Environmental Chamber Testing of a Rock Sampling Drill for Venus Exploration


Abstract

Honeybee Robotics has developed a rotary-percussive rock sampling drill and high temperature (HT) electromagnetic actuator for a proposed mission to Venus known as VISAGE (Venus In Situ Atmospheric and Geochemical Explorer). The drill is powered by two brushless DC motors that have been characterized in dynamometer tests run at both room temperature and Venus surface temperature of ~462°C. Dynamometer test results are compared with performance estimates obtained using ANSYS Maxwell analysis software, demonstrating that losses at high temperature can be predicted with reasonable accuracy. Drilling trials conducted in JPL’s Venus Material Test Facility (VMTF) have demonstrated the feasibility of sampling threshold strength Venus analog material within a time window compatible with the proposed VISAGE mission concept of operations.

Introduction

The surface of Venus presents a harsh environment for robotic exploration. Many of the critical subsystems comprising a Venus lander would be housed inside an insulated pressure vessel protecting them from the extremely hot and dense atmosphere (95% CO₂ at 462°C and >90 bar pressure). Under these conditions, conventional thermal management methods can provide only a few hours of mission life before the lander interior overheats. The surface sampling subsystem, on the other hand, must be mounted externally to interact directly with rocks and soil at the landing site. Environmentally “hardened” robotic mechanisms and high temperature (HT) sensors and actuators are needed to deploy to the ground, drill into rock and transport samples into the lander.

A logical first step in designing a mechanism for an extreme and unfamiliar environment like Venus is to build and test a high-fidelity prototype. In order to survive Venus conditions and yield useful performance data in a realistic test, albeit a very short one, the prototype should be built using high TRL (i.e., flight-like) materials, components and fabrication techniques. Per the proposed VISAGE (Venus In Situ Atmospheric and Geochemical Explorer) mission concept, the rock sampling drill breaks up surface rock into fine powder that can be pneumatically transported via an airlock into the cool interior of a lander, where science instruments can analyze the sample to determine elemental composition and other properties. Due to the short mission life, the drill should nominally penetrate to a 5-cm depth in threshold strength Venus analog material (Saddleback Basalt ~130 MPa) in 10 minutes. This desired penetration rate drives the drilling power which, in turn, drives the actuator sizing.

Honeybee Robotics has developed a rotary-percussive rock sampling drill and high temperature (HT) electromagnetic actuator (motor, sensor and gearbox) for Venus [1]. The motors have been characterized in dynamometer tests and simulations to study the effects of the high temperature environment. Drilling trials have been conducted in a CO₂ gas atmosphere at full Venus temperature and pressure (VTP) in JPL’s Venus Materials Test Facility (VMTF). These tests have demonstrated the feasibility of collecting surface samples in threshold strength Venus analog material within the time window allocated for sampling. The paper will present a comparison of predicted and measured motor performance at room temperature and

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Venus temperature and the resulting drill performance in each case. The work described herein represents the first pass through the design-build-test cycle that would eventually culminate in a flight drill.

**Honeybee’s HT Motor and Sensor Technology**

Electric motors offer many advantages for actuation of robotic systems deployed to Solar System destinations. They are versatile, simple to control and a variety of materials are available to suit different environments. With support from NASA’s SBIR program beginning in 2005, Honeybee Robotics has built and tested a number of different HT sensor and actuator technologies including a Switched Reluctance Motor (SRM), a Brushless DC (BLDC) motor, a resolver, and a variable reluctance commutation sensor known as PIPS (Pulse Injection Position Sensor) [2]. Based on this work, the BLDC motor was selected for further development because it can produce more torque than the SRM, although the BLDC motor operating temperature is limited by the Permanent Magnets (PMs) installed in the rotor. The PIPS sensor was selected instead of the resolver to provide rotor position feedback for commutation and speed control due to ease of fabrication, although the resolver can provide better resolution than PIPS.

Under a recent two-year SBIR project ending in 2017, Honeybee designed and built a new HT actuator consisting of a BLDC motor, PIPS sensor and custom planetary gearbox to power a prototype rock sampling drill for Venus. This actuator, shown in Figure 1, has been successfully dynamometer tested at both room temperature and Venus temperature in a 1-atmosphere oven [3][4]. Remote PIPS interface electronics located outside the oven provide Hall sensor signals compatible with commercial servo motor controllers.

![Figure 1. Honeybee HT actuator with remote (i.e., room temperature) interface electronics](image)

In the following sections the measured motor performance will be compared with theory and estimates obtained using ANSYS Maxwell analysis software, demonstrating that losses at high temperature can be predicted with reasonable accuracy.

**Temperature Effects on Electric Motor Performance**

Actuator sizing for operation in high-temperature environments must account not only for variability in the driven load but also for reduced torque and efficiency available from the motor. The reduced performance at elevated temperature is due to two important temperature dependencies that must be accounted for when designing for operation across a wide temperature range. The first is the increase in electrical resistance \( R \) of the motor coils at elevated temperature, which both decreases \( i^2R \) losses (self-heating) in
the motor and decreases the theoretical stall current (and, therefore, stall torque) of the motor for a given supply voltage. It can be calculated using the temperature coefficient of the magnet wire $\alpha_R$. The second is the decrease in magnetic flux density $B_g$ in the air gap between the rotor and stator, which can be calculated using the Reversible Temperature Coefficient (RTC) of the PMs. This decreases the motor torque constant $K_t$, which, in turn, reduces the stall torque even further. The motor speed constant $K_e$ is decreased by the same amount, thereby increasing the no-load speed. The overall effect is a reduction in motor maximum power output.

The equations used to calculate theoretical motor stall torque and maximum power output and their dependency on temperature are collected here [5][6]:

\[
\text{Stall Torque} = \tau_{st} = K_t I_{st} \tag{1}
\]

\[
\text{Max Power} = P_{\text{max}} = \frac{\omega_m \tau_{st}}{4} = \frac{V_{dL_{st}}}{4} = \frac{V_s^2}{4R} \tag{2}
\]

\[
K_t = 2NB_g L_{st} R_{ro} \quad (N, L_{st}, R_{ro} \text{ fixed by motor geometry}) \tag{3}
\]

\[
I_{st} = \frac{V_s}{R} \tag{4}
\]

\[
R = R_{\text{ref}} \left[ 1 + \alpha_R (T - T_{\text{ref}}) \right] \tag{5}
\]

\[
B_g = B_{g,\text{ref}} \left[ 1 + \text{RTC}(T - T_{\text{ref}}) \right] \tag{6}
\]

For the temperature range of interest (i.e., room temperature to $500^\circ$C), the temperature coefficients for the Ni-plated Cu magnet wire and Sm$_2$Co$_{17}$ PMs used in the Honeybee motor are, respectively:

\[
\alpha_R = 0.0038/^\circ\text{C}
\]

\[
\text{RTC} = -0.060%/^\circ\text{C}
\]

Competing motor designs may be compared on the basis of how efficiently they produce torque. For a given design, this performance characteristic can be quantified by calculating the motor constant $K_m$, defined in Eq. 7.

\[
K_m = \frac{T}{\sqrt{I^2R}} = \frac{K_t}{\sqrt{R}} \quad \text{in units of} \quad \left[ \frac{\text{Nm}}{\sqrt{\text{W}}} \right] \tag{7}
\]

In Eq. 7, $T$ is the torque output of the motor when supplied with current $I$ and $R$ is the resistance of the motor windings. In general, motors with a higher $K_m$ can produce more torque and they can operate for longer periods of time before overheating. Larger motors have a clear advantage in this regard. A given motor’s $K_m$ will be reduced at high temperature, however. Table 1 presents a comparison between theoretical performance of Honeybee’s HT motor at room temperature and high temperature. The calculations predict a reduction of 72% in stall torque and a reduction of 62% in maximum power output at high temperature. Actual test results will vary due to the simplifying assumptions made in these calculations.

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1 N = number of turns of wire in motor coil, $L_{st}$ = axial length of motor, $R_{ro}$ = air gap radius
Table 1. Comparison of theoretical motor performance at RT and Venus temperature

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Room Temp. 20 °C</th>
<th>High Temp. 482 °C</th>
<th>Units</th>
<th>Ratio HT/RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>V_s</td>
<td>48</td>
<td>48</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Coil Resistance</td>
<td>R</td>
<td>1.05</td>
<td>2.74</td>
<td>ohms</td>
<td>2.61</td>
</tr>
<tr>
<td>Stall Current</td>
<td>I_{st}</td>
<td>46</td>
<td>18</td>
<td>A</td>
<td>0.38</td>
</tr>
<tr>
<td>Torque Constant</td>
<td>K_t</td>
<td>0.115</td>
<td>0.083</td>
<td>Nm/A</td>
<td>0.72</td>
</tr>
<tr>
<td>Speed Constant</td>
<td>K_e</td>
<td>12.04</td>
<td>8.70</td>
<td>V/krpm</td>
<td>0.72</td>
</tr>
<tr>
<td>Stall Torque</td>
<td>ς_{st}</td>
<td>5.26</td>
<td>1.46</td>
<td>Nm</td>
<td>0.28</td>
</tr>
<tr>
<td>Max Power</td>
<td>P_{max}</td>
<td>549</td>
<td>210</td>
<td>W</td>
<td>0.38</td>
</tr>
<tr>
<td>Motor Constant</td>
<td>K_m</td>
<td>0.112</td>
<td>0.050</td>
<td>NmW^{0.5}</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Motor Model Validation and Simulation Results

Like ordinary electric motors, custom HT BLDC motors can be designed to meet mission requirements using conventional modeling and simulation tools. If the temperature dependency of winding resistance and magnetic flux density are known, motor performance at any temperature can readily be simulated. Other temperature-dependent properties, such as magnetic permeability of the magnet steel used in the rotor and stator, can be modeled as well if data are available. Prior to detailed modeling, rough estimates of motor torque and efficiency can be obtained from simplified scaling calculations.

A 2-dimensional finite-element model of Honeybee’s HT motor was built using ANSYS Maxwell (Figure 2). The motor is a 3-phase brushless DC motor with 6 slots and 4 poles. The PMs are housed in the rotor and the coils are mounted on the stator.

![Figure 2. Finite-element model of Honeybee’s HT motor](image)

Motor Back-EMF (Test vs. Simulation)

To check the accuracy of the model, the simulated back-EMF waveforms of the unloaded motor were compared with actual motor data captured at RT and 500°C at two different speeds. The back-emf measurement is passive and the test equipment does not introduce any significant additional losses or dynamics, making it especially useful in validating the motor model. To collect the waveforms, the HT motor was placed in a 1-atmosphere oven and all three motor phases were connected to an oscilloscope. A second conventional brushed DC motor was then used to rotate the motor armature at the desired speed.
by means of a feed-through in the oven door. The results indicate excellent agreement between the model and the test data at both operating temperatures, as shown in Table 2. The measured and simulated waveform plots at 3000 rpm are included in the Appendix.

Table 2. Unloaded motor back-EMF Vrms per phase at RT and 500°C (measured and simulated)

<table>
<thead>
<tr>
<th>Motor Shaft Speed</th>
<th>Test</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT (20°C)</td>
<td>HT (500°C)</td>
</tr>
<tr>
<td>1500 rpm</td>
<td>5.34 Vrms</td>
<td>3.65 Vrms</td>
</tr>
<tr>
<td>3000 rpm</td>
<td>10.68 Vrms</td>
<td>7.26 Vrms</td>
</tr>
</tbody>
</table>

Calculated Motor Phase Back-EMF Constant

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>K_e per phase</td>
<td>3.56 V/krpm</td>
<td>2.41 V/krpm</td>
<td>0.68</td>
<td>3.53 V/krpm</td>
<td>2.25 V/krpm</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Motor Performance Under Load (Test vs. Simulation)
The motor model was further validated by comparing simulated performance under load against actual dynamometer test results at RT and 482°C. These simulations, however, require modeling of additional components, including the commutation feedback sensor, motor controller and power supply, to generate the motor excitation signal (see schematic in Figure 3). Because they are idealized representations, these models introduce error and uncertainty that should be considered when evaluating simulation results. For example, an ideal DC power supply can generate a steady output at 100% of the nominal voltage, regardless of the current demand. However, the ideal model overlooks potentially significant inefficiencies that could impact motor performance in a control system, resulting in a simulation that may overpredict motor performance. If possible, these inefficiencies should be measured and included in the model to improve its fidelity. Clearly, validating the standalone motor model using back-emf measurements helps build confidence in the integrated control system model, as well.

Figure 3. Schematic of modelled components required to generate motor excitation signal

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The plots shown in Figure 4 through Figure 7 demonstrate excellent agreement between simulated and measured performance at RT (where confidence in material properties is high) and reasonable agreement at 482°C (where material properties are extrapolated).

**Figure 4.** Motor current vs. torque plots at RT & 482°C (measured and simulated)

**Figure 5.** Motor speed vs. torque plots at RT & 482°C (measured and simulated)
Table 3 compares the measured and simulated motor torque constant $K_t$ calculated at RT and HT (482°C for the test and 500°C for the simulation). The ratio of $K_t$ at HT to RT matches the theoretical result in Table 1 almost exactly.
Table 3. Motor torque constant $K_t$ at RT and HT (measured and simulated)

<table>
<thead>
<tr>
<th>Test</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT (20C)</td>
<td>HT (482C)</td>
</tr>
<tr>
<td>0.12 Nm/A</td>
<td>0.08 Nm/A</td>
</tr>
</tbody>
</table>

These comparisons validate the HT motor model and support the use of a similar model to aid in the design of the flight motor for the Venus drill. The effects of high temperature on motor performance can be estimated with reasonable confidence and, therefore, the motor design can be optimized for power output vs. mass and volume.

The Venus Drill

Drilling Power
Drilling tools have been successfully deployed on the Moon, Mars and Venus to sample surface rock. In these applications, drill rate of penetration (ROP) depends on several variables including the strength of the rock (Unconfined Compressive Strength or UCS, expressed in MPa), weight on bit, drilling power, and whether percussion is used or not [7]. For a given rock type, specific energy (SE) can be defined as the amount of energy required to break up a unit volume of rock into fine particles that can be transported out of the borehole. Since the efficiencies of different drilling heads, bits and feed mechanisms can vary widely, specific energy (expressed in Whr/cc or J/mm$^3$) provides a convenient measure to compare the performance of different drilling systems.

Applied to a single drilling system, specific energy can be used to compare performance at different environmental conditions, such as temperature and pressure. It can be calculated from the results of a drilling trial by measuring the average rate of penetration ($v_{ROP}$) achieved when drilling with a bit of diameter $d_b$ while controlling drilling parameters such that the average drilling power ($P_{ave}$ = motor power output) remains approximately constant.

$$SE = \frac{4P_{ave}}{\pi d_b^2 v_{ROP}}$$  \hspace{1cm} (8)

Rearranging the equation slightly, drilling power is seen to be proportional to specific energy, rate of penetration, and the square of the bit diameter.

$$P_{ave} = SE \left( \frac{\pi d_b^2}{4} \right) v_{ROP}$$  \hspace{1cm} (9)

Before the actuators for the Venus drill can be properly sized to deliver this power, the specific energy for drilling at Venus conditions must be determined by conducting drilling trials at VTP, underscoring the need for a high-fidelity prototype drill. A discussion of the design and fabrication of the prototype drill can be found in [3] and [8]. The prototype is a HT version of a proven Honeybee design that has previously demonstrated the desired drilling performance [9]. The selected drill design parameters are listed in Table 4.
Table 4. Venus drill design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit Diameter</td>
<td>2 cm</td>
</tr>
<tr>
<td>Weight on Bit</td>
<td>105 N</td>
</tr>
<tr>
<td>Spindle Speed</td>
<td>120 rpm</td>
</tr>
<tr>
<td>Spindle Torque</td>
<td>1.1 Nm</td>
</tr>
<tr>
<td>Net Spindle Power</td>
<td>13.7 W</td>
</tr>
<tr>
<td>Percussive Energy</td>
<td>2.0 J/blow</td>
</tr>
<tr>
<td>Percussive Frequency</td>
<td>980 blows/min</td>
</tr>
<tr>
<td>Net Percussive Power</td>
<td>33 W</td>
</tr>
<tr>
<td>Target Penetration Rate</td>
<td>0.5 cm/min</td>
</tr>
</tbody>
</table>

Test Configuration Used in Drilling Trials

Following performance characterization on the dynamometer, two HT motors were integrated with the prototype drill and a series of drilling trials were conducted at Venus temperature and pressure in JPL’s VMTF environmental chamber. The VMTF is a heated-wall pressure chamber with an electrical feedthrough mounted in the lid. The test article is suspended from the lid so that it hangs down inside the chamber when the lid is installed (see Fig. 8). The high temperature environment in the VMTF severely restricts the choice of materials that can be used for both the test article (i.e., the drill) and test instrumentation, in particular materials suitable for electrical insulation and termination. Details of the material selection for the drill and actuators are reported in [8].

![Figure 8. VMTF lid with Venus drill installed](image)

Drilling Test Results

Table 5 shows the average motor torque and speed for each of the two mechanisms comprising the Venus drill under different test conditions. Average torque was calculated by taking the average motor current over the entire drilling time and multiplying by the motor torque constant $K_t$. Peak torque was measured directly.
by driving the percussor cam through the second stage of the spur gear with a torque watch and then dividing the maximum reading by the first stage spur gear ratio.

Table 5. Venus drill motor torque and speed under various test conditions

<table>
<thead>
<tr>
<th>Drilling Test</th>
<th>Motor</th>
<th>Motor Peak Torque* (Nm)</th>
<th>Motor Current, Ave. (A)</th>
<th>Kt (Nm/A)</th>
<th>Motor Cont. Torque, Ave. (Nm)</th>
<th>Motor Velocity, Ave. (RPM)</th>
<th>Power Output, Ave. (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bench (Flat Basalt, RT Spring)</td>
<td>Auger</td>
<td>1.561</td>
<td>0.115</td>
<td>0.180</td>
<td>2945</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Percussor</td>
<td>0.57</td>
<td>2.816</td>
<td>0.115</td>
<td>0.324</td>
<td>3217</td>
<td>109</td>
</tr>
<tr>
<td>RT3 (Sloped Basalt, HT Spring)</td>
<td>Auger</td>
<td>1.362</td>
<td>0.115</td>
<td>0.157</td>
<td>2900</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Percussor</td>
<td>0.68</td>
<td>3.469</td>
<td>0.115</td>
<td>0.399</td>
<td>3521</td>
<td>147</td>
</tr>
<tr>
<td>VTP3 (Flat Basalt, HT Spring)</td>
<td>Auger</td>
<td>1.217</td>
<td>0.084</td>
<td>0.102</td>
<td>2931</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Percussor</td>
<td>0.57</td>
<td>3.874</td>
<td>0.084</td>
<td>0.325</td>
<td>2867</td>
<td>98</td>
</tr>
</tbody>
</table>

* estimates based on measurement with a torque watch

Whereas it has been shown that surface sliding friction at the bit to rock interface increases with temperature under both Earth and Mars atmospheric pressures [10], the results of the VMFT drilling trials with the Venus drill (see Table 6) suggest that temperature would not significantly impact specific drilling energy at Venus conditions, at least for rotary-percussive machines. On the other hand, the rate of penetration at high temperature is expected to be slower because the stiffness of the percussive spring (and, therefore, the percussive energy per blow) is reduced. Furthermore, increased electrical (i^2R) losses are expected at high temperature because the resistance of the motor coils is increased. However, it should be noted that specific energy, as defined herein, reflects mechanical performance only and does not include electrical losses. Accordingly, SE is calculated using Total Power Output in Table 6, which is the combined mechanical power output from both motors, rather than Estimated Power Consumption, which applies efficiencies read from dynamometer test results in Figure 7.

Table 6. Specific energy for drilling measured at room temperature and high temperature

<table>
<thead>
<tr>
<th>Drilling Test</th>
<th>Total Power Output, Ave. (W)</th>
<th>Est. Power Consumption (W)</th>
<th>Drilling Depth (cm)</th>
<th>Drilling Time (sec)</th>
<th>ROP (mm/min)</th>
<th>Specific Energy (Whr/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bench (Flat Basalt, RT Spring)</td>
<td>164</td>
<td>261</td>
<td>4.81</td>
<td>568</td>
<td>5.08</td>
<td>1.67</td>
</tr>
<tr>
<td>RT3 (Sloped Basalt, HT Spring)</td>
<td>195</td>
<td>358</td>
<td>4.19</td>
<td>429</td>
<td>5.86</td>
<td>1.71</td>
</tr>
<tr>
<td>VTP3 (Flat Basalt, HT Spring)</td>
<td>129</td>
<td>202</td>
<td>2.36</td>
<td>373</td>
<td>3.79</td>
<td>1.75</td>
</tr>
</tbody>
</table>

Motor Torque Margin and Thermal Considerations

Per spaceflight mechanism design requirements in AIAA S-114-2005 Moving Mechanical Assemblies, the flight drill would need actuators capable of providing at least twice the nominal torque (both peak and continuous) needed to operate the drill in worst-case environmental conditions. This margin allows for modelling uncertainty, such as the detrimental effects of operating in the Venus atmosphere, and unexpected failures that could cause additional drag on the mechanism, such as a seized bearing.
Like conventional DC motors, the continuous output torque of the HT motors is limited by their ability to dissipate waste heat generated in the coils. The motors could be operated intermittently at higher torques if they were periodically turned off and allowed to cool down but such operational constraints would not be compatible with the unusually short life (only a few hours!) of a Venus surface mission. The motor peak torque, on the other hand, may be limited by either the demagnetization potential of the PMs, which can be determined from the characteristic B-H curve of the magnetic material, or the magnetic permeability of the magnet steel used in the motor stator and rotor. The continuous and peak current capacity of the motor controller and power supply should not be overlooked, either, though they are remotely located and not affected by the test chamber environment.

Since the Sm$_2$Co$_{17}$ PMs mounted in the rotor should be kept below a temperature of 525°C to minimize the risk of demagnetization, the allowable temperature rise over the 10-minute drilling duration specified in the proposed VISAGE mission timeline is 63°C (starting at an ambient temperature of 462°C). The difference between the continuous average torque needed to drill to the target depth of 5 cm in 10 minutes and the controlled constant torque load at which the motors reach their maximum allowable operating temperature in the same period of time is the motor continuous torque margin. This margin can be accurately determined using a dynamometer.

Figure 9 presents drill depth and motor thermocouple data from a successful drilling trial performed at VTP. In this test, the drill reached a depth of 5 cm in 13.5 minutes and the drill motors reached steady-state temperature with a 25°C temperature margin left on the percussor motor. If thermal constraints were removed, however, a quick inspection of the high temperature torque vs. speed curve in Fig. 5 shows an available torque of 0.4 Nm at 3000 rpm, or a margin of 23% over the average torque required to drive the percussor from Table 5.

These results highlight the need for better thermal modelling of the motor, since the thermal coupling between the stator, where the heat is generated in the coils, and the rotor, where the temperature-sensitive PMs are mounted, has not been characterized. If it can be demonstrated that the rotor stays significantly cooler than the stator while the motor is operating, the maximum allowable operating temperature of the motor could be increased. In addition, passive heat sinks (e.g., fins, etc.) could be added to the motor housing to improve heat dissipation to the ambient environment. After these thermal effects have been accounted for and the motor torque margins have been accurately measured, the flight drill motors can be correctly sized to achieve the desired drilling performance.
Summary

The HT motor model has been validated with test data, confirming that conventional methods can be used to size these motors and account for losses at high temperature. The VMTF drilling trials have confirmed the feasibility of drilling into rock at Venus temperature and pressure to generate fines suitable for pneumatic transport per the proposed VISAGE mission concept of operations. They have also produced drilling performance and average power consumption benchmarks useful for mission resource planning. The motor torque margins are limited by the maximum operating temperature of the PMs. However, these margins can be improved by accurate thermal modelling of the motor and the addition of passive heat sinks.

Acknowledgements

This work was funded by NASA’s HOT (High Operating Temperature) Technology Program. We owe our sincere thanks and appreciation to Program Officer Dr. Quang-Viet Nguyen and Technology Coordinator Dr. Gary Hunter. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Appendix

Measured and simulated back-EMF waveform plots at 3000 rpm and two different operating temperatures are included here for reference.
Motor Back-EMF Simulation (3000 RPM, RT)

Motor Back-EMF Test (3000 RPM, 500°C)
References