, travertine is a useful Mars analog in studying sampling system performance on rocks of principal interest. On Earth, travertine is commonly used for interior and exterior decorative purposes. The UCS of travertine is somewhat variable but a typical value of 88 MPa was assumed (Fener et al., 2005).

Water ice was selected for study because of its applicability to Mars, Europa, and Titan. Although not tested here, the experimental apparatus used is also capable of testing ice/soil mixtures of arbitrary concentrations. An icy soil mix with perchlorate additions may provide useful data in studying Mars soil sampling in regions of interest. Such mixtures are recommended as candidates for future study.

2.2. Rock sample preparation

Sample preparation for rock testing began with large rocks, typically between basketball and kitchen sink size. These rocks were cored using a large rock drill apparatus with an 81 mm ID coring bit. Next, the core samples were sawed on their tops and bottoms into sections 103 mm in height. The same saw was used once more to slice the rocks into halves along each rock cylinder's axis of rotational symmetry.

A Dremel rotary tool was used to cut voids in the rock for sensor placement as well as channels to run wires through the samples. Following this step, the rocks were rinsed with water to remove dust.

After coring, sawing, channel cutting, and rinsing were complete, the rocks were baked for at least 24 h at 200 °C. This step was performed to remove water content introduced by the industrial drill and saw, as well as to remove the moisture from the rocks introduced by the humidity in the atmosphere. Following baking, the rocks were cooled and stored in a dessication chamber until needed.

For each rock sample, six sensors were installed. Two Omega 5TC-TT-K-40-36 PFA insulated K-type thermocouples (TCs) were used along the centerline to measure temperature along what would eventually become the 10 mm diameter, 55 mm long core sample. The response time constant of these sensors is approximately 0.05 s. Thermocouples were chosen here because of their small size. With thermal gradients in the core expected to be high, the small size of the sensors was preferable. Additionally, the small wire size meant that the thermocouples could be installed with minimum rock material removed from the core. The vacuum chamber's feedthrough connector did not allow for the K-type thermocouple wire materials to be used. However, since the span of the feedthrough was small and assumed to be in thermal equilibrium, errors were minimized.

Four Omega F2020-100-B-100 resistance temperature detectors (RTDs) were used for the remaining sensors. These RTDs were used within the rock but exterior to what would become the core, and also on the exterior of the rock. Response times for these sensors is under a second. By utilizing a four wire connection, accuracy was improved over that of the thermocouples, making the RTDs suitable in all cases where their 4 mm^2 footprint would allow. Although LN_2 testing brought the senors to a temperature below their suggested range, the temperature measured while submerged in the nitrogen was very close to the known value of LN_2's boiling point.

Resin Technology Group KONA 870 FTLV-DP thermally conductive potting epoxy was used to install all sensors. This epoxy was chosen to hold the sensors in place, insulate against electrical shorting of any sensors, and prevent impedance of heat flow into the sensors from the rock. The thermal conductivity of this epoxy is 1.0–1.15 W/m K, which is very similar to that of most rocks used for testing. The two rock halves of each sample were held together with hose clamps to allow the epoxy to dry. Fig. 2 shows the sensors within a limestone sample.

Prepared samples were held in place during testing by a mount. The aluminum mount consisted of a bottom plate and two movable side plates which were clamped together to hold the rock tightly. This removable mount was loaded with a rock sample and positioned inside the vacuum chamber.

Prior to the commencement of a coring test, a starter 1 mm deep hole was created. This starter hole was also modeled in the coring simulations so that experimental and simulated depths would be in agreement.

For a cold test, LN_2 submersion was performed. The rock sample, now having been installed with a starter hole and removed from the mount, was placed in a container of liquid nitrogen until thermal equilibrium was reached. The sample was then carefully lifted back into the mount. For low pressure tests, the chamber was pumped down at this time. Two webcams recorded video inside the chamber, while a point-and-shoot camera recorded from a tripod placed outside the chamber. A 40 N weight on bit was applied for each test. Thermal recording was enabled, and a 54 mm penetration command was issued to