A thermal model for analysis and control of drilling in icy formations on Mars

Akul Aggarwal

The presence of ice poses a threat to drilling systems acquiring rock or soil samples on Mars. Testing has shown that heat generated by drilling produces water vapor or liquid which may refreeze on the surface of a drill bit. Further experience has shown that the adhesion of ice is sufficient to cause drill bits to stall, resulting in permanent loss of the bit. In addition, heat created during drilling can impact the chemical and physical composition of the sample even at temperatures below the melting point of ice, so restrictions may be imposed upon the allowable heating of a soil or rock formation during a mission. Developing a thermal model of the bit and formation is essential to prevent the loss of scientific data and drill bits, as well as to prevent complete failure of the mission in a spacecraft carrying only a single drill string. Using only properties of the formation and drilling system, a computer model has been created to predict temperatures throughout the bit and formation. This model has been shown to be in agreement with preliminary data acquired from tests performed under Mars-like conditions and using a prototype Mars Sample Return (MSR) drill. This model may be used to create schedules for drilling operations by determining the frequency and duration of pauses necessary to let the borehole cool before drilling may safely resume. This method has advantages over alternative scheduling methods such as monitoring drill parameters (e.g., motor torque) which may only change after ice has already frozen to the bit. The thermal model will be an essential tool in safely acquiring unaltered geologic samples, either for in situ analysis or for return to Earth.

I. INTRODUCTION

Low temperatures and pressures on Mars create ambient rock and soil conditions in some locations that are near the triple point of water. The presence of water ice in the top meter of soil is well documented by the Mars Odyssey mission and ice has been sampled in one location by the Phoenix lander.

When water ice is contained in rocks or soil, heat created by friction during coring or drilling may be sufficient to cause sublimation of the ice, causing gaseous water and rock cuttings to eject from the borehole. Although this phenomenon may be useful in assisting or replacing the auger’s role in removing cuttings from the borehole, it presents a serious problem in the form of vapor-deposited ice. Gas particles which contact cooler areas of the bit further from the cutting site may refreeze, creating deposits of ice which grow throughout the duration of a test. The adhesion of ice onto many metals is substantial: the shear strength of ice adhering to steel at temperatures below -7 °C is about 2 MPa. As these deposits grow, they have the ability to freeze to the borehole or create a rough surface that may restrict the ability of the bit to rotate. Additionally, these deposits may clog the auger channels and inhibit the ability of the bit to remove cuttings from the borehole. Removal of the cuttings from the borehole is essential, otherwise existing cuttings would be reground indefinitely and further penetration would be impossible.

An additional consequence of heating while drilling or coring is the modification of the rock or soil content and subsequent loss of scientific validity of the samples. Evolution of volatile materials located within the geologic sample, due to substantial heating of the sample’s contents, will be detrimental to analysis. Therefore, a heating system which can dislodge a frozen bit is not an acceptable means of acquiring samples, although such a system may be useful as a last resort on a mission with a single or limited quantity of bits.

For these reasons, regardless of the water content of the formation to be sampled or the ambient temperature and pressure, a temperature threshold may be placed as a requirement for sample acquisition operations. A thermal model will be vital in ensuring that this requirement is satisfied for a number of reasons. Using a set of sensors to measure temperatures of the rock while drilling is extremely challenging to implement from a hardware design point of view, considering that bits will likely be changed or a single string may be constructed from a stack of segments, and that a large number of slip rings would need to be incorporated into the drill. Additionally, an embedded sensor would not be in direct contact with the formation and might not necessarily measure the hottest location of the rock or soil during all sample acquisitions, as this location may vary depending on the composition of the formation.

A computer simulation with the sampling system’s operating parameters and the thermal parameters of the rock, which may be estimated from inspection of the rock using cameras or other sensors, could provide a complete and accurate thermal profile for the duration of the test. This model could be used to create drilling schedules, composed of periods of drilling and pauses to allow the borehole to cool, which could keep all locations within a rock below a specified threshold temperature. Such a schedule would aid in protection of the scientific validity of samples, prevention of lost bits, and acquisition of samples in minimal time.

II. EXPERIMENTAL SETUP

In order to acquire data to test the validity of a thermal model, a sequence of drilling tests was run on a block of 45 MPa Indiana limestone. These tests were conducted in a vacuum chamber at 6.0 torr to simulate Mars pressure and specifically to significantly reduce the convection of heat to the atmosphere. The Honeybee Robotics System for Automated Subsurface Sampling (SASSI) corer/drill, a prototype for an MSR mission, was equipped with a 2 cm diameter full face powder-acquisition bit used to conduct all tests. The SASSI can be seen in Figure 1, along with the arm and z-stage used to position and preload it against the rock.

Table 1 provides relevant parameters of the rock and drill, while Table 2 summarizes the tests performed. All of this information was input into the computer simulation to model each of the experiments.

Four 4-wire resistance temperature
detectors (RTDs) were placed on and inside a block of Indiana Limestone at a variety of locations in order to provide surface and interior temperature values. These RTDs can be seen installed on and in the limestone block in Figure 2. The positions of the RTDs are displayed in Figure 3. Henceforth, RTDs 1 and 2 are referred to as exterior RTDs, since they are mounted to the top face of the rock, while RTDs 3 and 4 are referred to as the interior RTDs. The RTDs are attached or potted using thermally conductive epoxy to prevent additional thermal resistance and provide firm fixture. The entire experimental setup, including the chamber interior, limestone block, and support and positioning structures, is visible in Figure 4. The Omega F2020-100-B-100 RTDs used for testing have a maximum error in accuracy of about ±0.5°C at the temperatures encountered during testing.

The goal of each test was to acquire thermal profiles at the locations of the RTDs as the rotating bit generated heat during drilling. Although the SASSI is capable of rotary percussive drilling, only rotary drilling was enabled for these tests. In test 1, a rest period allowed the drilling site to cool before drilling resumed. No active cooling system was employed; all cooling refers to equilibration of hot material with cooler areas of rock further from the drilling site. Test 2 was an uninterrupted test. Both tests were concluded with rest periods.

### III. DISCUSSION OF THERMAL MODEL

The computer model, which was programmed in MATLAB, is based upon a cylindrical discretization of the formation and bit, as well as the temporal discretization of the duration of the cutting process of the bit. An axisymmetric assumption was used, allowing a two dimensional display along the r and z-axes to represent the entire system. The code is based upon the discretized heat equation. At present, the simulation allows for full-face drill bits of any size, although coring bits have not yet been incorporated into the code. Frictional heat is supplied at the interface of the bit cutting surface and rock at the bottom of the borehole. In accordance with results from research on frictional heating in drilling; 15% of this heat enters the bit, and the remaining enters the rock at the bottom of the borehole. Friction is reduced when pressure is reduced to that of ambient conditions on Mars, so it is crucial that the correct frictional heating power levels be input into the model.

The outer edge of the bit and the inner surface of the bit are assumed to be in thermal contact at all times. Therefore, thermal equilibrium is enforced between each element of the bit along bit’s exterior edge and each corresponding element on the innermost surface. No heat is assumed to be created at these sites. The simulation allows for penetration and power input to be paused in order to simulate a rest period, but heat transfer still occurs within the bit, within the rock, between the outer surface of the bit and inner surface of the borehole, as well as at the bottom of the hole where thermal equilibrium is enforced between the drill elements and the corresponding rock elements beneath.

The rock simulated in the tests was 160 mm in radius - extending about four times as far from the bit as the furthest location actually measured in the experimental testing, and 120 mm in height.

### Table 1 Rock and drill parameters

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock</td>
<td>Indiana Limestone</td>
<td>1.3</td>
<td>880</td>
<td>2760</td>
</tr>
<tr>
<td>Bit cutter</td>
<td>Carbon Steel</td>
<td>54</td>
<td>490</td>
<td>7850</td>
</tr>
</tbody>
</table>

### Table 2 Summary of tests.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Borehole Center X-Pos [mm]</th>
<th>Borehole Center Y-Pos [mm]</th>
<th>Avg Auger Power [W]</th>
<th>Average Rate or Penetration (ROP) [m/min]</th>
<th>Duration/Rest Periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>18.58</td>
<td>6.75</td>
<td>2.40E-04</td>
<td>Drilled for 9 minutes, rested for 24 min.</td>
</tr>
<tr>
<td>2</td>
<td>22.46</td>
<td>-18.46</td>
<td>7.01</td>
<td>1.50E-04</td>
<td>Drilled for 90 minutes, rested for 28 min.</td>
</tr>
</tbody>
</table>
- nearly 10 times the depth of penetration of any test. Element spacing in MATLAB was 2 mm in the r-direction, and about 0.2 mm in the z-direction (exact spacing is calculated based on the penetration rate of the experiment to be simulated).

IV. COMPARISON OF SIMULATION AND EXPERIMENTAL DATA
The recorded experimental data and the predictions created by the computer simulation are shown in Figures 5 and Figures 6 for test 1 and test 2, respectively. Ambient temperatures were 25.4 °C and 24.2 °C for the tests. As can be seen in Figure 5 and Figure 6, the experimental and simulated results show good agreement, with average errors being 0.86 °C and 1.26 °C, respectively. These errors correspond to 4.8% and 9.0% of the maximum rise in RTD 1 temperature for test 1 and test 2. This agreement confirms the accurate modeling of thermal profiles in a bit and formation during a sample acquisition operation. Figure 7 shows the thermal profile of the sub-region of rock closest to the borehole at 480 seconds into test 1. Figure 8 shows the thermal profile of the bit at the same moment.

The maximum rock temperature at 480 seconds is 120 °C, corresponding to a rise of about 100 °C above the ambient temperature. If this temperature had exceeded a threshold established for an actual drilling operation on Mars, a rest period would need to be scheduled prior to the 480 second mark, or the power usage of the drill would need to be restricted.

There is a small amount of disagreement between the simulation and the experimental results, primarily in test 2, and in particular for the RTDs closest to the 480 second mark, or the power usage of the drill would need to be scheduled prior to the actual drilling operation on Mars, a rest period would need to be scheduled prior to the 480 second mark, or the power usage of the drill would need to be restricted.

After penetrating past 7.0 mm, cuttings removal is made more difficult as two of the four pathways become blocked (the left one in Figure 9), while the other two become increasingly blocked (the right one in Figure 9). When cuttings can no longer escape quickly, thermal power input to the rock reaches the expected value entered into the simulation. At this point, the simulated and experimental curves are seen to be nearly parallel, although an offset has been created during the first regime of penetration which provides error throughout the duration of the test.

Additionally, gaseous convection to the thin atmosphere may cause a non-negligible reduction in temperatures. At present, convection is not included in the simulation. During early phases of penetration, while heat is being generated by the cutter close to the surface of the rock, convection at the surface of the rock may play a more substantial role than in later phases when the borehole is deeper. This may also explain the reduced rate of temperature increase experienced at depths less than 7.0 mm. Convection could also play a role in the borehole where the bit causes rapid movement of air near the hottest regions of the rock and bit.

Although the cutter is v-shaped and not flat as it is assumed to be in the simulation, the entire diameter of the bit reaches the rock quite quickly, so the effects of the v-shaped cutter are assumed to be negligible. Much of this small v-shaped region penetrates the surface during a short “hole start” routine designed to prevent the bit from wandering across the surface of the rock.

It is hypothesized that prior to penetration depths of about 7.0 mm, the bit is more effective at removing cuttings from the borehole than at later times. This may be due to the fact that although the cutter sweeps out the full cross-sectional area of the bit, there are large tapered sections in the bit which provide pathways for cuttings to escape the borehole. These pathways are viewable in Figure 9. An increased cutting removal rate would allow hot, freshly cut particles less time to conduct heat into the formation. The temperature of these cuttings is critical to determine, since these particles may contain quantities of volatile water.
V. CONCLUSIONS

The agreement of the results from simulated and experimentally conducted drill tests demonstrates that complete knowledge of the thermal environmental of a rock or soil formation during sample acquisition is possible and reliable, making it a powerful tool for Mars exploration. The ability of a thermal model to regulate power usage and create a schedule of periods of drilling and pausing provides a means for obtaining samples with minimal risk to hardware or scientific validity. Without such a model, achieving these gains would require observation of motor feedback parameters, such as auger current, at which point substantial and irreversible ice deposits may have already formed.

In addition, more recent versions of the simulation have been expanded to allow coring bits to be modeled, since core samples are of particular interest to MSR. Besides the obvious differences in cutter geometry, core sample simulations and experiments vary from full face simulations because the core samples inside the bit are subjected to different boundary conditions than rock elsewhere, so the thermal profile of core rock may differ from the rock studied thus far.

Further work on this research topic includes more advanced modeling on the motion of cuttings and heat transport as powder travels upward and piles on top of the rock surface. Currently, the model does not account for the effects of cuttings once they have left the borehole. In the experiment and in actual Martian drilling operations performed on surfaces level to the ground, hot cuttings are piled on the rock’s surface. The model predicts these cuttings to be at high temperatures, as these cuttings are created from the hot rock cut just beneath the bit. These cuttings convect little heat to the atmosphere because of the reduced atmosphere on Mars, and may conduct significant amounts of heat back into the top surface of the rock. However, the cuttings may serve as a heat sink once they have cooled and heat continues to flow from beneath the surface where frictional heating is still continuing. Since tests on Mars may be performed by coring vertical surfaces such as crater walls, the piling characteristics of the cuttings should be allowed to vary as a function of surface orientation.

Future research should also include investigations into increased clearing efficiency at the early stages of penetration, and should bit geometry be the cause of the change in temperature rise as hypothesized, the simulation should be made to account for variations in clearing rate. Additionally, gaseous convection should be included in the model to attempt to more closely model losses of heat at the surface of the rock and in the borehole.

Lastly, future testing should incorporate creation and testing of acquisition schedules. These schedules will be created by the model to prevent threshold temperatures from being reached. These schedules can then be used to control experimental testing and verify that samples can be acquired without creating unsafe temperatures. Long-term test plans include performing schedule-controlled tests on icy formations at Mars ambient temperature and pressure to demonstrate the effectiveness of the simulation in realistic conditions and the necessity of using a thermal model to guide sample acquisition on future missions.

VI. ACKNOWLEDGEMENTS

This research was made possible by the financial support of JPL’s Strategic University Research Partnership (SURP). The authors would like to thank Samad Hayati, Chad Edwards, Lori Shiraishi, and Kristo Kriechbaum of the Jet Propulsion Laboratory (JPL) for their input and discussions. The authors would also like to thank Gale Paulsen of Honeybee Robotics for aid in conducting the experimentation.

The author states co-authorship with Timothy Szwarc, Prof. S. Hubbard, Prof. R. Christensen, Prof. Brian Cantwell, Dr. K. Zacny.
Fig. 7 Thermal profile of the rock in test 1 after 480 seconds (8 minutes) of drilling. Ambient temperature is 25.4 °C. The borehole can be seen at the top left corner of the image represented by a white rectangle. The system is axisymmetric, with the left edge of the image representing the axis of symmetry. Hottest temperatures are shown to be at the bottom center of the borehole in this image.

Fig. 8 Thermal profile of the bit in test 1 after 480 seconds (8 minutes) of drilling. Ambient temperature is 25.4 °C. Note that because MATLAB draws contour plots by connecting midpoints instead of drawing boxes for each element, the bit actually spans from 0 to 1 mm along the r-axis. Hottest temperatures are at the bottom of the bit during drilling.

Fig. 9 A close-up image of the bit shows the pathways by which particles escape. Notice that the pathway on the left becomes nearly closed once penetration has reached a depth of 7.0 mm, while the pathway on the right becomes increasingly blocked as penetration increases. The reverse side of the bit has the same two pathways as the two seen here.

Akul Aggarwal is from Fremont, CA. He is majoring in Engineering Science with an emphasis in Mechanical Engineering at UC San Diego. Akul is interested most in the design and fabrication of mechanical parts, especially for cars, planes, submarines, and rockets (essentially, things that move, and move fast). In his spare time he loves to read, swim, and run. He is currently working on the Human Powered Submarine at UCSD. During the winter, he enjoys going to Tahoe to carve some snow.