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Methods for cuttings removal from holes drilled on Mars

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Abstract

Background: The process of rock excavation consists of breaking the rock and the extraction of cuttings from the hole. Failure to remove the cuttings results in their being pulverized into progressively finer particle sizes, making drilling very inefficient and in the extreme case halting the drilling process altogether. A unique feature when drilling exploration boreholes on Mars is that, unlike almost all terrestrial drilling, no fluid (gas or liquid) will ordinarily be available to clear the cuttings from the borehole. Until the present, therefore, it has been supposed that an auger system will be used. The behavior of auger systems in the size range that may be used on Mars should therefore be investigated and consideration should be given to other possible means for removing the cuttings

Method: We have investigated the use of augers during simulated Mars drilling under different likely sets of conditions. We have also investigated two alternative or supplementary methods for cuttings removal. These are, respectively, the use of the heat of drilling to vaporize ice if it is present in the pore spaces of the terrain being drilled, and the use of intermittent blasts of gas to blow the cuttings out of the hole if ice is not present.

Conclusion: Augering appears to be the most universally applicable means of clearing cuttings from the borehole. Augers are generally successful if the cuttings remain dry (or frozen) and if the rate of penetration is kept low enough to prevent the auger becoming choked. However, it is not uncommon for auger torques to be an order of magnitude higher than the bit torque (reaction torque during the rock breaking process). Under special circumstances, if there is ice in the terrain being drilled, the cuttings may be cleared very efficiently by the water vapor resulting from the subliming ice, although that would preclude taking pristine samples for volatiles assessment. Alternatively, a gas flow, provided either from a high pressure reservoir on the drilling platform, as a byproduct of monopropellant combustion, or by a compressor compressing the Martian atmosphere may serve the same purpose. Because of the expected small size of the cuttings and the low atmospheric pressure on Mars (allowing very large expansion of the water vapor or gas), only small quantities of ice or compressed gas are sufficient to completely clear the cuttings from the hole.

Introduction

During drilling, the rock excavation process consists of two stages that can occur either simultaneously or separately. The first stage is breaking the rock and the second stage is the extraction of cuttings from the hole. Failure to promptly remove the cuttings results in their being pulverized into progressively finer particle sizes, making drilling very inefficient and in the extreme case halting the drilling process altogether.

Conventional Earth drilling typically uses liquid or gas for flushing the rock cuttings from the hole bottom. The flushing medium has the dual purpose of removing the newly formed rock debris and cooling the drill bit. Removing the rock cuttings in a timely manner in itself contributes to keeping the bit cool. This is because up to 70% of the heat generated during the rock breaking process is trapped in the cuttings

(Uhlmann 2003). The very low pressure on Mars (5 torr), coupled with the low temperature, around -100°C, preclude the use of liquids. In addition, using circulating gas to clear out the cuttings might be problematic due to compressor power requirements. Thus, the most likely method of clearing the cuttings will be by mechanical means, such as an auger or by novel means such as those that have been investigated during the course of the present research.

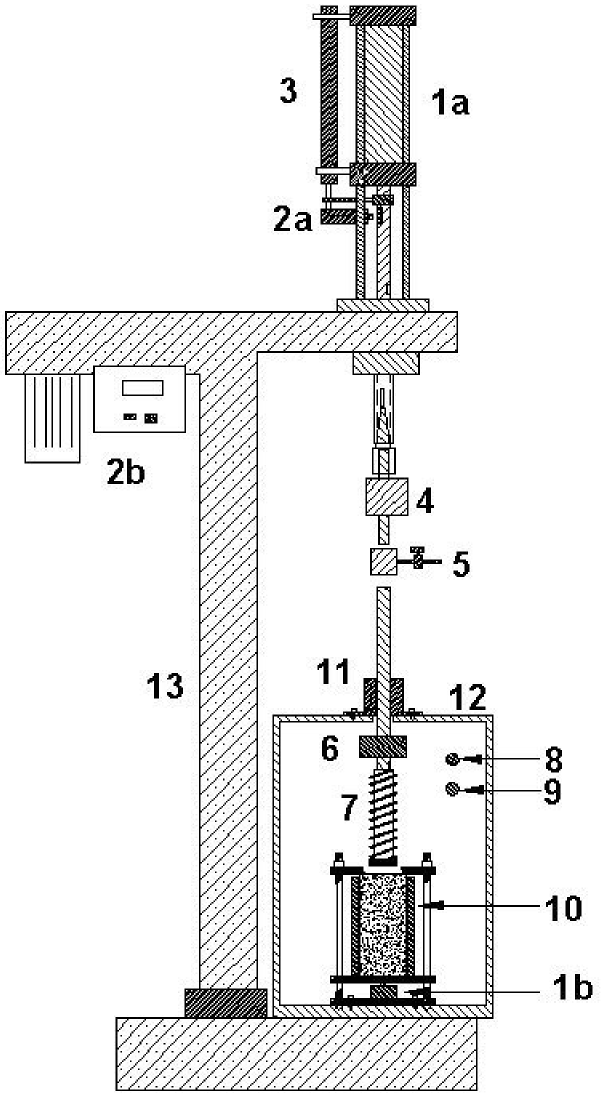
In this paper, we consider the problem of drilling holes into the subsurface of Mars, but we do not consider the specific issue of preserving the volatile content of materials removed.

In this paper we present three methods for clearing of cuttings from the bottom of the hole using an auger: (1) dry,. (2) use of gas and (3) use of sublimation of water-ice.

Effect of Poor Bottom Hole Cleaning

To determine the effect of poor bottom hole cleaning, a drilling experiment was devised in which the drill string assembly incorporated a swivel (see item 5 in **Figure 1**). It is called a swivel because it allows the flushing fluid to pass from a non-rotating part to a rotating part of the equipment. It is not a valve because it is always open, and in no way serves to control the flow of the fluid. The sketch also shows a valve that is adjacent to the swivel that can be used to control the flow, but is not the swivel itself. The swivel was always in the open position during the tests.

When the pressure inside the test chamber was reduced (by adjusting a valve in the line connecting the vacuum chamber to the vacuum pump, monitored by the pressure sensor connected to item #8) to below the Earth's atmospheric pressure, the differential pressure created between the higher pressure on the outside and the lower pressure inside the chamber, forced air (from the laboratory) through the swivel, down the drill pipe (item 7 in Figure 1) and out into the annular space between the hole wall and the auger. This flow of air cleaned the hole bottom of the drilled cuttings. In this test a PDC (Polycrystalline Diamond Compact) bit (Figure



	Description
1a	Pneumatic Cylinder
1b	Load Cell
2a	Tachometer
2b	Electric Motor Drive
3	Displacement Transducer
4	Torque Sensor
5	Swivel
6	Sliprings
7	Drill Bit and Auger
8	Chamber: Pressure Sensor
9	Chamber: Thermocouple
10	Rock Sample
11	'O' ring Feedthrough
12	Vacuum Chamber
13	Drill Press

Figure 1. Schematics of the instrumented drill press showing placement of various components. (figure1.jpg)

2) was used to drill basalt rock with an Unconfined Compressive Strength of approximately 300 MPa.

The test results of this experiment are plotted in Figure 3. At the onset of drilling, the pressure inside the chamber was below 760 torr and thus drilled cuttings were continuously being cleared out of the hole. Once the pressure was equalized to that of the outside pressure (time mark: 160 seconds), the air circulation stopped, which allowed the accumulation of cuttings at the bottom of the hole. This led the bit to `skid' on the surface of the rock powder and a drop in the rate of penetration from 440 mm/hr to 80 mm/hr. All cuttings removal thereafter was solely by the auger. Only when the pressure inside the chamber was reduced again (time mark: 330 seconds), was the flow of air re-started, allowing the clearing of the cuttings from the bottom of the hole and allowing the bit to penetrate the rock. The result was an immediate increase in the rate of penetration. Note that opening the valve next to the swivel (item 5) allows air to flow freely into the swivel, down the drill stem, out through the bit nozzles, up the hole annulus and into the chamber. To the extent that the chamber pressure is below atmospheric, air will flow along this path, into the chamber and ultimately out to the vacuum pump. To a first approximation, the flow rate will be proportional to the difference between the chamber pressure and that of the outside atmosphere.

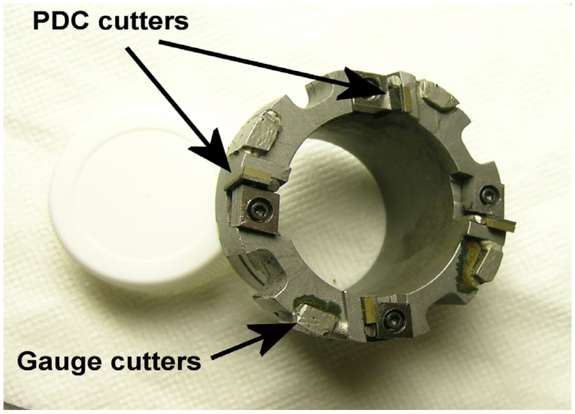


Figure 2. PDC bit with exchangeable cutters. The bit diameter is 1.5 inches and the core hole is 1.0 inches. (figure2.jpg)

This experiment showed that it is imperative to have a very effective cuttings removal system for any drilling apparatus to be successful. Thus, the next question concerns the means for removing the cuttings from the bottom of the hole.

Cuttings Removal by Means of Augers

Currently, the method for removing cuttings that is receiving the most attention from those interested in exploration drilling on Mars is the use of augers. A typical arrangement envisages the use of a hollow-stem auger allowing recovery of a core. Alternatively, the hollow space inside the auger may contain a down-the-hole (DTH) instrument such as a neutron probe. The auger may or may not be shrouded, and may either continue all the way to the surface or convey the cuttings to a suitable catch basket situated immediately above the coring assembly and inside the auger tube.

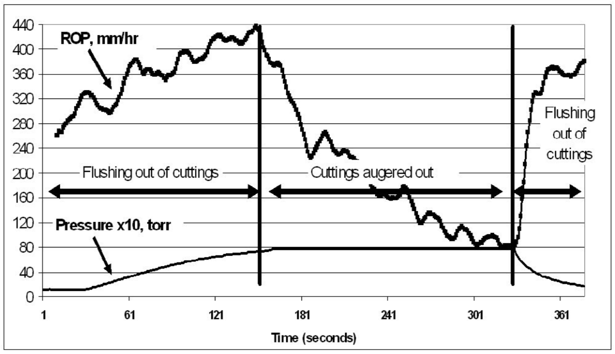


Figure 3. Effect of poor hole cleaning on the rate of penetration showing high rates of penetration with flushing and low rates without flushing. (figure3.jpg)

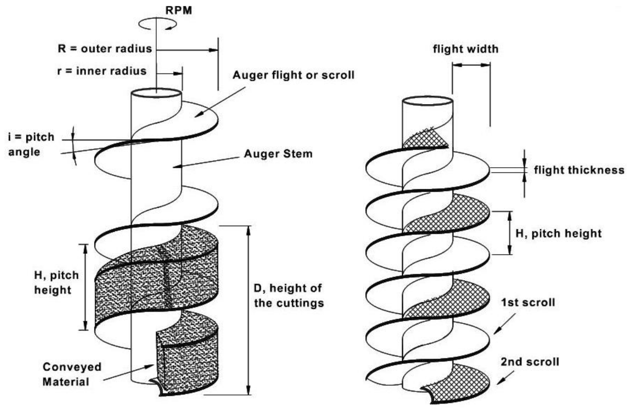
The power consumption for the actual drilling process, i.e. rock breaking, does not change much as the depth of the hole increases. The power for the removal of the rock debris, on the other hand, increases with the depth of the hole. At a sufficient depth, this component of the total drilling power becomes so large that the power required for rock breaking will be relatively insignificant.

The rate of power increase required for cuttings removal has been found to be a function of the properties of the conveyed material, its water saturation and the geometry of the auger itself (Thusing 1958; Roberts and Willis 1962; Ross and Isaacs 1961a; Ross and Isaacs 1961b). Since it is very difficult (but not impossible as shown in section “Cuttings Lift by Sublimation of Ice”) to change the properties of the conveyed material, the only parameter that is available for adjustment is the auger geometry.

The energy required to drill a rock is proportional to the specific energy of the rock and the volume of the rock removed. The power required to drill a hole can be reduced by reducing the volumetric rate of the rock to be removed (the excavated area in the rock x the rate of penetration.) The rate of penetration can be adjusted during drilling, while the kerf (the annular area between the outer diameter of the hole and the core, i.e. the part of the rock actually removed by drilling) is set by the geometry of the drill bit, so it is constant. The bit diameter sets an upper limit on the auger diameter. Since it is imperative to reduce the drilling power, the Martian drill bit, and in turn the auger, will have a small diameter (Auger diameters currently proposed by various groups working on prototype Mars drills are not more than 5 cm in diameter). Additionally, since the drilling power is directly proportional to the rotational speed, the Martian drill, due to the imposed low power budget on all currently proposed missions, would have to operate at modest rotational speeds. The next step, therefore, involves designing an auger that will give best performance, given its small diameter and low rotational speed.

Principle of Auger Operation

Drilled material is conveyed up an auger by sliding it along the helical ramp known as a scroll or a flight of the auger (see Figure 4).



One scroll auger

Two scroll auger

Figure 4. Auger terminology used in this paper. [(figure4.jpg)](figure4.jpg)

In the optimal case, the material would move up vertically. This would occur only if the material were to `adhere' to the surface of the hole wall, while being pushed up by the rotating surface of the scroll. The degree of "adhesion" of the material to the wall depends on the force with which the material presses against the wall and the coefficient of friction between the wall's surface and that of the material. The degree of pressure that the material applies on the surface of the wall is a function of the centrifugal force and, in turn, the rotational speed of the material itself and the diameter of the auger. Thus, as long as the material rotates with the auger, it is pressing against the wall. As soon as the frictional drag of the material against the hole wall slows the material down, the centrifugal force decreases.

The upward movement of the material inside the auger is resisted by the weight of the cuttings as well as the friction against the surface of the flight (the spiral ramp attached to the central stem of the auger, also known as the scroll) and against the stem of the auger itself. Thus for the material to move up, there must exist a reaction force (Mellor, 1981). The main reaction force is a frictional force against the hole wall. Considering the balance of forces acting on the unit material on the auger flight as shown in Figure 5 gives:

$$mg\sin(i) + \mu_s mg\cos(i) = \mu_w \frac{mv^2}{R}\cos(i) \qquad (1)$$

Simplifying the above equation and noting that

$$v = \frac{2\pi}{60} * N * R \qquad (2)$$

where, N is rotational speed in RPM (revolutions per minute), the threshold RPM required to initiate movement of the material up the scroll is:

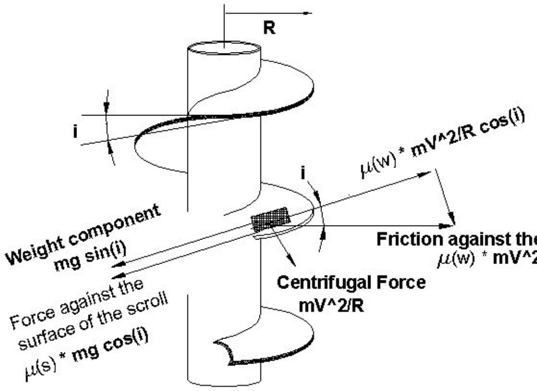


Figure 5. Force balance acting on unit material on the auger surface. [(figure5.jpg)](figure5.jpg)

$$N = \frac{30}{\pi}\sqrt{\frac{2g}{D}\,\frac{\tan(i) + \mu_s}{\mu_w}} \qquad (3)$$

where

- $D = 2R$ = diameter of the auger.
- g = acceleration due to gravity.
- i = helix angle of the scroll or the pitch angle.
- μ_s = coefficient of friction between the surface of the scroll and the material.
- μ_w = coefficient of friction between the material and the surface of the hole wall.

Equation 3 shows that the critical speed required to start movement of the cuttings up the scroll increases as the auger diameter is decreased or as the pitch angle is increased. The critical speed decreases as the coefficient of friction between the conveyed material and the surface of the auger flight (μ_s) decreases or as the coefficient of friction between the conveyed material and the surface of the hole wall (μ_w) increases. However, since the auger diameter cannot be changed much, the only adjustments that can be made are to decrease the pitch angle and/or to decrease the coefficient of friction of the scroll surface.

Based on equation 3, Figure 6 shows the range of required rotational speeds in revolutions per minute (RPM) that the auger would need to have in order for the material to move up. Two values for the coefficient of friction of the scroll surface (μ_s) were chosen: 0.1 and 0.3.

Low values were chosen because, based on equation 3, it is desirable to have as low a friction coefficient as possible. Three values of the friction coefficient of the bore hole wall (μ_w) were chosen: 0.5, 0.6 and 0.7. Again, equation 3 implies that μ_w should be as high as possible. One can apply low friction coatings to the surface of the scroll, but the coefficient of friction between the cuttings and the hole wall is whatever it is. Since we don't have a good idea of what that will be for martian materials in that environment, it seemed best to cover a range to give the reader an idea of the sensitivity of the critical speed to changes in the friction coefficient. The actual values are therefore of less importance as absolutes than they are in indicating the trend.

Note that the RPM values of 100 rpm to 300 rpm are in the range of the rotational speeds considered for a Martian drill by teams currently working on prototype Mars drills. It should also be noted, that once the cuttings start moving up the scroll, the frictional force against the wall changes its direction. This is because the movement of the material is no longer around the hole in a circular path but along a helical path. The angle of this helical path depends on the velocity of the material up the scroll. The change in the direction of the frictional force reduces the magnitude of this force. To account for this decrease, the rotational speed should actually be higher than the value specified in Figure 6.

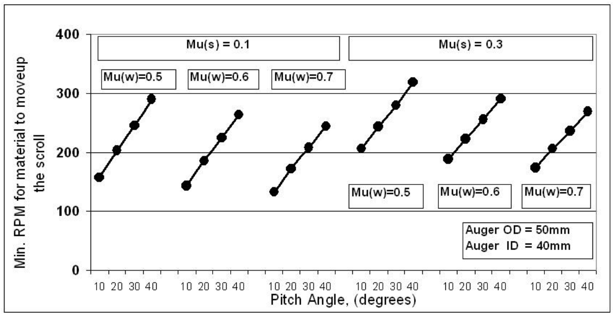


Figure 6. Minimum rotational speed required to initiate movement of material up the auger. Mu(s) = coefficient of friction between the scroll surface and the material. Mu(w) = coefficient of friction between the surface of the borehole wall and the material. (figure6.jpg)

Figure 7 shows the auger torque per meter of auger length (i.e. per meter of hole depth) as a function of rotational speed in revolutions per minute measured during a drill test in simulated lunar regolith, FJS-1. The simulant, FJS-1, is manufactured by the Shimizu corporation of Japan (Kanamori et al. 1998). This is one of the few occurrences where auger torque could be experimentally related to rpm so well (normally, auger torque is very erratic indicating that cuttings flow is intermittent). The reason for such a good correlation is that the penetration rate was kept constant (WOB = Weight On Bit, i.e. the drill feed force) was continuously adjusted to maintain constant rate of penetration) and in turn the flow of cuttings up the auger flutes was uniform and, secondly, the cuttings themselves were very abrasive and thus provided a high amount of friction against the auger. Note that at low rotational speed of 50 rpm the auger torque was very high (in the range of 10 Nm). By doubling the rotation speed to 100 rpm, this torque dropped to 2 Nm. Since power is related to torque and speed by the following equation, Power = Torque * RPM *(2π/60), it can be easily calculated that also by doubling the rpm, the power dropped from 50 Watts to 20 Watts.

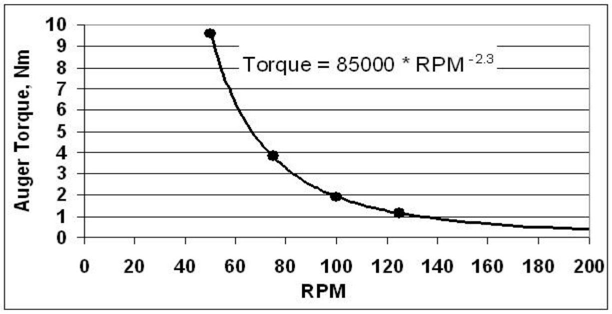


Figure 7. Experimental data showing Auger torque in Nm as a function of rotational speed in revolutions per minute (RPM). The tests were conducted in simulated lunar regolith, FJS-1 made by Shimizu Corporation. (figure7.jpg)

The best fit line in Figure 7 is asymptotic to a value of around 0.5 Nm at a speed of 200 rpm. Thus, this particular speed seems to be ideal for that particular auger design (auger diameter, D, of 40 mm and pitch angle, i, of 25 degrees). Substituting these auger values into Equation 3, and assuming that the coefficient of friction between the conveyed material and the surface of the auger flight (μ_s) is 0.3 (smooth surface) and that the coefficient of friction between the conveyed material and the surface of the hole wall (μ_w) is 0.7 (rough surface), the threshold rpm, N, required to move the cuttings up the auger is approximately 230. This is in the same range as the RPM found from the experimental data.

Augers (also known as screw conveyors) are used every day in the materials handling industry and particularly in grain silos. A good deal of research has therefore been conducted to determine the optimum auger parameters such as the pitch angle, the choke length and the diameter that are required at various rotational speeds (Gutyar 1956; Vierling and Sinha 1960; Colijn 1985). Several equations were also derived to try to estimate the minimum rotational speed necessary for the material to move up the auger (Roberts and Willis 1962; Ross and Isaacs 1961a; Ross and Isaacs 1961b) and most equations are very similar to equation 3.

Choking - The Most Serious Case of Auger Failure To Convey Material

Drilling tests also revealed that there exists a fine point between the cuttings flowing smoothly up the auger and suddenly jamming in place. Once the auger became clogged (also referred to as auger choking), it was almost impossible to clear it. Such a scenario occurred when the throughput of the auger was too great. It is thus extremely important to determine the maximum lifting capacity of the auger under anticipated operating conditions and then to limit the rate of penetration of the drill so as not to exceed this value. This will require deliberately limiting the rate of advance of the bit, especially in easy drilling formations.

Theoretical Analysis of Choking Phenomenon

When the auger becomes clogged, the material exerts equal pressure against the bottom and the top of the scroll, the stem wall and the hole wall as shown in Figure 8. For the material to move up the scroll, the friction against the hole wall must be larger than the remaining three components of the total resistive forces. If, on the other hand, the three components are higher, the material will remain in place and auger choking will result.

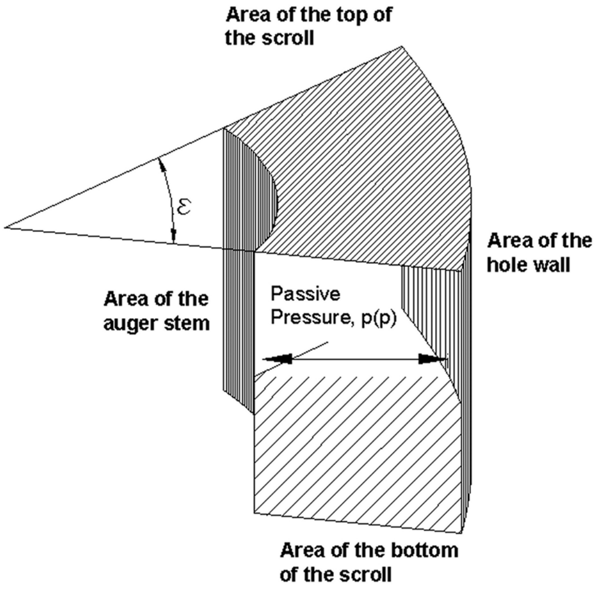


Figure 8. Highly compacted material in the form of a wedge, exerts the same pressure on all four surfaces. (figure8.jpg)

Note that each of the forces is proportional to the surface area, which cannot be altered much, and the coefficient of friction, which can be changed (especially the scroll friction coefficient which is typically changed by polishing or by the application of low-friction materials, e.g. PTFE).

Therefore, for auger choking to be avoided:

$$pA_w\mu_w \geq 2pA_s\mu_s + pA_{stem}\mu_s \tag{4}$$

where

- p = lateral pressure exerted by the material.
- A_w = area of the hole wall = $HR_o\varepsilon$.
- A_s = area of the bottom of the scroll = $\frac{(R_o^2 - R_{in}^2)}{\cos(i)}\frac{\varepsilon}{2}$.
- A_{stem} = area of the auger stem = $HR_{in} * \varepsilon$

for small angle, ε.

It has been assumed that the areas and the coefficients of friction of the bottom and top surfaces of the scroll are the same and that the coefficient of friction of the auger stem is equal to that of the scroll surface.

Substituting and solving, the minimum pitch height, H, required to prevent choking is:

$$H \geq \frac{\mu_s}{\cos(i)} * \frac{R_o^2 - R_{in}^2}{\mu_w R_o - \mu_s R_{in}} \tag{5}$$

Figure 9 shows the minimum required pitch height, H, as a function of the pitch angle and the coefficients of friction for an auger with an outside diameter (OD) of 50 mm and an inner diameter (ID) of 40 mm. Three low values for the friction coefficient of the scroll surface (μ_s) were chosen: 0.1, 0.3 and 0.5 as covering the range that might be attainable with various low friction materials. In addition, two higher values for the borehole wall coefficient of friction (μ_w) were chosen. These were 0.5 and 0.7. The most important case exists when μ_s and μ_w are equal. In this scenario, the pitch height for the pitch angle of 20° needs to be around 48 mm (see dotted circle in Figure 9. In other words, the pitch height of 48 mm is required in order for the surface area of the wall to be larger than the surface area of the scroll (top and bottom) and stem combined, given the same friction coefficient on all surfaces. Note that we are dealing with a balance of the "forward" and "backward" forces: since we are considering the forces to be generated by pressures, they will be proportional to the areas over which they act. Thus, if the coefficients of friction are everywhere the same, the balance will be achieved when the areas are equal.

Note that it is not the absolute values of the coefficients of friction of the scroll and the wall, but their relative values that matter. In fact, if the coefficient of scroll friction is smaller by 0.2 than the coefficient of wall friction, the required pitch height for any reasonable value of the pitch angle is less than 10 mm. This difference of 0.2 should be enough to initiate the movement up the scroll and in turn prevent the auger from choking.

If the auger has a shroud, a high friction surface could be easily achieved by a special coating or vertical ribs. If the auger does not have a shroud, the wall of the hole will be covered by the drilled material. Since for very fine sands and silt size material the peak internal friction angle is around 35°, the equivalent coefficient of sliding friction against the wall would be approximately 0.7 (tan 35° = 0.700)

However, irrespective of the friction coefficient of the hole wall, it is imperative to make the surfaces of the auger as smooth as possible. In addition, since it is likely that the material to be conveyed will be abrasive, those surfaces should also be made of highly abrasion-resistant material. Also note that due to the centrifugal force, material on the scroll will move to the outside i.e. towards the borehole wall and away from the surface of the auger stem. This could provide an additional reduction in the frictional force at the surface of the stem and increase the frictional force at the surface of the hole. The result should be a somewhat higher efficiency of the auger.

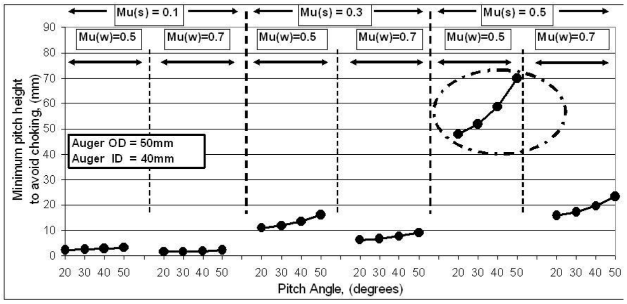


Figure 9. Minimum pitch height required for cuttings movement, when the auger is full. Mu(s) = coefficient of friction between the scroll surface and the material. Mu(w) = coefficient of friction between the surface of the borehole wall and the material. (figure9.jpg)

Since material might be also "dragged" up the auger by the frictional force against the hole wall, it might be beneficial to make the auger scroll depth very shallow. In this way, a thin layer of material will interact directly with the auger surface on one side and the surface of the auger stem on the opposite side. Provided that the stem surface is very smooth, material can be dragged up the auger very easily. In this case, the auger could be rotated at lower rotational speeds as centrifugal force does not play a role in lifting the cuttings up the auger. If the scroll depth, however, is made too deep, the thin layer of material in contact with the wall will interact with bulk material on the scroll rather than the auger stem. In this case, the movement of the material up the auger will be less efficient, as the friction between the thin layer in contact with the wall and bulk material is governed by the frictional angle of the bulk material. This friction angle is very high, in the range of 35° corresponding to a coefficient of friction of 0.7. In this case, the auger rotational speed must be high enough for the centrifugal force to take effect. Note, however, that making the auger scroll too shallow also decreases auger throughput. Thus, there exists an optimum scroll depth that will provide the most effective conveyance of material, yet maintain reasonable throughput.

Signs of Auger Choking

Figure 10 shows an example of auger choking (a "zigzag" pattern of Rate of Penetration or ROP and Power) during a drilling test in Briar Hill sandstone. The zigzag pattern is explained as follows: initially, a high rate of penetration, in excess of 100 cm/hr caused production of cuttings in excess of the maximum allowable auger throughput. As the auger became clogged with excess cuttings, the rate of penetration started to drop from `0' to `220' second time mark in Figure 10 until it reached 5 cm/hr at the 241 second time mark. At this stage, almost no new cuttings were being produced. The build up of cuttings at the bottom of the hole caused lateral stresses to develop inside the material. Since the cuttings were pressing against the stem of the auger on one side and on the surface of the hole on the opposite side, the resultant friction increase caused an increase in the torque (and in turn power) required to rotate the auger. Only once did the torque (and in turn the power) increase to a value that exceeded the frictional resistance of cuttings pressing against the hole wall (time mark: 245 seconds), allowing the cuttings to move up the auger and leave room for new cuttings to enter into it. This was reflected in a drop in power and an increase in the rate of penetration. The total power, shown in **Figure 10** has two components, namely the drilling power and the power required to remove the cuttings. Thus, at the time mark of 241 seconds, the sudden drop in the rate of penetration together with an insignificant reduction in power, meant that the drilling power dropped, while the power required to remove the cuttings increased. This condition could become dangerous if the motor torque is not high enough to exceed the frictional force of the cuttings pressing against the auger and the surface of the drilled hole. If this occurs, the auger can permanently jam, trapping the drilling assembly inside the hole.

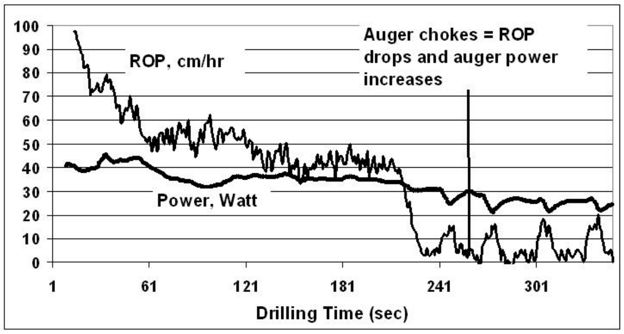


Figure 10. When the auger throughput exceeds a certain value, the auger chokes. This leads to a fluctuating power and rate of penetration. (figure10.jpg)

Thus, the main reason for auger choking was exceeding the maximum allowable throughput at the beginning of the test. Since the initial Rate of Penetration was in excess of 100 cm/hr, a volume of 0.17 cm^3 of cuttings was produced each second. Considering the geometry of the auger, this indicates a sliding velocity of 4.7 m/hr past the auger surface. This velocity represents the throughput velocity of the auger under that set of experimental conditions (auger geometry, rotational speed and the properties of the conveyed material). Note that it is more appropriate to quote the throughput velocity rather than the volume, since the throughput velocity also takes into account auger geometry, while the volumetric throughput does not.

This zigzag pattern, indicating choking, was also confirmed by conducting experiments using a medium-to-coarse grained Monterey sand as shown in Figure 12. The results are plotted in Figure 11. The choice of sand instead of fine rock powder was made to enhance clogging of the auger. This is because larger grains are more difficult to rearrange and thus have much higher shear strength (friction angle). In all tests, a sinusoidal fluctuation of power with a sinusoidal fluctuation in the rate of penetration (two waves separated by an approximately 150° angle) was observed. In addition, the sand leaving the auger on top was found to be much finer than the sand entering the auger at the bottom. Therefore, part of the energy was used to grind the sand particles, as they moved up the auger. In addition, the sand particles,

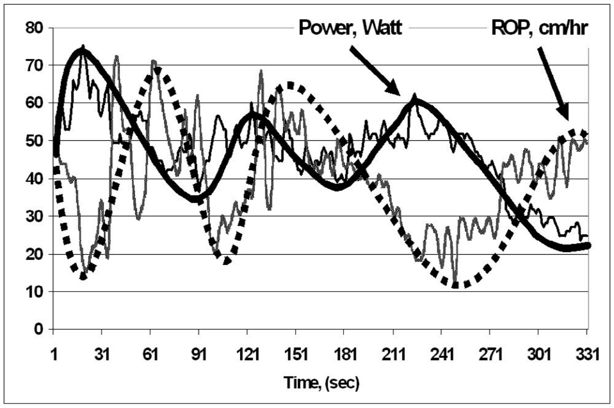


Figure 11. Choking phenomenon recorded in auger experiments with coarse grain sand. (figure11.jpg)

Figure 12. Experimental arrangement for observing choking phenomena. (figure12.jpg)

being made of quartz (hardness 7 on the Mohs scale), caused extensive surface wear to the auger and the casing.

Methods of Choking Prevention

The most effective method of un-choking the auger was to keep the auger rotating while lifting it up and down. This loosened the compacted cuttings. Although this method was found to be effective, it would be better not to allow choking conditions to occur. There are at least three possible ways of monitoring and possibly preventing the auger from clogging with excess cuttings. These are listed as follows:

Solution No.1

One way to prevent choking would be to monitor the amount of cuttings being produced and compare it with the known (i.e. previously determined) throughput of the auger. If the mass flow of the cuttings exceeds the auger's throughput, the rate of penetration should be decreased by decreasing the weight on the bit (WOB). For this method to be effective, the mass of cuttings produced per revolution must be known. This, consequently, depends on the density and porosity of the formation (or the mineralogical composition and abundance of each mineral) . Since the density and porosity will typically not be known to much accuracy, this method can only provide rough estimates.

Solution No.2

Another way to prevent the auger choking would be to compare the amount of the cuttings forming at the bottom of the hole with the amount of cuttings actually exiting the auger on top. This method, however, might not be very accurate either, since it would be very difficult to establish the porosity and density of the formation. Additionally, it would be difficult to determine the volumetric expansion of the rock as it turns from a cohesive material (rock) into a rock powder. Granular material may also have various densities that depend on the degree of compaction, known as a void ratio “e”. The void ratio is defined as:

$$e = \frac{Volume_{voids}}{Volume_{solids}} \tag{6}$$

For example, the void ratio of uniform fine-to-medium sand can range from $e_{\max}$ 0.85 (loose state with 46% voids) to $e_{\min}$ of 0.5 (dense state with 33% voids) (Hough 1969).

Solution No.3

An approach for monitoring the choking phenomenon would be to position pressure sensors on the stem and flute surfaces of the auger. These would indicate the lateral stresses built up at the bottom of the hole and, in turn, anticipate any increase in the frictional torque required to convey material up the auger. If the frictional torque were to approach the limiting torque of the drill motor, the weight on bit could be immediately reduced, while the rotational speed could be either increased or maintained constant.

Final Remarks Concerning Augers

For the auger geometry used in the current experiments, it was calculated that the most effective auger would have a large pitch height and a low pitch angle (**Figure 4**). The optimum pitch angle was found to be around 20°. Since the pitch height is directly proportional to the pitch angle, a trade-off was required to optimize the design. (Note that the pitch height could be increased without increasing the pitch angle only by decreasing the number of scrolls. For example, the auger could have two scrolls instead of four.) Taking this into consideration, the pitch height for a 40 mm diameter, two-scroll auger, was calculated to be around 20 mm. By increasing the cross-sectional area for the cuttings to flow through, the flute thickness should be minimized.

An important change that can improve auger effectiveness is to reduce the coefficient of friction of the auger surfaces. This can be achieved by coating the surface with a material that has a low friction coefficient and is highly abrasion resistant, such as Nedox (Magnaplate). If a coefficient of friction of 0.2 could be achieved, the clogging of the auger, which is the worst-case scenario in auger failure, might be completely eliminated. Note also that the bit should have strategically placed channels, to allow for the unobstructed flow of the cuttings from the hole bottom to the auger.

An auger is ineffective if there is no new material being fed into it (the auger will never empty itself).

Cuttings Removal by Sublimation of Ice

An alternative possibility for lifting the drilled cuttings occurs if the formation being penetrated contains water ice and if the ambient pressure is sufficiently low. In experiments on ice-containing rocks and soils, it was found that when drilling under conditions of low pressure, the heat generated by the drilling process caused the ice to melt and then immediately to boil to vapor. At a pressure of 5 torr, the volume expansion occurring in converting ice to vapor is 150,000 times. Even relatively small concentrations of ice in soils or in the pore spaces of rocks could generate enough water vapor to blow the cuttings out of the hole (Figure 14). Since the water is converted to vapor at the drill bit, the cuttings blown out of the hole are, in effect, freeze dried, and thus do not stick to the drilling equipment or to the hole walls as they leave the hole. An additional advantage is that the latent heat of sublimation of water (2.6 kJ/gm), removes a large quantity of heat from the hole. This helps to keep the bit cool and to maintain the core in a frozen condition.

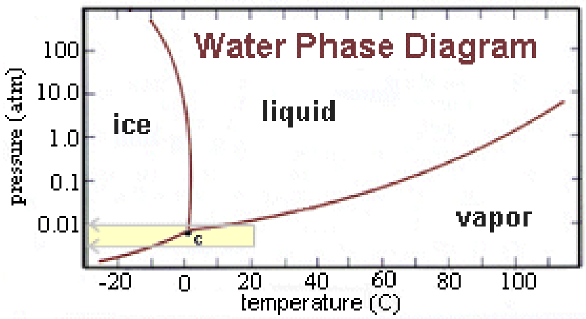


Figure 13. Water phase diagram. The 'triple point' (labeled "C" in the diagram) is the temperature and pressure where all three types of water can exist at once. Liquid water cannot exist below 6.1 millibars. Any water that might form on a warm afternoon from melting water would quickly disappear in the desiccated martian atmosphere (courtesy of NASA). (figure13.gif)

Note also that the surface of the core is dried, but the bulk of it is untouched. Indeed, because of the cooling provided by sublimation, the core keeps cooler than otherwise. We have found that when drilling ice-bound soils, if there is no sublimation, then there is melting, and the melted material allows the liquid water (and cuttings) to migrate here and there in the core. One can then not be sure if the ice in the core is as originally present, or whether some has been lost or gained. At least, if sublimation is occurring, any ice found is where it was originally, even if somewhat less in quantity near the core surface (comparing ice concentrations at core surface and in the interior will shed light on this).

We believe it would be imprudent in the extreme to count on finding water ice in the drilled formations and to rely on that as an essential part of the drilling process. Whatever we send to Mars will have to be able to make progress without ice. However, since we may encounter ice, and it causes such interesting and potentially valuable effects, it's well worth documenting how it does it, and to be prepared to benefit from it.

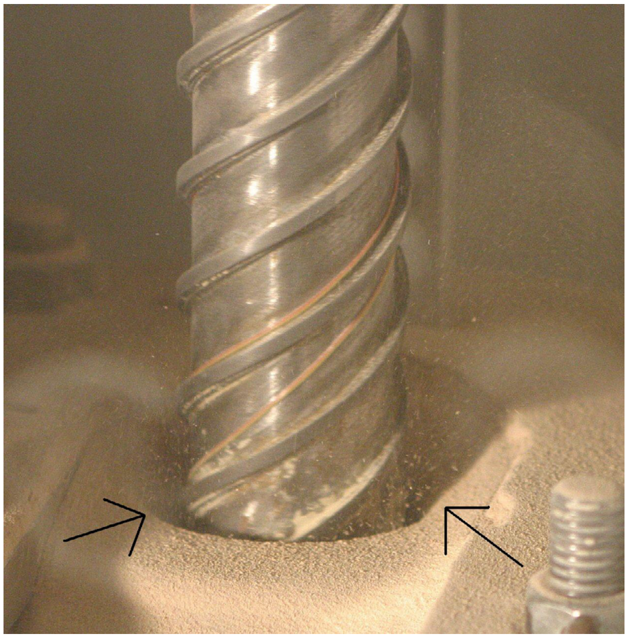


Figure 14. A close up of the drill and the hole showing rock cuttings being blown out of the hole. The auger diameter is 39 mm (Zacny at al. 2004). (figure14.jpg)

Drilling with a Diamond-Impregnated Bit

In experiments with diamond-impregnated bits it was found that the efficiency in drilling ice-filled rocks at Martian pressures was much greater than in drilling under Earth atmospheric pressures. Typically, rates of penetration doubled and the drilling power halved under Martian conditions. By comparison, under Earth conditions, or whenever the pressure exceeded that of the triple point of water, liquid water formed and mixed with cuttings to form a paste. This paste was more difficult to auger out than vacuum dried cuttings. In addition, in some instances, the paste refroze around the bit and the auger, trapping the bit inside the hole. The drilling efficiency under Earth conditions was additionally decreased because small diamonds on the surface of the cutting segments could not penetrate through the paste into the rock.

A typical drilling record is shown in Figure 15, with the Power and the Rate of Penetration (ROP) plotted as a function of drilling time. The figure shows that the initial Rate of Penetration was 25 cm/hr, and the Power was approximately 50 Watts. During this time, the cuttings were observed to be blown out of the hole in the form of a fine dust (Figure 14). This dust was completely dry, and 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 little part in the transport of cuttings. After approximately 850 seconds, the pressure was raised to above the water vapor pressure. During this period, the vaporization process ceased, which 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 the liquid water causing the cuttings to stick together around the bit cutting structure. The pressure was later reduced to 5 torr after about 150 seconds, which restored the ROP and decreased the power. See Figure 14. The reason for the observed sudden increase in the temperature was the drop in the sublimation rate, which otherwise would consume heat in the form of latent heat of melting and vaporization. Soon after the pressure was restored to 5 torr, the power decreased, and the ROP increased. At the same time, the cuttings were again seen being blown out of the hole.

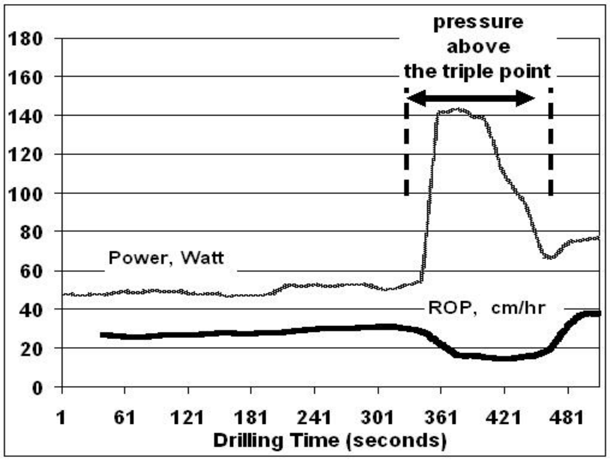


Figure 15. Drilling data showing the effect of vigorous sublimation or “boiling” (analogous to clearing of cuttings with gas flow) on the rate of penetration and power (Zacny at al. 2004). (figure15.jpg)

Core recovery under Martian pressure was found to be much better, both because of the reduced tendency of the core ice to melt and because of the more efficient removal of cuttings, which reduced the tendency of the core to jam in the core barrel. The bit wear, however, was much different. Under the Earth's atmospheric pressure, the cuttings were cleared via volumetric displacement and the action of the auger, which is an inefficient method. Upon inspection of the bit surface, it was found that a layer of rock powder was adhering to the surface of the cutters as shown in Figure 16. This layer protected the underlying metal matrix from wear and in turn, diamonds were not being replaced in a timely manner. Under Mars pressure conditions; on the other hand, newly formed rock powder was continuously being blown out of the hole allowing the metal matrix of the diamond segments to slide against the bottom of the hole. Since the matrix wear was very fast, diamonds were being replaced very frequently and did not have the time to wear (Figure 17). The matrix wear was due to the abrasive action of the rock debris flowing in the gap between the unbroken rock and the matrix.

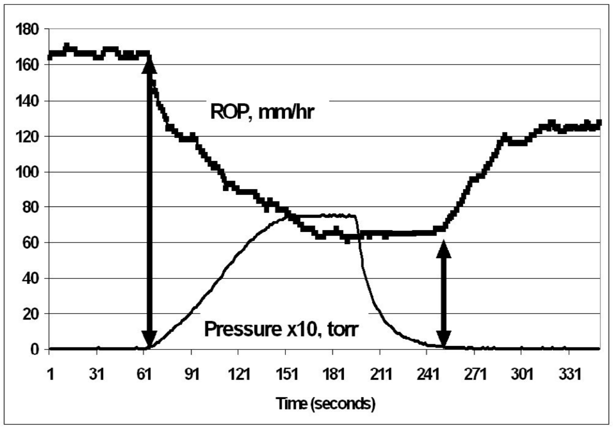


Figure 16. Effect of the vapor flushing on the rate of penetration in water-saturated frozen basalt. (figure16.jpg)

Drilling with a PDC Bit

In another set of experiments, a PDC bit (shown in **Figure 2**) was used to drill into a fully water saturated (saturation of 100%) and frozen basalt rock having an Unconfined Compressive Strength of approximately 300 MPa and porosity of approximately 1%.

The test data are shown in Figure 15. Initially, the pressure was below the triple point of water, allowing the ice to sublime directly into vapor. The flow of water vapor continually lifted the cuttings off the bottom of the hole and permitted the PDC cutters to bite into the rock. As soon as the pressure was increased to above the triple point of water (time mark of 61 seconds), the vapor flushing stopped and consequently caused an accumulation of cuttings on the bottom of the hole. The accumulation of cuttings led to a drop in the rate of penetration, since the PDC cutters were sliding on top of the rock powder and could not penetrate the rock surface. When the pressure was restored to that of the triple point of water (time mark of 250 seconds), it allowed the pore water to sublime and flush the cuttings out of the hole. Since the cuttings were cleared, the bit could again penetrate the rock surface and the rate of penetration increased.

Effect of Various Saturation Levels on the Sublimation Process

The rate at which cuttings are cleared out of the hole depends on the heat input into the formation (a function of drilling power) and the amount of ice inside the formation. Therefore, there are two cases that need to be considered, (1) not enough heat to sublime ice, and (2) too much heat for the amount of ice.

Not Enough Heat to Sublime All the Ice

This scenario occurs when the drilling action does not generate enough heat to sublime all of the ice in the formation directly below the kerf area of the bit and within the immediate surface of the core and bore hole wall. The worst case scenario would occur when insufficient flow of water vapor removes only a fraction of the cuttings. The remaining rock powder would remain inside the hole, trapping some of the water vapor at the bottom of the hole. If this happens, a region of higher pressure might develop due to a build up of water vapor. Since the pressure would be above the triple point of water, ice could melt and remain in the liquid state. Cuttings that are moist would not only be more difficult to auger out, but could also clog the auger much faster. In the experiments conducted in wet sandstone under Earth's atmospheric pressure, it was found that the auger choked when the drill reached a depth of only 5 cm. An additional implication of the presence of wet cuttings is that due to possible stoppage of the drill, water could refreeze and trap the bit inside the hole. From the forward and cross-contamination standpoint, wet cuttings would also be disadvantageous. A number of tests conducted by the authors have shown that liquid water is a key transfer medium for contaminants.

Too Much Heat Generated for the Amount of Ice

When there is not enough ice to absorb frictional heat in the form of latent heat of fusion and vaporization, the excess heat would warm up the drill and the surrounding formation as well as the rock core itself. Although the amount of water vapor generated might be insufficient to blow all the cuttings to the top, all the cuttings would be freeze dried and fluffy and thus much easier to auger out. Note also that no re-condensation will occur, since cuttings will be relatively warm.

The Best Approach

In consideration of the two scenarios outlined above, it is “safer” to warm up the drill string, if necessary, possibly by supplying gas blasts that are heated, to make sure that all of the water will be sublimed. If the formation is very `easy' to penetrate, it will require little power to drill through it and, in turn, not much heat will be generated. In this case, additional heat that will be required to sublime the ice could be channeled from a Radioisotope Thermal Generator (RTG).

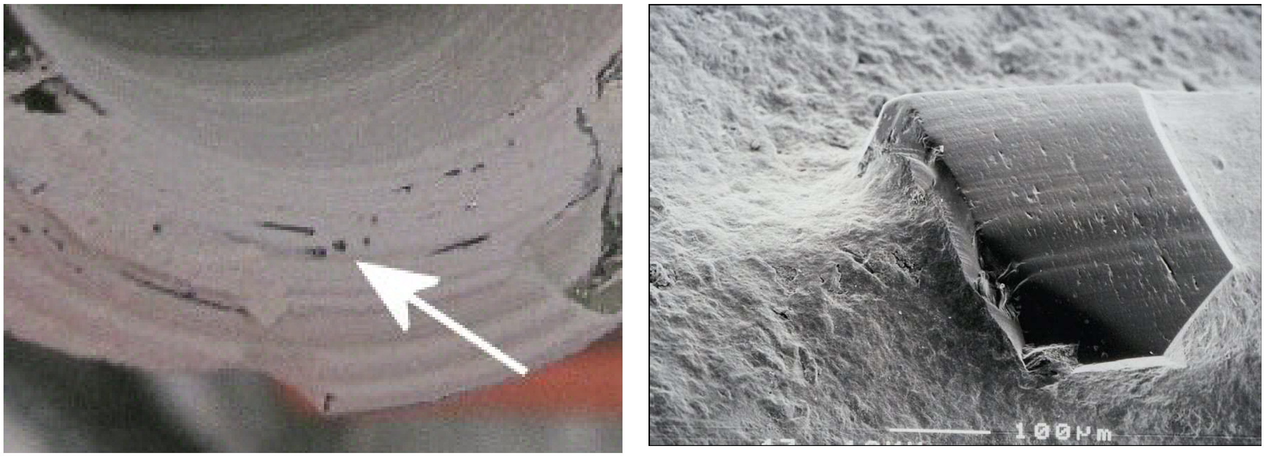


Figure 17. The wear of the drill bit in dry sandstone under terrestrial conditions. (a) Bit covered with rock dust after being lifted out of the hole. White arrow points to the diamonds. (figure17a.jpg) (b) Diamond wear under Earth atmospheric conditions is extensive. (figure17b.jpg)

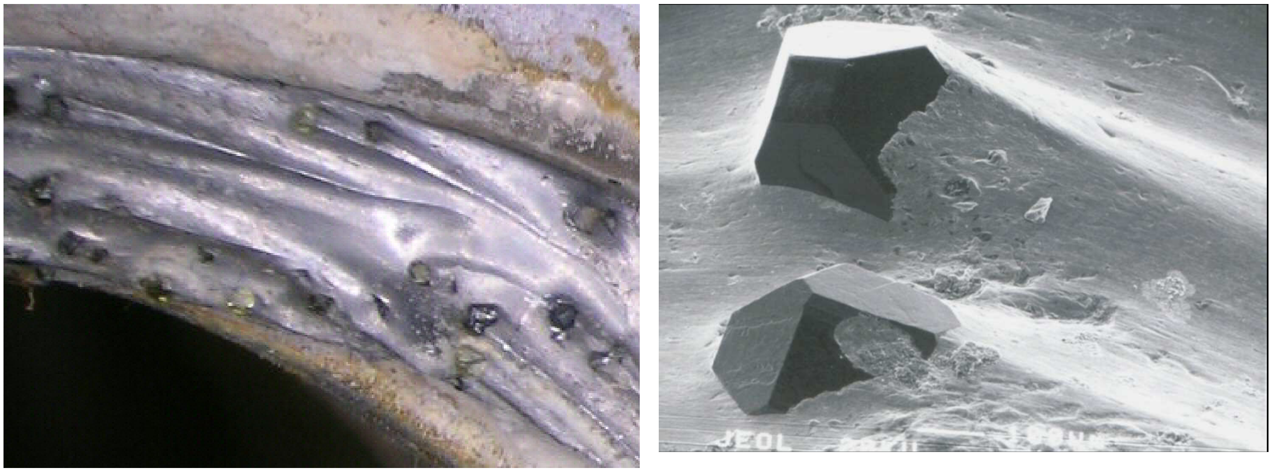


Figure 18. The wear of drill bit in frozen water saturated sandstone under Martian pressure. (a) The bit after being pulled out of the hole was clean. (figure18a.jpg) (b) Diamonds are replaced before they wear. (figure18b.jpg)

RTGs, which are the power sources of choice for drilling missions, generate approximately 1500 Watts of heat in addition to 75 Watts of electrical power (Palluconi 2004). This heat would normally be dissipated to the atmosphere via radiators on the lander/rover, but it could also be supplied to warm up the drill string, if necessary.

Particle Sizes of the Cuttings Blown Out vs. Augured Out

Figure 19 shows the particle size distribution of the cuttings that were augured out vs. those that were lifted out of the hole by the escaping water vapor. It can be seen that the cuttings that were blown out of the hole are much smaller than the cuttings that were augured out to the top. In particular, d_{50}= 65 microns for augured cuttings and 25 microns for flushed out cuttings. If the larger cuttings that remained in the hole were not augured out, they would be pulverized into smaller sizes. In turn, these smaller cuttings would then be lifted out of the hole by the escaping water vapor.

Final Remarks Concerning Cuttings Removal via Ice Sublimation

For the process of water vapor flushing to be effective, it is important that the ambient pressure stays below the triple point of water so that no liquid water can be formed. (More accurately, no liquid water will be formed if the drill bit temperature is greater than the boiling point of water at the ambient pressure.) Note, also, that the process will only be effective if ice is present in the formations being drilled. However, even if not enough vapor is generated to remove all the cuttings, the escaping water vapor would help to keep them "fluffy" and make it easier to auger them out. We should emphasize that since it cannot be guaranteed that ice will be present at a future drilling location, it would be unwise to design the drilling equipment so as to rely on the effect. Rather, it should be considered to provide a significant bonus to the drilling efficiency in those cases where ice is present.

For more information on ice sublimation and its implication to drilling on Mars, please refer to the authors' publication (Zacny et al. 2004).

Enhancing Cuttings Removal with Gas Blasts

The majority of proposed Martian drills utilize an auger for the removal of cuttings. As was noted above, the problem with augers is that they do not work well at low rotational speeds and small diameters. The rate of penetration during coring under simulated Martian conditions was found to be strongly dependent on the efficiency of the cuttings removal system. If the power required for cuttings removal were to exceed the maximum power provided by the Martian lander/rover, the drill would jam and the drilling mission might fail. Therefore, it might be prudent to use an additional method for cuttings removal that would supplement the auger's cuttings removal system, or to free the auger in case of choking.

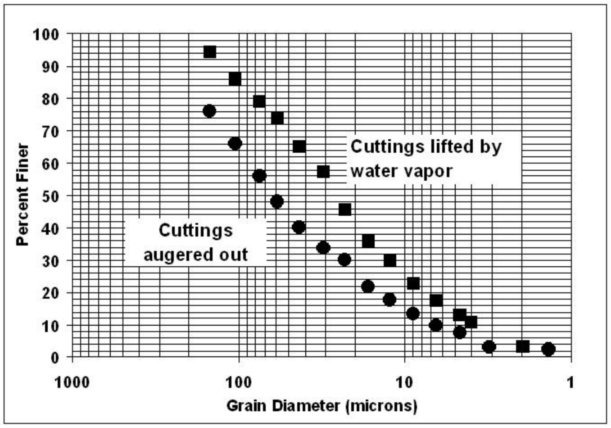


Figure 19. Particle size distribution of the augured and flushed out cuttings. (figure19.jpg)

One possibility would be to use a gas stream, either from a supply of compressed gas brought to Mars on the spacecraft, or generated by compressing the Martian atmosphere.

Experimental Details

Approximately 300 tests were performed in order to determine parameters that affect the efficiency of cuttings removal with gas blasts. In all tests, 0.93 liters of gas at various pressures were used to clear the cuttings from the hole bottom.

Figure 20 shows the experimental arrangement used for the tests. In order to simulate the gas blasting experiments, a few modifications were made to the existing vacuum chamber and drill bit assembly. In particular, an air swivel was added to the drill string, acrylic tubes of different lengths and diameters were attached to the base to simulate the borehole or a casing, and a metal rod was attached to the center of the base to simulate the rock core.

Initially, the required mass of the rock cuttings was weighed out and poured into the casing. Next, valves "1", "2", and "3" (refer to Figure 20) were opened, and the main vacuum chamber was pumped down to the desired inlet pressure. Valves "2" and "3" were closed to keep the 0.93 L chamber at the desired inlet pressure. The main chamber was then pumped down to 5 or 7 torr and then valve "1" was closed, sealing the chamber. The bit was lowered down into the cuttings, 2.5 or 5 mm from the bottom of the borehole. These steps were followed before each gas flushing experiment. To eject the cuttings from the borehole valve "3" was opened. After the cuttings were cleared, the main chamber was vented, and the amount of the cuttings left in the borehole was weighed to determine the amount of the cuttings ejected.

The parameters that were investigated included particle size, the differential pressure, the ambient pressure, the initial amount of rock powder, the gap distance between the drill and the hole bottom, the annular clearance, as well as the gas type. In addition, extra tests were performed to establish the

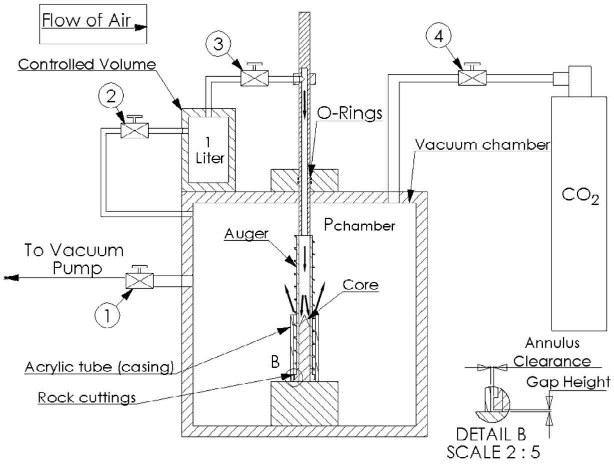


Figure 20. Experimental arrangement for gas flushing experiments (Zacny et al. 2005). (figure20.jpg)

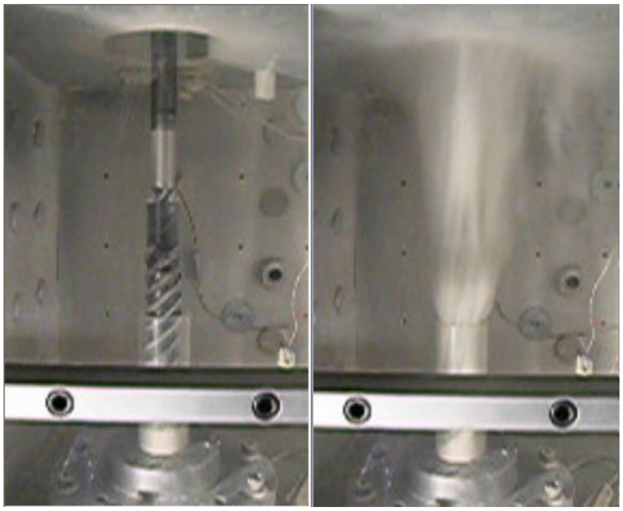


Figure 21. A view of the drill and a simulated drill hole (clear acrylic tube) before and during gas flushing (Zacny et al. 2005). (figure21.jpg)

precision of the data and to determine whether the tests were reproducible. A set of tests was also videotaped (see Figure 21) to investigate the flow regime, to determine the velocity of the cuttings leaving the bore hole, and to determine the duration of the gas blast (Zacny et al. 2005).

Results - Effect of Particle Size

One of the results, shown in Figure 22, indicated that the size distribution of cuttings affects the efficiency of the cuttings removal considerably. In particular, SBSS (Santa Barbara Sandstone) rock powder is much finer than Basalt Rock powder and, in turn, the differential pressure required to clear 50% of the cuttings was only 10 torr as opposed to 30 torr for Basalt cuttings.

These results, however, are only true for the current set of experimental conditions. Note also that the type of drill bit used would also influence the results. This is because the size of the cuttings depends on the type of drill bit used for coring or drilling. Overall, the results show that it is not the absolute difference between the flushing and ambient pressure that is important in determining whether the cuttings are lifted efficiently from the hole, but their ratio. Thus, under Martian conditions with an ambient pressure of the order of 5 torr,, it is only necessary to compress the Martian atmosphere to 50 torr or so. This would require far less power than would be needed for gas flushing on Earth, where compression up to 5-10 (Earth) atmospheres is required. The net result is therefore that the use of gas blasts on Mars to clear the cuttings out of the hole may turn out to be a much more promising method than was previously believed. For a more thorough analysis of gas blasts, please refer to the authors' publication, cited as Zacny et al. 2005.

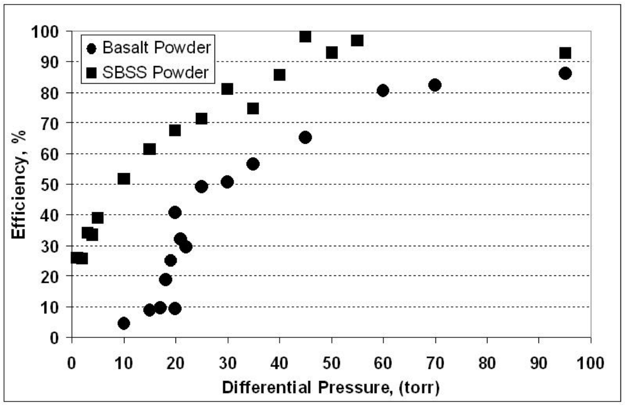


Figure 22. Extraction efficiency of the Santa Barbara Sandstone (SBSS) and Basalt rock powders as a function of differential pressure (Zacny et al. 2005). (figure22.jpg)

Using a Gas Blast to Remove the Core from the Core Barrel

During the drilling process, cuttings penetrate into any possible opening or void. It was found that when the clearance between the inner core barrel and the rock core was too large, there was an accumulation of cuttings in this annular space, as shown in Figure 23. As more and more cuttings were pushed in, lateral stresses inside the material developed and exerted larger stresses onto the rotating inner wall of the core barrel. This, in turn, was registered as an increase in the drilling torque.

It was also found that larger thrust values needed to be applied to maintain the rate of penetration. This was because the lateral stresses inside the material resisted movement in any direction, be it rotary or vertical (as was the case when the bit advanced into the formation.)

On several occasions, the thrust required to maintain the penetration rate had to be increased from 200 Newtons to over 800 Newtons. The difference was attributed to the drill trying to push the cuttings past the rock core. The most serious scenario occurred when initially wet rock cuttings dried out in the annular space between the rock core and the inner wall of the core barrel. As the cuttings became progressively drier, their internal friction angle increased and

Figure 23. Cuttings packing around the rock core during the drilling process. (figure23.jpg)

jamming occurred. These conditions not only increased the drilling torque and required larger weight on bit values, but also resulted in a difficult rock core recovery.

One of the ways to remove a core that was surrounded by a packed layer of cuttings was simply to blast it out with a short burst of compressed air. This method proved to work very well on many occasions.

Gas Provided by a Rocket Engine

Another possibility is to use combustion products from a small rocket engine as the cuttings removal fluid (Zacny et al. 2007). Analogous to terrestrial pneumatic drilling using chemical fuel (i.e. gasoline and air), a pneumatic drill, which has been proposed by in a collaboration between Honeybee Robotics and Firestar Engineering, would derive its mechanical power from a high energy density chemical monopropellant (precombined fuel and oxidizer). After combustion and mechanical power extraction, the exhaust gases can be used to fluidize cuttings for removal during drilling. The demands of rocket propulsion require a fuel with a very high energy density, given that propulsive mobility is an inherently inefficient process in terms of energy and mass. Thus, even very small residual portions of propellant typically budgeted for margin in lander descent operations carry large energy reserves.

These reserves can be tapped for carrying out pneumatic tool operations, including drilling. Gas generation for the pneumatic drill can be provided, for example, by partial decomposition of a new, high Isp, non-toxic, low freezing point, NOFB monopropellant. Hydrazine, a commonly used monopropellant for the maneuvering thrusters of spacecraft, or in terminal descent of spacecraft (for example used in both Viking landers as well as the Phoenix lander scheduled to launch in August 2007) can also be used but it is highly toxic and very unstable. One of its decomposition products is ammonia, which, if trapped in the soil during the decent stage of a lander, would make interpretation of organic analysis more difficult (Chyba et al. 2006).

Final Remarks Concerning the Use of Gas Blasts

When drilling under simulated Martian conditions, it may not be very difficult to use a gas flow to remove the cuttings. There are two reasons for this. First, because it is expected that the drilling operation will be carried out at low energy levels, the cuttings will be very fine. In the experiments with either diamond-impregnated or PDC bits, it was found that the typical cuttings particle diameter was a few tens of microns. In the lower gravity of Mars, such cuttings will be lifted relatively easily. Second, it was found that it is not so much the pressure drop occurring at the drill bit that is effective in lifting the cuttings, but the volume expansion of the gas flow as it crosses the bit face, and the resulting gas velocity as it returns to the surface in the annular space between the drilling assembly and the hole wall. For example, under an ambient pressure of 5 torr (typical of Martian conditions), the majority of the cuttings can be blown out of the hole by a gas flushing pressure of 30 torr (Figure 21 and Figure 22).

In the most recent work, it was found that mass efficiency ratio (mass of gas to mass of cuttings lifted) is of the order of 1:3000. This means, that with 1 gram of gas over 3 kg of cuttings can potentially be lifted out of a hole.

Note that clearing the cuttings in a timely manner has the further advantage of helping to keep the bit cool. The gas can be provided either from pressurized gas canisters brought from Earth, combustion of a propellant or by an in-situ compressor. The power required to compress the Martian atmosphere to a useful pressure between the consecutive gas blasts (every few minutes) was found to be on the order of a few Watts, which is well within the power budgets of the current or proposed Mars missions.

Conclusions

In this paper, three methods were presented for the removal of cuttings from holes drilled on Mars. These were auger methods, ice sublimation, and gas blasts. Although the auger will remain the `heart' of the cuttings removal system of the Martian drill, the other two methods could enhance cuttings removal and, in turn, reduce drilling power in conjunction with use of an auger.

Sublimation of ice only applies when the formation that is penetrated contains ice. Since this method of removal of cuttings is a function of Martian formation properties, which might not be fully known before drilling commences, it might be prudent to actually implement gas blasts into the drilling assembly. This alternative method for the removal of cuttings could be used for either continuously assisting the auger or be limited to the case of auger choking.

Future Work

The current work was done on rocks and soil simulants that were essentially unchanged by the presence of water, as either liquid or ice. Clays and shales are chemically affected by water, and the Mars Exploration Rovers have found extensive deposits of evaporite salts. These may affect the process of cuttings lift by ice sublimation and this possibility should be checked. In addition, if gases supplied from an external source are used for cuttings removal, one should investigate possible contamination arising from, e.g. combustion products, or the simple oxidation, reduction or drying of samples by such gases.

Directory of supporting data

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Fig. 3 figure3.jpg full-resolution image
Fig. 4 figure4.jpg full-resolution image
Fig. 5 figure5.jpg full-resolution image
Fig. 6 figure6.jpg full-resolution image
Fig. 9 figure9.jpg full-resolution image
Fig. 10 figure10.jpg full-resolution image
Fig. 14 figure14.jpg full-resolution image

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