Laboratory drilling under Martian conditions yields unexpected results

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[1] Current plans to drill boreholes in the surface of Mars suppose that diamond drill bits will be used on drilling equipment developing drilling power of 100 W or less. Such drilling produces very fine cuttings. At Martian ambient pressure, it has been shown that quite small gas flows are capable of clearing these cuttings from the hole. For example, the release of 1 L of gas compressed to 50 torr is capable of removing 25 g of cuttings from a borehole 50 mm in diameter and at least 250 mm deep. Generating such volumes of gas by compressing the Martian atmosphere would not be difficult. Alternatively, the required volume of gas could be provided by the sublimation of ice trapped in the pore spaces of soil or rock in the Martian surface. Once heated by the friction of the drill bit, the ice transforms into vapor, and blows the cuttings out of the hole. Since the cuttings are, in effect, freeze-dried, they do not choke the drill bit or hole, with the result that the drilling efficiency is much greater than under terrestrial pressures and temperatures. *INDEX TERMS:* 0994 Exploration Geophysics: Instruments and techniques; 0999 Exploration Geophysics: General or miscellaneous; 6225 Planetology: Solar System Objects: Mars; 6297 Planetology: Solar System Objects: Instruments and techniques; 6299 Planetology: Solar System Objects: General or miscellaneous; *KEYWORDS:* drilling, Mars

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1. Introduction

[2] Drilling on Mars presents some specific problems. While it is expected that the process of rock destruction will be broadly similar to that on Earth, the combination of low temperature and low atmospheric pressure on the Martian surface means that it will be difficult to use either a gas or liquid flow to remove the cuttings. The low pressure causes liquid water to be stable only between zero and a few degrees Centigrade (depending on ambient pressure), so it is unreasonable to expect to keep liquid water in the borehole without it either boiling or freezing. In addition, the near vacuum conditions imply that heat removal from the hole will be poor, with corresponding risk of overheating the bit and also of altering the material being sampled. Current proposals for Mars drilling equipment therefore center on the idea of dry drilling, using a mechanical means for removing the cuttings, typically an auger, and of drilling with low power input to avoid overheating. Concerns of weight and contamination preclude the use of any "exotic" liquid that might be brought from Earth. A gas-flushing fluid would need to be brought from Earth or the local Martian atmosphere would have to be compressed.

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[3] *Blacic et al.* [2000] estimated that it would not be practical to use the compressed Martian atmosphere to clear the cuttings out of an experimental borehole on Mars. They concluded that for a continuous flow of gas the flow rates and hole bottom pressures would be such that the Martian atmosphere could not be economically compressed to sufficient values to allow effective drilling within the allowable power and weight limits that would be available on a future Mars lander or a rover. However, they also mentioned that an intermittent air blast might be used for cuttings transport but needs to be modeled and demonstrated under Martian conditions of low pressure and temperature. This note reports that both blasts of gas and a continuous flow of gas may be usable to clear cuttings from boreholes drilled on Mars.

[4] Blasts of gas could be provided by a low power compressor that compresses the Martian atmosphere into a reservoir whose contents are periodically discharged at the bottom of the hole. Alternatively, a continuous flow of gas could be provided by the melting and vaporization of ice that may be found in the terrain being drilled. Under the Martian atmospheric pressure of 5 torr, a given quantity of ice increases in volume by 170,000 times as it vaporizes. This increase in volume could provide enough gas flow to remove the drilled cuttings from the hole provided that a

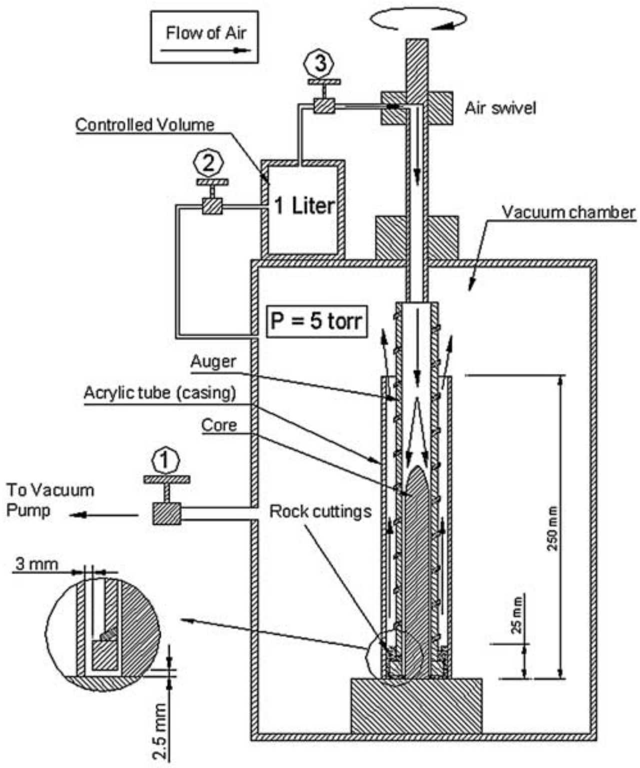

Figure 1. The air-flushing experimental arrangement, showing the main vacuum chamber, the control volume chamber, and the drill arrangement.

sufficient quantity of ice is present in the terrain being penetrated. The cuttings could be collected by a catch basket above the bottom hole assembly.

2. Air Flushing

[5] In this section, results from a simple experiment show that it is possible to remove the rock cuttings from the hole bottom using small blasts of air.

2.1. Experimental Arrangement

[6] Figure 1 shows a schematic of the experimental equipment. Its features included a main vacuum chamber kept at 5 torr to simulate the Martian surface pressure, and a control volume chamber, which housed the required air for the cuttings removal air blast. In the experiments, this control volume was kept at approximately 1 L and only the differential pressure was varied. The differential pressure was defined as the difference between the pressure inside the control volume chamber and the pressure inside the main vacuum chamber, which was always 5 torr.

[7] To represent the rock cuttings to be removed from the hole, actual cuttings were taken from an experiment in which Santa Barbara sandstone had been drilled by a diamond drill of similar type to that which may be used on Mars. Because of the low power used by such a drill, the cuttings were very fine and angular as shown in the Scanning Electron Micrograph in Figure 2.

[8] To conduct the experiment, a quantity of dry rock cuttings was weighed and placed inside an acrylic tube of 50 mm internal diameter that simulated a bore hole. Next, a simulated drill pipe was rotated and lowered into the tube. The "drill pipe" was a tube of outer diameter 44 mm, which then formed an annulus of 3 mm between the "drill pipe" and the "borehole." A slightly oversized acrylic tube had to be used as the drill could not rotate smoothly inside a 44 mm diameter tube. The next size of tube the supplier could provide was 50 mm. The cuttings would typically cover the end of the "drill pipe" to a depth of around 2.5 cm. All three valves were then opened and the vacuum pump was turned on. If a differential pressure of 5 torr was required, valves two and three were closed at the moment the pressure reached 10 torr and valve one was closed when the pressure inside the main vacuum chamber reached 5 torr. Once the required conditions were established, valve three was opened and all the air from the 1 L reservoir at 10 torr would flow into the drill assembly, to the hole bottom and up through the annular space between the "borehole" and the "drill pipe," and into the main vacuum chamber (at 5 torr). The gas flow would thereby lift the rock cuttings out of the hole. The clearing process lasted for no more than 2 s. The cuttings which remained in the hole were collected and weighed. This procedure was repeated several times at various differential pressures.

2.2. Results

[9] The collected data are plotted in Figure 3. The y axis shows the clearing efficiency, which is defined as the mass of the cuttings removed divided by the original mass of the cuttings. The x axis shows the pressure difference or the gauge pressure (the pressure above 5 torr). There is a steady increase in the amount of cuttings being lifted out of the hole as the pressure in the 1 L reservoir increased. At a differential pressure of 45 torr (absolute pressure of 50 torr), the clearing efficiency approached 100%.

[10] If the air is kept at 20 torr above the atmospheric pressure of 760 torr and then released into the atmosphere,

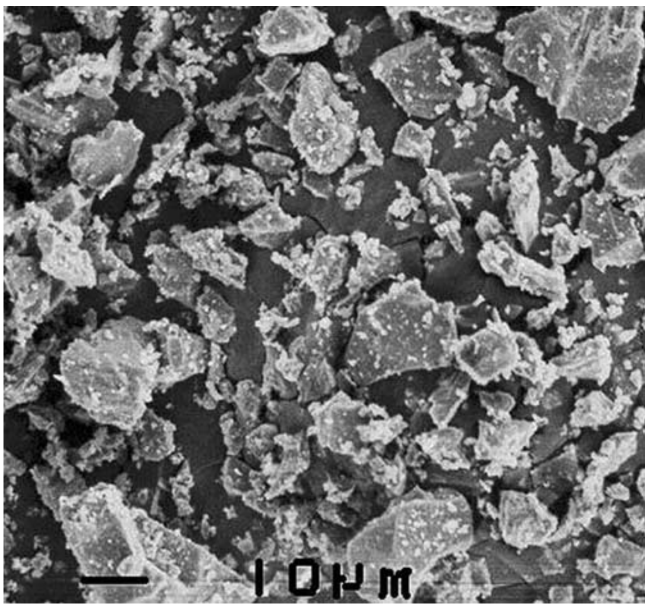

Figure 2. Scanning electron micrograph of the Santa Barbara sandstone rock cuttings used for the air-flushing experiments.

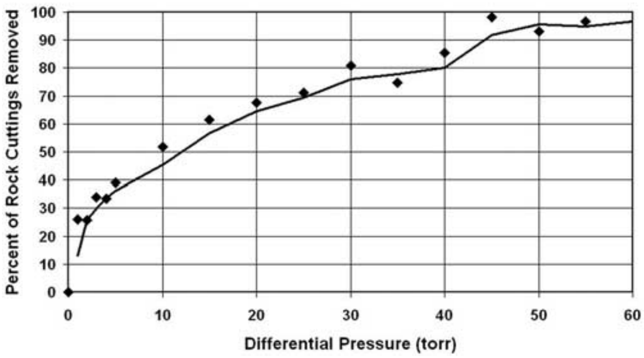

Figure 3. Experimental data: cuttings clearing efficiency versus differential pressure. Shown are the data points and the best fit curve.

its volume will increase by only 2%. Test experiments showed that the flow provided by this volume change was incapable of lifting the cuttings. On the other hand, if the air is kept at 20 torr above the Martian pressure of 5 torr and then released, its volume will quadruple, and this was very effective in clearing cuttings from the hole.

[11] The isothermal work in compressing the air into the 1 L chamber from 5 torr to 50 torr is approximately 15 J. Drilling results indicate that at a rate of penetration of 25 cm/hr, 20 g of rock cuttings are produced approximately every two minutes when core drilling with a 44 mm diameter core drill. Thus the rock cuttings need to be cleared every 120 s or so. Assuming the efficiency of the system to be only 10%, this adds 1.2 W to the total power requirements of the lander or the rover.

2.3. Discussion of Results

[12] The results show that a relatively small volume of gas, e.g., 1 L at 50 torr, is capable of clearing a few tens of grams of drilled cuttings out of an annular space that would be typical of a borehole drilled on Mars. This encouraging result is no doubt dependent first upon the low ambient pressure on the surface of Mars that allows a large volumetric expansion of the flushing gas and second that the drilled cuttings are very fine. We believe that the experiment shows that clearing drilled cuttings from the hole by periodic air blasts may be a practical method for maintaining hole cleanliness on Mars. However, this finding must be regarded as tentative at present in view of the large number of variables that may be involved in practical drilling work.

3. Coring Under Martian Conditions of Low Temperature and Pressure

[13] The experiments described above show that cuttings can be effectively removed from the borehole by a small mass flow of gas if the ambient pressure is low enough. The source of the gas could perhaps be provided by the vaporization of water ice in the pore spaces inside Martian rocks or soil. We therefore carried out an experiment to see if this was indeed possible.

3.1. Experimental Arrangement

[14] Drilling experiments were carried out using a laboratory drill press provided with a vacuum chamber to contain the rock to be drilled and the drilling assembly. The drilling assembly shown in Figure 4 consisted of a drive shaft, a hollow stem auger to remove rock debris and to house a 24 mm diameter core. The bit was a 44 mm diameter diamond impregnated core bit. A control system allowed the automatic maintenance of preset values of rotary speed and weight on bit and the recording at one Hz of all the drilling and chamber conditions (weight on bit, rotary speed, shaft torque and chamber pressure and temperature). Temperatures were also measured on the bit at 11 mm from the bit face, and in the rock sample at various distances from the drilled hole.

[15] A thermocouple was embedded in the center of the rock to measure the temperature of the rock core during drilling. This thermocouple was used to indicate whether the rock core, which would be required for scientific analysis, reached the melting temperature of ice. In addition, another three parameters were derived from the acquired data, namely the power, the apparent coefficient of friction and the rate of penetration (ROP) of the drill, which was calculated over intervals of 30 s. The drilling test was conducted in the vacuum chamber at a temperature of 24°C and a pressure of around 5 torr, the lowest pressure recorded by the Viking 1 lander on Mars. A water vapor pressure of 5 torr corresponds to a vaporization temperature of 2°C. Thus liquid water could exist in the temperature range between 0°C and 2°C at the chamber pressure.

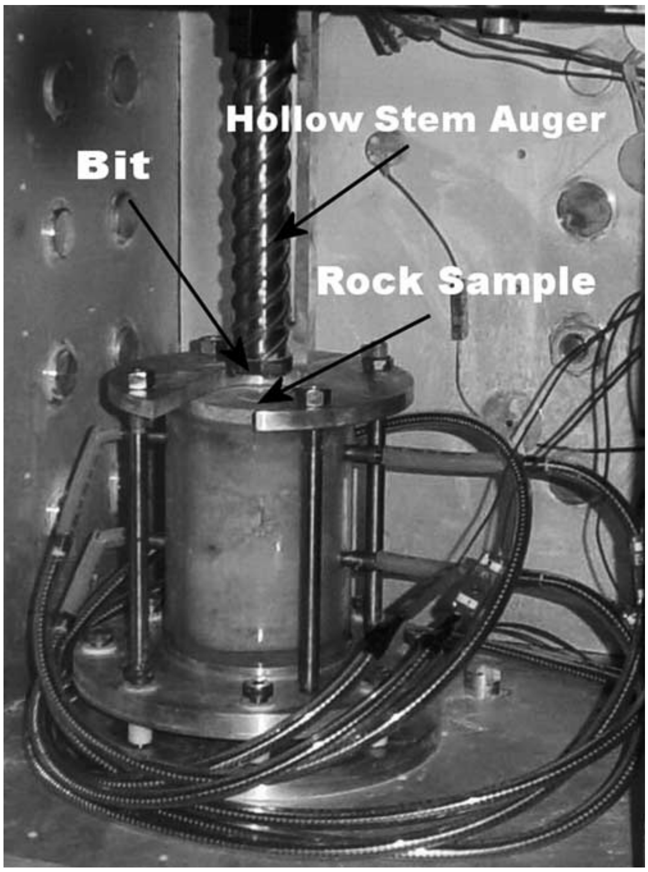

Figure 4. Drilling arrangement, showing the test rock with attached thermocouples and the bit and the auger above.

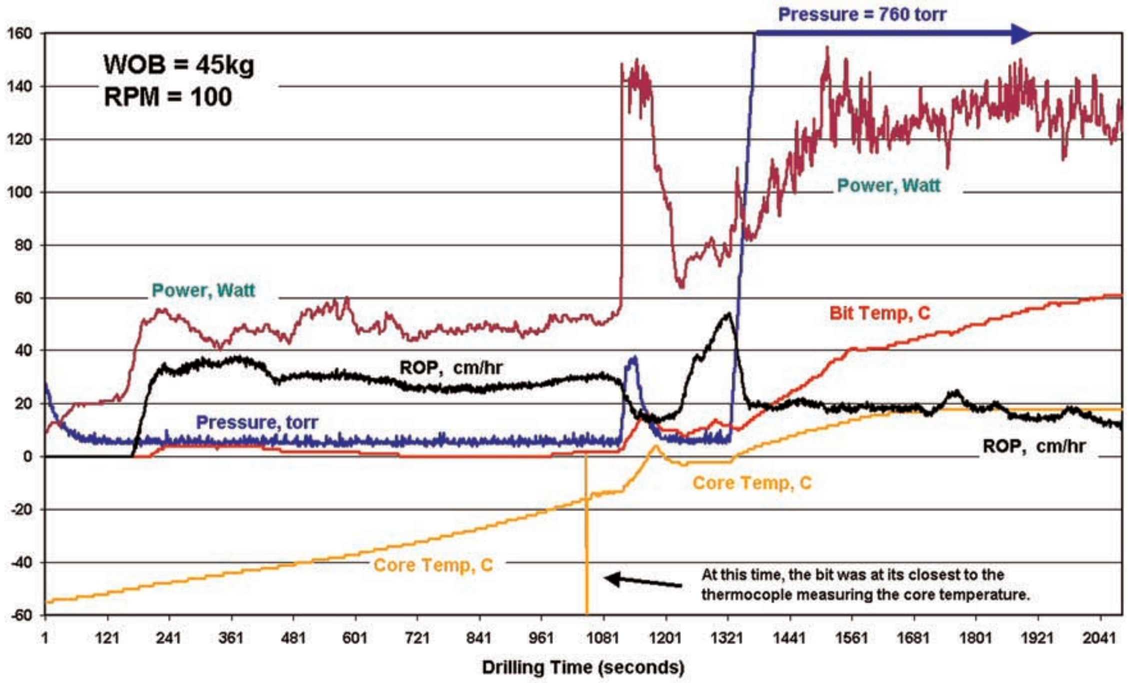

Figure 5. Drilling data for the water-saturated, frozen Ohio sandstone rock.

[16] The Ohio sandstone rock used for the drilling tests had a specific gravity of 2.06, a porosity of 20% and an unconfined compressive strength of approximately 48 MPa (Briar Hill Stone Co., Glenmont, Ohio). The rock sample was a cylinder, 165 mm high and 90 mm in diameter. It was initially oven dried for 36 hours and subsequently saturated with water to 60%. The remaining pore space contained trapped air. The rock sample was then placed in a freezer at −80°C for 48 hours. Prior to the drilling test, the rock was placed inside an acrylic cylinder with threaded holes to assist in the placement of the thermocouples, and then placed in the vacuum chamber.

3.2. Results

[17] A typical drilling record is shown in Figure 5, with various parameters plotted as a function of drilling time. The figure shows that the rate of penetration (ROP) was initially zero. This was due to the bit sliding on top of a thin ice layer formed on the surface of the rock. After two minutes or so, the bit warmed the ice enough for it to melt and vaporize and for the bit to contact the rock. Thereafter, the ROP increased as the drilling commenced. The ROP was initially very high at 36 cm/hr but slowly dropped and oscillated at around 30 cm/hr.

[18] During this time, cuttings were seen being blown out of the hole in the form of a fine dust (Figure 6). This dust was completely dry, and sometimes fell at a considerable distance from the hole. The gas driving the cuttings out of the hole was evidently water vapor generated at the bit-rock interface by the heat of drilling, which caused ice in the pores of the rock to melt and vaporize. Note that during this time, the auger, which would otherwise have been instrumental in conveying the cuttings to the surface, was entirely clean and played no part in the transport of cuttings.

[19] After approximately 1100 s the pressure was raised to 40 torr, i.e., above the water vaporization pressure, and then reduced to 5 torr after a further 60 s, approximately. During this period the vaporization ceased and this manifested itself in a threefold power increase and a drop in the ROP of 50%. This was presumed to be the result of the presence of liquid water causing the cuttings to stick together around the bit cutting structure. In addition, the bit temperature rose sharply from 2°C to 17°C. Since the bit at that time was very close to the thermocouple inside the

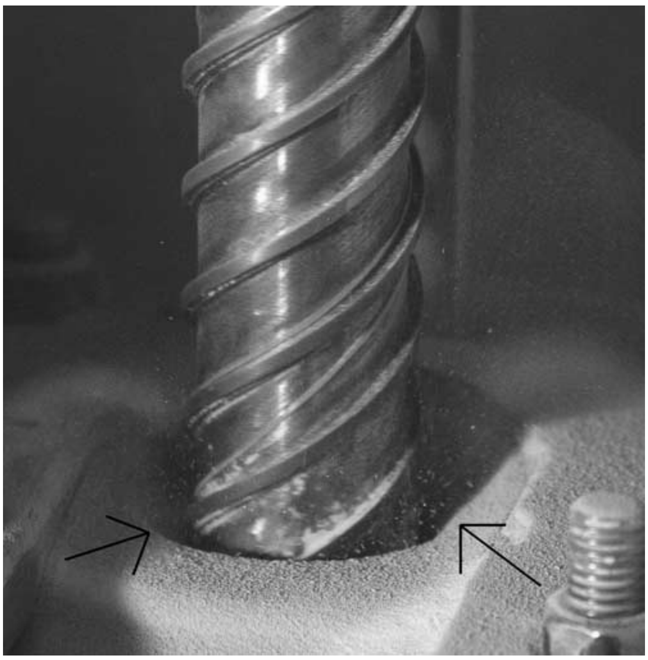

Figure 6. A close-up of the drill and the hole showing rock cuttings being blown out of the hole. The auger diameter is 39 mm. (Photo courtesy of A. Cooper.)

core, the core temperature increased from −15°C to 3°C, which indicated that the water inside the core had melted and was in a liquid state. The reason for this sudden increase in the temperature was the drop in the vaporization rate.

[20] At a pressure of 5 torr and a temperature of 2°C, water is in the vapor state. As the drill rotated, it raised the temperature of the ice in contact with the drill bit to 2°C or more above freezing, and this allowed the water to vaporize. It is possible that this melting and vaporization process occurred so rapidly that the ice was effectively sublimed directly into vapor. During this vaporization or sublimation period, a large amount of energy was used up as latent heat of fusion and vaporization. Since the energy in the form of heat was consumed to vaporize the water, it kept the remaining ice, rock and bit cold. The moment the pressure was raised to 40 torr, the vaporization rate dropped and the heat, which would normally have been used up, now melted the ice and heated up the rock and the bit. Note that at a pressure of 40 torr, a temperature of 35°C is required to vaporize the water. Since the latent heat of fusion is 7 times smaller than the latent heat of vaporization (333 kJ/kg versus 2256 kJ/kg), the amount of energy consumed in the melting of ice was too low to keep the bit and the rock cold. Thus the temperatures of the rock and bit kept rising. However, soon after the pressure dropped to 5 torr, the bit temperature dropped by a few degrees and the core temperature dropped again to below freezing. In addition, as the pressure was lowered, the power decreased, and the ROP increased. At the same time, cuttings were again seen being blown out of the hole.

[21] After 1300 s the chamber was vented to the atmosphere and kept at atmospheric pressure until the end of the test. The ROP decreased and the power increased as anticipated. In addition, the ROP continually kept decreasing and sooner or later the bit would have stopped drilling altogether. The most probable explanation for the decrease in the ROP was the bit being clogged by the cuttings. Indeed, when the bit was removed from the hole at the end of the test, the bit and the lower portion of the auger were seen to be completely covered by sticky wet cuttings.

[22] Calculations showed that when the water vapor was clearing the cuttings from below the bit, the power consumption was 45 W and the ROP was 30 cm/hr. Once the auger and the volumetric displacement became the only source of conveying the cuttings out of the hole, the power increased to 125 W and the ROP dropped to 13 cm/hr.

[23] During the time span from approximately 200 s to 1100 s, the ROP was on the order of 36 cm/hr or 0.1 mm/s. Since the outer and inner diameters of the borehole were 44 mm and 25 mm, respectively, the volume of rock drilled per second was 100 mm^3. As previously reported, the porosity of the rock was 20% and the saturation was 60%. Therefore 12 mm^3 of water ice were liberated per second. It can also be assumed the heat zone within the hole wall and inside the rock core extended 3 mm deep. Thus an additional 4 mm^3 of water ice were liberated in this region. This brought a total of 16 mm^3 or 16 mg of water ice being converted into vapor per second. Since the latent heat of vaporization and fusion of water is 2.6 KJ/g, this meant approximately 42 W of power were used to convert the ice into water vapor. The additional energy required to raise the temperature of the ice from −20°C to the melting point, i.e., by 20°C, was small and can be ignored at this stage. The power supplied to the bit (Torque × RPM) was calculated to be approximately 45 W. Thus the majority of the power was first converted into heat during the rock breaking and comminution process and then the heat was used to melt and vaporize the water. This helped to keep both the rock core and the bit cold.

3.3. Discussion of Results

[24] In all the tests, the rock and the bit were cold as there was enough water to consume the excess heat from the bit friction against the rock. The scenario might have been different if there had been only a small amount of water present or if the pressure had been much higher. For example, the maximum pressure on Mars is estimated to be 11 torr. At this pressure, the water temperature has to be above 13°C to be vaporized. If there is enough water, the bit will only reach a few degrees above 13°C. This is because the bit will heat up and as it does it will melt and vaporize the water. The latent heat of vaporization would bring the bit temperature down, but never below 13°C. If the bit temperature falls below 13°C, the vaporization will stop and the bit will heat up again until it reaches 13°C or more. Thus, if the pressure is known, the lowest temperature the bit can have is the temperature of the water at the corresponding vapor pressure. Of course, if there is not enough water, the bit temperature might rise much higher.

[25] The volume increase of water ice as it turns to vapor at 5 torr was approximately 170,000 times. As calculated previously, 16 mm^3 of water ice were liberated per second. This resulted in a volumetric flow of water vapor of 2700 cm^3 per second. Since the annular area between the 39 mm diameter drill string and the 50 mm diameter tube (the borehole) was 730 mm^2, the flow velocity of water vapor in the annular space was about 4 m/s. Isothermal expansion of this quantity of initially highly dense material (ice then vapor) to a pressure of 5 torr generates approximately 24 W. If a mechanical compressor were to reverse this process, by compressing the ambient Martian atmosphere from 5 torr up to a pressure necessary to blow the cuttings out of the hole, then 24 W or less would be required, depending on the degree of compression that would be necessary.

[26] The particle size distribution was determined by the sieve and the hydrometer analysis as described by the American Society for Testing and Materials standard D 422. The results were plotted in Figure 7. The particle size analysis revealed that 80% were smaller than around 60 microns and 40% were smaller than around ten microns. In addition particle size distributions were very similar in both tests conducted under the atmospheric and Martian pressures. This indicates that diamond drilling produces very fine cuttings, whose sizes are unaffected by the method of cuttings removal.

3.4. Relevance to Drilling on Mars

[27] During gas flushing, the optimal gas velocity for hole clearing is governed by the size of the coarsest particles [*Adewumi and Tian*, 1990]. If the velocity is too low for the large cuttings to be lifted out, those particles will be reground into smaller cuttings at the bottom of the hole. This, of course, will reduce the total drilling efficiency, as in

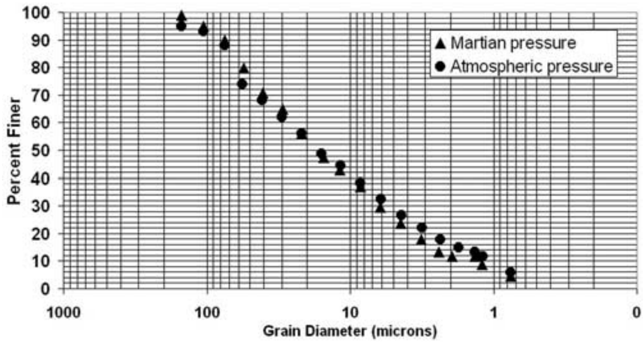

Figure 7. The particle size distribution of the cuttings obtained from drilling in the water-saturated and frozen Ohio sandstone under Martian and atmospheric pressures.

general, coarser particles indicate a more efficient drilling process. On Mars, the rock particles will be much lighter due to the lower gravity and in turn, the drilling process should be more efficient. However, we have no means of estimating the degree of improvement. The lower gravity will also set a lower upper limit on the weight on bit if the weight on bit is to be provided by the weight of the rover or lander.

[28] Recent Mars Odyssey neutron spectrometer data revealed that from about 50° latitude to the poles, the approximate top meter of Martian soil contains between 20% and 50% water by mass in the south and up to 100% in the north. Closer to the equator, the proportion of water ranges from 2% to 9% [*Feldman et al.*, 2003]. Although these findings do not imply a uniform water distribution, there still exists a high probability that the drill might encounter frozen water deposits. Provided the heat generated during the drilling process is high enough, the ice in direct contact with and around the drill bit will change phase to either liquid or gas.

[29] In addition, the Mars Orbiter Laser Altimeter on the Mars Global Surveyor (see http://ltpwww.gsfc.nasa.gov/tharsis/mola.html) data confirmed that the elevation in the southern hemisphere is much higher than in the northern hemisphere. The atmospheric pressure in the southern hemisphere is usually below the triple point of water and that in the northern hemisphere is above the triple point of water [*Haberle et al.*, 2001]. The direct implication is that in the southern hemisphere, the water ice around the rotating drill bit may sublime and vapor leaving the hole may enhance the drilling efficiency, while in the northern hemisphere, the water ice will melt first. If it then freezes, the drilling equipment may become stuck.

[30] Therefore the danger of thaw followed by refreezing appears to exist only in the northern hemisphere. Two drilling options to combat this are either to keep the drilling parameters low enough to prevent the water-ice from melting or to deliberately generate sufficient heat via aggressive drilling to vaporize all the liquid water. The advantage of the first option is that the bit will not get stuck. However, the disadvantage is that another method of cuttings removal such as a mechanical auger will have to be used. This alternative method will reduce the drilling efficiency and add to the total power requirement of the drill system (although the auger may well have to be retained in all cases since parts of the terrain may be entirely dry). The advantage of the second option is that no or reduced mechanical means of cuttings removal is required, but the disadvantages include the possibility of the bit getting caught if the water refreezes for some reason (this is a major problem while drilling in the polar regions on Earth [see *Sellmann and Brown*, 1965]). Further issues concern the higher drill power required to generate sufficient heating during the process to vaporize the water, and the danger of altering the core physical properties by melting its water-ice. It seems that the first option is more advantageous. However, an additional problem posed by the first option may occur if these low drilling parameters are not sufficient to penetrate the rock and a higher weight on bit and rotational speed need to be used to clear the cuttings with an auger. Again, this may generate enough heat for the ice to reach its melting point. In this case, intermittent stops during drilling to allow for heat dissipation may prove to be the only possible solution. An additional complication of drilling under different conditions relates to the different bit wear regimes. This issue is addressed in detail in our companion paper [see *Zacny and Cooper*, 2004].

4. Conclusions

[31] A simulated drilling test involved the injection of 1 L of air at 50 torr into the bottom of the annular space between a 50 mm diameter "borehole" and a 44 cm diameter "drill pipe" placed in the hole. The "borehole" and its exterior environment were held at 5 torr, allowing the 1 L of air to expand ten times as it escaped through the annulus. The resultant air flow was able easily to clear a mass of 25 g of rock cuttings from a 25 cm deep hole.

[32] A second test involved the diamond core drilling of a water-saturated Ohio sandstone sample held at −50°C and 5 torr. It was found that the heat generated by the drill bit while drilling caused the ice in the pore spaces of the rock to be melted and immediately vaporized. The resultant flow of water vapor up the annulus between the drill pipe and hole wall was sufficient to clear all the cuttings from the hole. The cuttings were ejected with considerable speed from the hole and fell at some distance from the hole in a completely dry condition. Typical rates of penetration were twice those measured on the same rock under warm atmospheric conditions, while the power consumed was reduced by 50%.

[33] It is likely that a future drilling mission on Mars will encounter water ice. Whereas drilling in ice and ice-bound soils on Earth carries the risk of melting, refreezing and becoming stuck in hole, the present results indicate that if the atmospheric pressure is low enough, no liquid water will be formed. The risk of getting stuck in hole is thus much reduced, while the water vapor exiting the hole may well be enough to clear the cuttings. Further, the consumption of the latent heats of fusion and vaporization of the ice will provide a powerful cooling effect that will help protect the drill bit and preserve the material being sampled. In the southern hemisphere, where the higher elevation results in pressures below the triple point of water, the drilling process may generate enough heat to sublime the ice. Released water vapor will clear the cuttings and in turn, improve the drilling efficiency. In the northern hemisphere, where the lower elevation results in pressures above the triple point,

there is a danger that water ice will melt and refreeze. Liquid water, upon refreezing, can trap the drill bit in place. Therefore the drilling parameters must be chosen to generate minimum heat. If this cannot be achieved, intermittent stops must be made to allow for heat dissipation.

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