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A NOVEL METHOD FOR CUTTINGS REMOVAL FROM HOLES DURING PERCUSSIVE DRILLING ON MARS[*]

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Acquiring samples from the subsurface of Mars poses many challenges. The scientific return increases with the depth from which the samples are obtained, but so does the risk. Thus, it is important to develop a fully autonomous drilling platform that will be capable of accessing the required depth and retrieving cores for scientific analysis. The method of drilling most likely to succeed will be a conventional mechanical core drill, either rotary or percussive, with a mechanical system for removing the cuttings and rock core from the hole. Instead of fluid flushing systems for removing cuttings, which would be very difficult to provide and in addition may contaminate the sample, an auger system is the best solution for rotary drilling. However, no such solution has been identified for the percussive drilling method. To solve this problem, a novel means of conveying cuttings out of the hole during percussive drilling has been developed and is presented in this paper. It relies on the reciprocating action between a pair of surfaces covered with bristles. Experimental results show that there is an optimum ratio of particle diameter to bristle length that gives the highest speed of particle conveyance. This new method also stabilizes the hole so that the drill string may be removed to recover a rock core sample.

1 Introduction

Pictures of Mars seem to reveal telltale signs of the presence of liquid water in the past: ice caps, dry riverbeds, and familiar erosion patterns. But where is the water now? The history of Mars' water is of the highest concern because in all experience on Earth, where there is water, there is life. Consequently, the natural first step in answering the question of life on Mars is finding water on Mars, and prior to that, developing the technology and instrumentation to do so. In order to gain the information necessary to develop techniques for searching for water on Mars, NASA has launched a comprehensive information gathering effort. NASA's series of Mariner and Viking missions has been returning pictures, atmospheric data and soil analysis since 1965. Currently the remote sensing

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missions, namely the Mars Global Surveyor and Mars Odyssey orbiters, are gathering photos and data while orbiting Mars. These photos indicate that if water is present on Mars, it is not visible on the surface. This, in addition to the inconclusive results of the Viking tests for life, suggests that if Martian water is going to be found, we are going to have to look below the surface. Thus in-situ sampling and analysis for water or bio-signatures must be the next step after remote sensing. Subsurface sampling methods have been explored in detail by numerous researchers including Blacic et al.[2] from Los Alamos National Laboratory. His work has led to the realization that drilling is the most likely means of recovering samples. As technology advances, an automated drilling and sample return mission to Mars becomes possible, but still poses daunting problems.

2 Problem Statement

In general, planetary exploration missions aim to carry out in-situ analysis and possibly return samples to Earth for more thorough examination. In particular, missions to Mars need such capabilities in the near future. Thus there is a strong interest in obtaining samples from below the surface.

The extreme conditions on Mars' surface and its great distance from Earth are the two largest obstacles to a drilling mission. Mars' atmospheric pressure is only one percent of Earth‘s atmospheric pressure. This has severe consequences because most drilling processes utilize compressed air or liquid to flush holes of the particles, or cuttings, that have been drilled. On Mars, the power necessary to compress the atmosphere to a useful pressure is more than it is reasonably possible to provide. Fluid, on the other hand, can not be used because it would freeze or evaporate and may contaminate the sample. The second obstacle on Mars, its great distance from Earth, requires any lander to be mostly autonomous. When Mars is in conjunction with Earth, the one-way communication delay is approximately twenty minutes. This delay would make attempting to operate a lander by remote control a virtual impossibility. In the following pages a plan for a simple, autonomous and efficient solution to these drilling problems is outlined. Major emphasis is given to the novel method of cuttings removal, which was invented specifically for a Mars-like environment that prohibits flushing fluids or air. First we examine the common methods of rock excavation.

3 Methods of Rock Excavation

The rock excavation process consists of two stages which 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 remove the cuttings in time results in their being pulverized into progressively finer particle sizes without extending the hole, making drilling very inefficient. Similarly, the drilling process should be engineered to produce the largest particle sizes that may be conveniently removed. This is because in general, the most efficient drilling process produces the coarsest particles.

3.1 Mechanism of Rock Drilling

Rock drilling devices remove rock by one of four basic mechanisms, as shown in Figure 1: melting and vaporization, thermal fracturing, mechanical breaking, and chemical reaction.

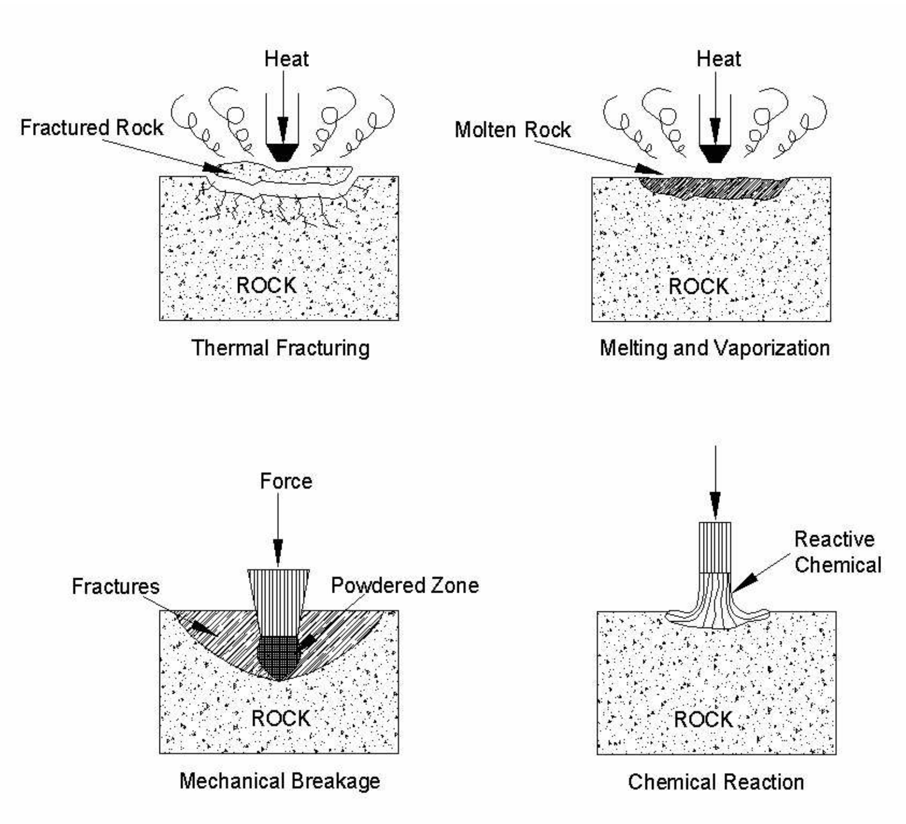

Figure 1: Basic methods of rock excavation.

Drills that melt and vaporize the rock such as laser and electron beams can not be used because they produce a change in the properties of the material being drilled. This same reason prohibits the use of thermally fracturing drills, because they might produce localized melting. Finally, chemical drilling can not be considered because it utilizes highly reactive chemicals to dissolve the rock. In addition, rock heating drills that thermally fracture the rock, can not be used because they produce localized heating and in turn change the properties of the rock. This leaves mechanical drills that drill the rock by impact, abrasion or erosion as the only reasonable method of acquiring samples. These mechanisms induce tensile or shear stresses, which exceed the rock strength and produce plastic yielding or brittle fracture. However, some of the mechanical drills such as jet drills, explosive charges, and pellet impact drills are not suitable, because they would contaminate the samples. Thus the drilling equipment most likely to succeed would be a conventional rotary or percussive core drill, with diamond cutting elements or tungsten carbide inserts, and a mechanical system for removing the cuttings and rock core from the hole.

3.1.1 Rotary Drilling

The clear benefit of using rotary drilling is that cutting removal can be accomplished using an auger; however this method has several drawbacks. First, rotary drilling requires both significant weight to push the bit against the rock surface and torque to turn the bit[6] . Both the weight on bit and rotational speed of the drill need to be carefully designed for specific rocks. On Mars, where the gravity is only forty percent as strong as Earth‘s, the problem of adequate weight on bit becomes even more serious.

Drilling in Arctic[7,9] has uncovered a more subtle drawbacks of drilling in extreme environments. Arctic drilling provides surface data, showing how rotary drilling performs in frozen rock and soils, specifically noting that rocks tend to get stronger as temperature decreases[5] . However, no experiments have been conducted in near vacuums, low temperatures, and carbon dioxide atmospheres. These parameters are important because diamonds, which will probably be used on the drill bits, tend to turn into graphite at temperatures above 870 Kelvin in carbon dioxide atmosphere due to their reaction with the oxygen in carbon dioxide[1] . High temperatures like these can occur during dry cutting if the rotational speed or weight on the bit are large.

Furthermore, although an auger, which can be used with rotary drilling, has been used for centuries, little is known about how various parameters affect the drilling and cuttings removal processes. Terrestrial experience with augers shows that close ‘hands-on’ control by the driller is often necessary to ensure success. Thus it is not certain how well an auger will work on Mars under automatic or remote control conditions.

3.1.2 Percussive Drilling

During percussive drilling, the drill bit vibrates up and down. Rotation, if it occurs, is not essential to the rock breaking process. The impact of the bit onto the rock performs the drilling. Considering the limitations of rotary drilling, percussive drilling has several benefits that may prove it to be the superior drilling mechanism for use on Mars. Percussive drilling does not require any rotation or weight on bit because it uses high frequency impacts to fracture the rock. In addition, the drill bit may not require sharpening, can be made to operate at cryogenic and high temperatures, and can be used to probe unconsolidated formations like sand as well as very hard rocks like a basalt. Bar–Cohen et al.[4] from JPL did extensive work with an ultrasonic drill, which very much resembles a percussive drill, and suggested that this form of drilling will be the most successful on Mars due its low power requirements. However, the major drawback with percussive drilling is that augers cannot be used for conveying cuttings from the hole bottom to the surface, unless the drilling device is made to rotate as well as reciprocate.

3.2 Methods of Cuttings Removal

Extracting cuttings from the hole is as important as breaking the rock itself. Failure to remove the newly crushed or cut rock results in them being pulverized into smaller particles. This makes drilling very inefficient. On Earth, liquid or gas is the most common method of cuttings removal. In addition to lifting the rock cuttings, the drilling fluid or gas also cools and lubricates the drilling bit; lack of lubrication would result in higher friction between the drill bit and the rock and thus larger heat production which can damage the drilling bit.

However, cuttings removal on Mars poses several special problems. Among these are the very low temperature (down to -150 degrees Celsius) and low atmospheric pressure (approximately 6 mbar). The low temperature precludes the use of liquids to remove cuttings from the hole as they might freeze. However, even if a drilling fluid was found with a very low freezing point, the use of it would be obviated by considerations of mass and sample contamination. Low pressure makes it unlikely that one will be able to use a gas flow for that purpose, since the energy requirement to compress a sufficient amount of the Martian atmosphere to blow the cuttings out of the hole is prohibitive[8] . A closed cycle system could be developed to reuse the gas, but it should be ensured that the gas would not permeate the Martian rock. This could only be guaranteed if the rock was impermeable, and no such assumption should be made. A remaining possibility is to use mechanical means to lift the cuttings. Of the various methods that can be considered, Blacic et al.[2] of LANL have suggested that the auger may be the only candidate for rotary drilling. For percussive drilling however, there is no obvious solution.

4 Approach to the Cuttings Removal Problem

The most effective ways to lift cuttings out of a hole include circulation of fluid or air. However, if for any reason air or fluid cannot be used, an auger can do the job provided the drilling motion is rotary. In dry percussive drilling, however, the motion is up and down and there is no mechanism to lift the cuttings out of the hole. For this reason we have developed a novel means for conveying the drilled cuttings of a rock or soil-like material, characterized by having two opposed surfaces covered by angled hairs or bristles. Both sets of bristles point approximately in the direction in which it is desired to convey the cuttings, usually upwards. The two sets of bristles are placed close enough to overlap or just barely touch, depending on the diameter of particles being transported. The process is illustrated in Figure 2. As well as cleaning the hole, the new method also stabilizes the hole so that a drill string may be removed to recover a core sample, and then placed back in the hole. Such a system should be successful on Mars as it requires minimal supervision.

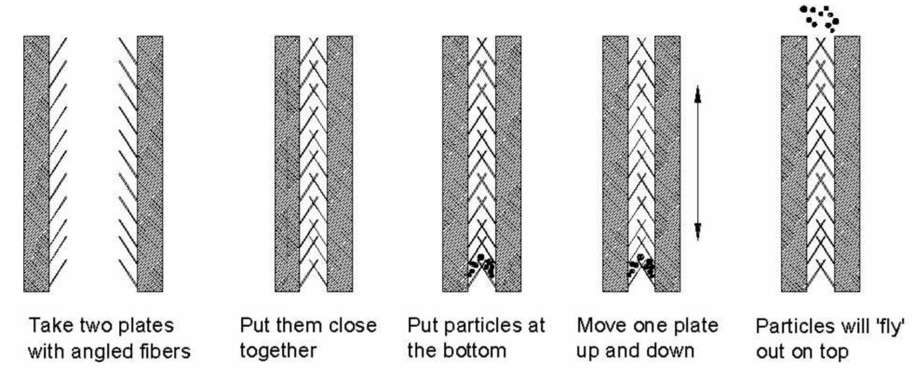

Figure 2: New method of lifting cuttings out of a hole.

The principle of the invention lies in the oscillatory motion of the two plates with angled bristles attached to them as indicated in the Figure 3. One plate can be stationary (but it doesn't have to be) and other one moves up and down with a low amplitude and high frequency. If a particle is trapped in one of the plates, the bristles of the other plate will scoop it out and transfer it to the other plate. This process lifts the cuttings out of the drilled hole.

4.1 Experimental Setup to test Cutting Removal Method

In order to test this theory of cuttings removal, we conducted a series of trials with an experimental apparatus simulating a casing and percussive core barrel. The experimental apparatus

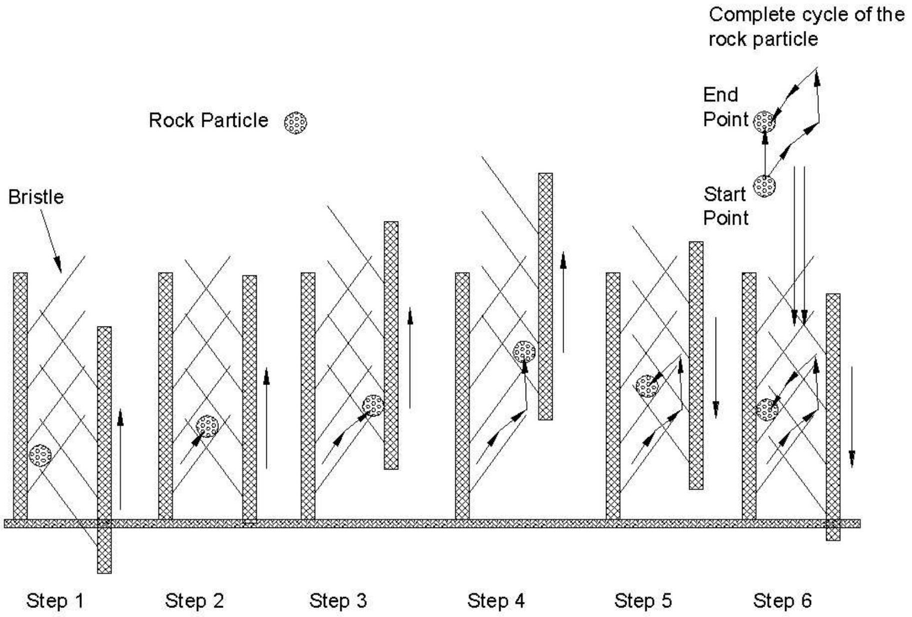

Figure 3: Principle of transferring of cuttings between the plates with the bristles.

Ski skin	Description	Length (mm)
Purple	Nylon plush laminated to cotton backing material	4.1
Blue Cow	Nylon plush laminated to synthetic backing material	4.3
Black	Mohair laminated to cotton backing material	3.2

Table 1: Length of bristles for given ski skins type

consisted of three main parts: a motor, an offset linkage, and two plates covered with bristles (Figure 4). The variable speed, electric motor was used to create a motion that simulates the vibrations of a percussion drill. The motor was connected to an offset linkage, which converted the rotation into a purely vertical movement of specified amplitude. The offset linkage was in turn connected to one of the bristled plates, while the other was held stationary. The two plates illustrated in Figure 5 correspond to the oscillating coring bit and casing of the drill mechanism. For the initial data, both the speed of the motor and the placement of the offset linkage were held constant, yielding a constant frequency and amplitude of vibration in the plates. However, in further research the amplitude could be varied. Rather than attempt to create plates of angled bristles, ski skins of various fiber types and lengths were used to cover the plates. The names of the ski skins together with the length of each fiber and type of the material is given in Table 1. Black Diamond Equipment, Ltd[3] provided the ski skins, along with the data for the skins' material composition and hair length.

To gather the data, a standard procedure was followed for several fiber and cutting sample types. First, the apparatus was loaded with a small amount of simulated soil cuttings. The samples of river sand and glass beads of various diameters as shown in Table 2. The loading was done by laying one plate on its side and placing the cuttings below a specified start line. The second plate was then closed against the first, holding the sample in place, and the apparatus turned upright. At

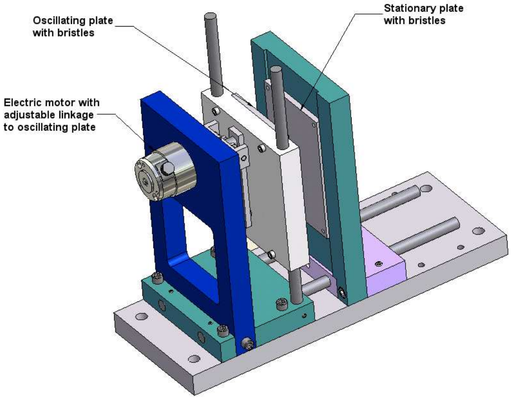

Figure 4: Cad drawing of Experimental Setup.

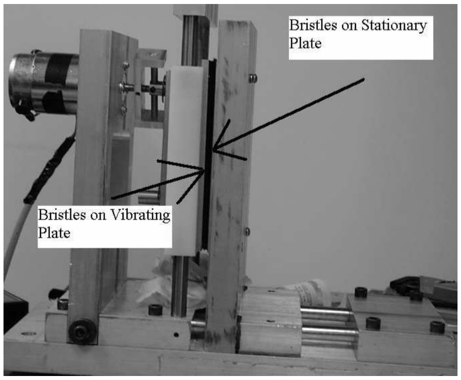

Figure 5: Photograph of Experimental Setup.

Particle type	Diameter (microns)
River Sand	< 75
River Sand	75-105
River Sand	75-105
River Sand	105-149
River Sand	149-177
River Sand	177-250
River Sand	250-295
River Sand	295-420
River Sand	420-590
River Sand	840-1190
Glass Beads	2000

Table 2: Particles used in the experiments.

a signal, the motor was turned on and a timing system started. When the first particle was ejected from the top of the plate, the time was marked. From this time and the known distance the particle had travelled, the velocity of each sample was determined; this was our independent variable. The velocity was then plotted against particle diameter for a constant fiber type, and a curve showing an optimal diameter-to-fiber length ratio was expected to be found. This procedure was performed for three different types of ski skin. For each set of variables a total of ten experiments was performed and the final results were averaged.

4.2 Experimental Results

We expected that the results of our experiment would show an optimum ratio between particle diameter and bristle length. Thus, we expect the graph of our results, velocity of particles vs. diameter of the particles, to take the form of a downward-pointing inverted curve shown in Figure 6. Given the length of the bristles, if the particles are too large or too small, they would move up slowly or not at all. Our task then was to determine this optimum ratio between particle diameter and bristle length. By extrapolating the results we also intended to be able to determine the best bristle length to use when given the size of particles that will be generated during percussive drilling.

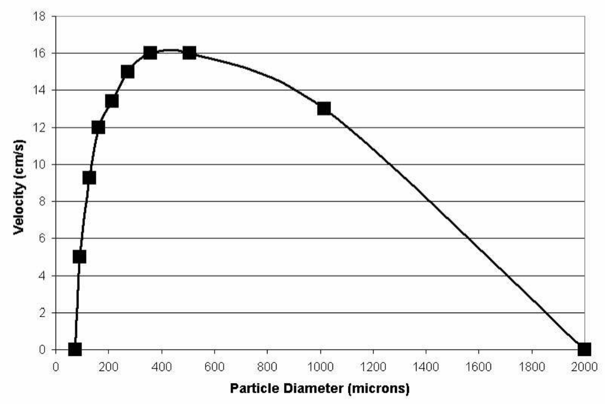

Figure 6: Anticipated shape of the curve.

The results of our initial experiments met our expectations as they showed a definite correlation between particle velocity and bristle length, given a particle size. Raw data for the experiment, using three different bristle lengths and a multitude of particle sizes, are plotted in Figure 7. Plotted in Figure 8 are the same data normalized against bristle length. Note that data points corresponding to zero vertical velocity were obtained when no particles appeared on top after an extended period of time.

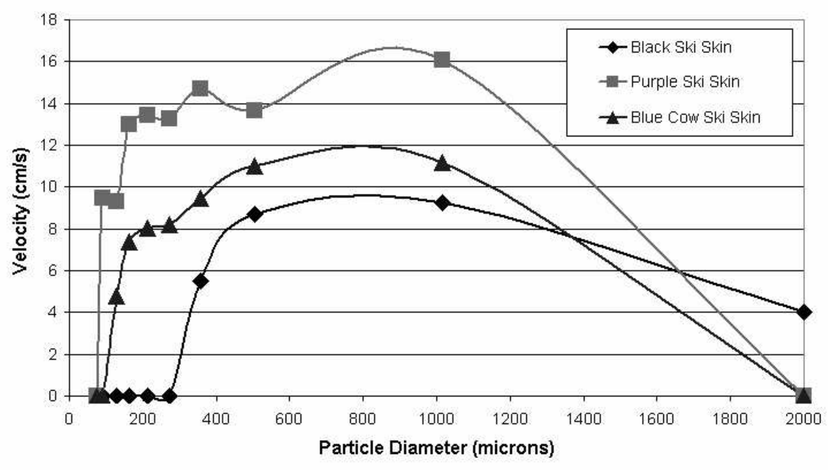

Figure 7: Cuttings removal results.

The results show that the purple ski skin proved best at handling most sizes of particles, from small (90 microns), to large (1015 microns). However, the purple ski skin failed to convey the large 2000-micron glass beads. The 'Blue Cow' ski skin transported all particles except 75, 90, and 2000 microns, the extreme ends of the range. However, across the range, it always had slower speeds than the purple ski skin. The black ski skin worked well for particles between 295 and 2000 microns, but failed to convey any particles smaller than 295 microns. Thus, each ski skin seemed to perform best with different sizes of particles. This is what we expect given the different bristle length of each ski skin. However, after normalizing the diameter of the particles against the length of the bristles we

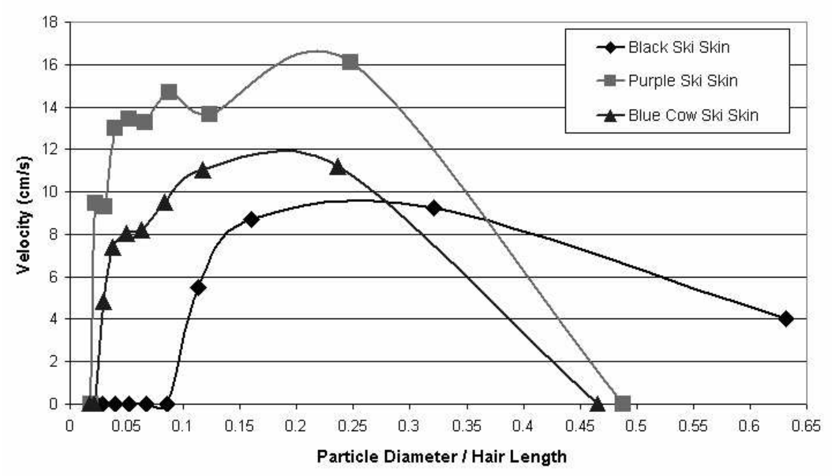

Figure 8: Cuttings removal results normalized against bristle length.

expected the peaks of the three curves to coincide. By comparing graphs with the raw data (Figure 7) and with the normalized particles diameter (Figure 8) it is clear that not only these peaks do not coincide but in fact they are shifted further away from each other. This leads to the conclusion that bristle length is not the only factor that needs to be considered. In order to explain these varying results we had to look at other physical characteristics of the ski skins such as areal density (number of bristles per unit area), angle between the bristle and the surfaces and material properties of the bristle, such as stiffness.

4.3 Discussion of Results

We believe that the angle between the bristles and the backing of the ski skin is the second most important factor after the bristle length. However, a close analysis of the results shows that this angle can also be influenced by the areal density and stiffness of the bristles. Thus when analyzing the effects of the angle, the stiffness and areal density of the bristles should also be taken into account.

If the bristles are very stiff, the angle with the vertical is maintained, whereas if they are very flexible the angle can be much larger as the bristles deflect under load. The amount of deflection could be due to two factors. Firstly, heavier particles would cause larger deflection than lighter particles. The second factor is the density of the bristles per unit area. If the density is too large, the bristles will tend to rub against each other and get stuck between each other. If this happens, bristles which are on the plate that momentarily moves down, can pull and deflect the bristles on the opposite plate down with them.

According to Black Diamond, the supplier of the ski skins, the skins are manufactured identically until the lamination process colors and coats the individual bristles on the skin. This lamination process definitely alters the stiffness of the bristles as well as their thickness. The larger thickness of the bristles in turn will alter the angle the bristles make with the vertical. We can assume that the initial density of bristles per given area before lamination and coloring was the same. Yet, because of the difference in thickness of the bristles, the resultant density of the bristles on different ski skins could vary. We were only able to measure the lengths of the individual bristles, but could not determine the exact angles, stiffens and density of the bristles on the ski skins. However, we managed to evaluate the stiffness of each skin qualitatively. The black ski skin was found to be the stiffest of all, while the purple ski skin was the least stiff. The 'Blue Cow' ski skin was moderately stiff.

In ideal conditions, to determine the effect of ski skins length we could obtain ski skins that would only differ in bristles length, and all remaining factors like density, stiffness and angle of bristles would remain the same. Similarly, we could evaluate the effect of the bristles density, by keeping bristles length, stiffness and angle the same and varying only bristles density.

In addition, two experimental parameters need to be considered. The first parameter is the amplitude of vibrations, which together with bristle stiffness and areal density can alter the angle of the bristles. If the amplitude is larger than two bristle lengths and the frictional forces are large, the bristles can deflect 180 degrees until they are pointing down. Thus, by changing the amplitude we can alter the angle bristles make with vertical to the one that is desired. The second experimental parameter is the distance between the two plates. If the angle of the bristles is small and the distance between the plates is large, only large particles will be conveyed, while small ones will be stuck between the plate and the root of the bristles. If the distance is decreased or the angle increased, then these small particles could be scooped out and conveyed upwards as indicated in Figure 9.

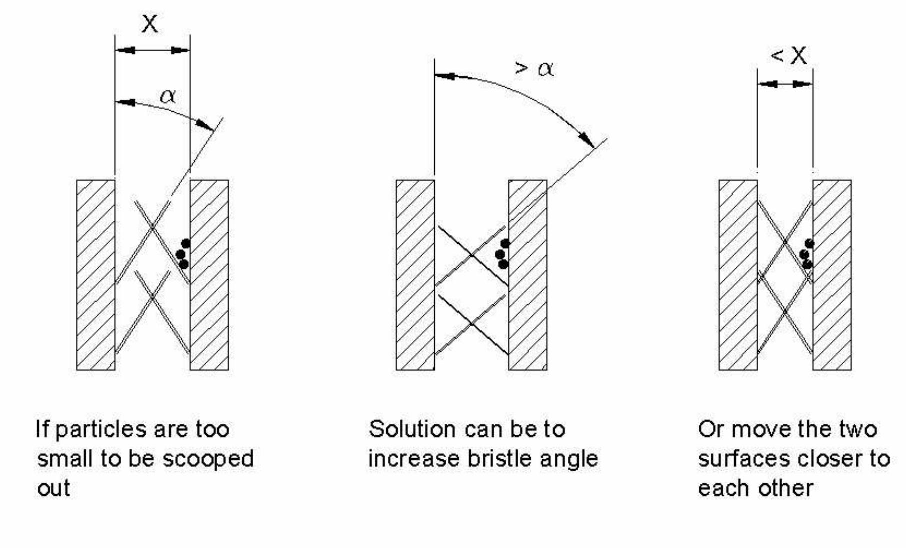

Figure 9: Effect of distance between the two surfaces covered with bristles.

Thus, we cannot assess with great accuracy the effect that bristle's angle, areal density or stiffness had on the performance on each ski skin. However, it is quite clear that these parameters together with the operational parameters like distance between the bristles and amplitude of vibrations affect the performance of the ski skins as well. Thus the main result is that bristle length can be viewed as the primary parameter affecting performance of the ski skins while secondary parameters are areal density, angle and stiffness of bristles.

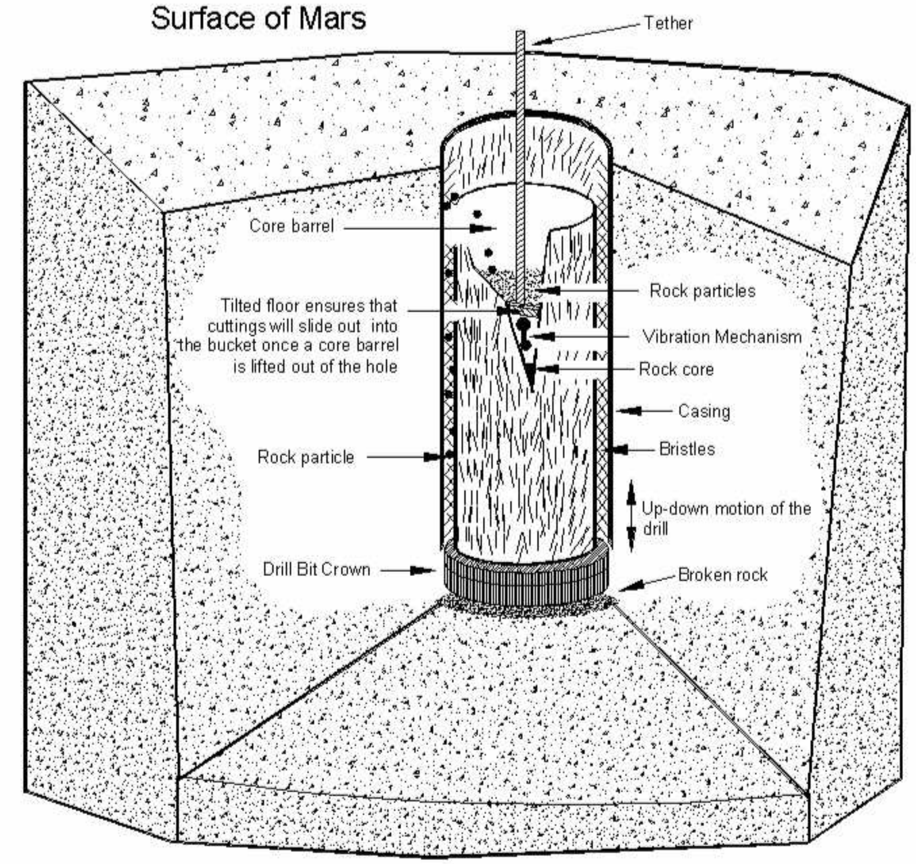

Figure 10: In-situ drill set up including casing.

5 Complete Percussive Drill Setup

Although the heart of our design is the novel way of conveying cuttings out of the hole, we decided to design a complete drilling apparatus. This set up includes a coring bit for crushing the rock, and a casing that aids in cuttings removal and stabilizing the hole. The bristles are placed on the inner side of the casing and the outer side of the drill or core barrel as indicated in Figure 10. The top of the core barrel/drill is open allowing the cuttings to fall inside and accumulate on top of the angled plate. Once the core barrel/drill is pulled out of the hole, cuttings will slide out into the surface container by gravity.

If a drilling setup is different from the one we described in this paper and it happens that the drilling string is continuous, each section of the drill string can have such a chamber. Thus if the lower one fills up, cuttings will be automatically transferred to the next level. It is also possible for the cuttings to be lifted all the way to the surface and entirely out of the hole.

The coring bit and casing are more closely described in the following sections.

5.1 Coring Bit

The coring bit consists of three main chambers and a tether cord, as illustrated in Figure 11. The purpose of the very top chamber is to collect fine cuttings that are conveyed from the hole bottom. The floor is slanted to aid in cuttings removal. Upon lifting the coring bit to the surface, the cuttings would slide out due to gravity into a bucket. These cuttings would be further conveyed into a pulverizer and examined by different instruments. The middle chamber houses the vibration inducing apparatus. This apparatus is part of a closed loop system where the frequency and amplitude are closely monitored and adjusted if necessary. The bottom chamber houses the rock core. Once the rock core fills up the chamber, its top surface would push against a latching system connected to the bottom of the coring bit, separating the core at the bottom and securing it so it does not slide out. The coring bit would have its outer wall covered with bristles. This would form a second surface required for convening of cuttings out of the hole. The tether from which the coring bit would be suspended consists of a power cord that would provide electricity to the vibrating apparatus, a signal cord for control signals (this would be a part of closed loop feedback system), and a tensile cord for pulling the core drill out of the hole.

5.2 Casing

The casing, illustrated in Figure 12, serves three purposes. The first purpose is to aid in cuttings removal by having the inner surface covered with bristles. The second purpose is hole stabilization which is especially important when the coring bit is lifted out of the hole. The third purpose is to keep the coring bit vertically aligned and in turn keep the hole vertical. This would be required only initially, as once the core drill starts cutting the rock, the drilled rock core inside the core drill would keep the drill vertical. Sometimes, however, the rock core that is supposed to keep the drill vertical might shear. Then the casing would be employed once again to guide the coring bit vertically. As an added benefit, the casing can have small slots cut out in its surface at different places. These slots can be very useful if at the end of coring process, a hole is to be used for in hole measurements. Many instruments can be lowered into such holes and in-situ measurements of the rock strata can be obtained.

6 Conclusions

A novel means for conveying the drilled cuttings during percussive drilling, characterized by having two opposed surfaces covered by angled hairs or bristles is described. Both sets of bristles point in the direction in which it is desired to convey the cuttings. As well as cleaning the hole, the new method also stabilizes the hole so that a drill string may be removed to recover a core sample, and then placed back in the hole. This method of cuttings removal was developed for drilling on Mars where conditions preclude the use of air or a flushing fluid for this purpose. The paper also describes a complete percussive drilling set up that could be used in the sample retrieval mission on Mars.

Experimental data showed that there is a relationship between particle size and bristle length for optimum cuttings removal. For different sets of surfaces we found an optimum diameter of particles that resulted in the fastest rate of particle removal. This optimum ratio differed between different types of surfaces pointing to the fact that length of bristle is not the sole factor that determines the rate of particles removal. Other parameters such as areal density of bristles, stiffness of bristles and

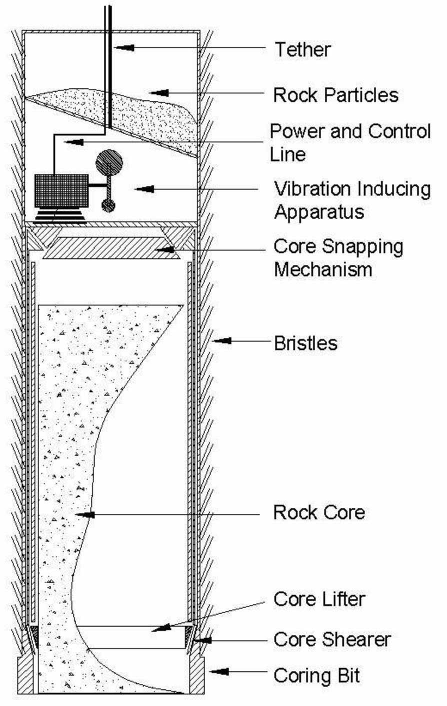

Figure 11: Percussive Coring Bit

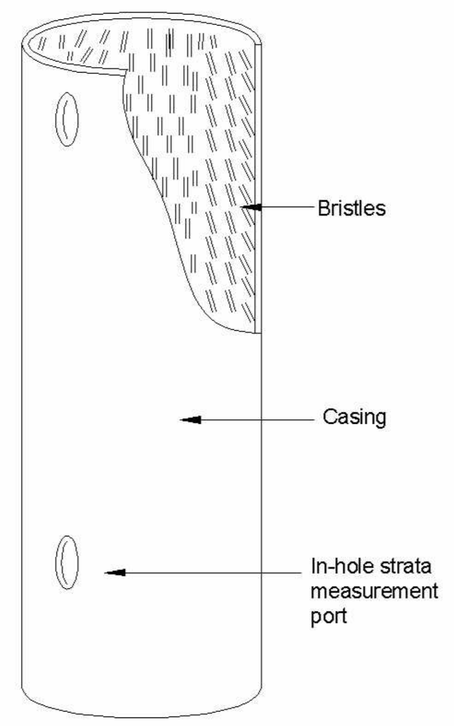

Figure 12: Casing.

the angle that the bristles make with the vertical must also be considered.

The operational parameters of the percussive drill, namely the distance between the two surfaces covered with bristles and the amplitude of the percussive drilling action can also alter the performance of the drilling system.

The problem with heat build up due to lack of circulating drilling liquid or gas can be overcome by stopping the drill periodically to let it cool.

7 Future Studies

We plan to improve and expand upon our research in two primary areas: first, by refining our data collection methods, and second, by broadening our data analysis. To complete our first goal of refining our data, we plan to normalize the velocity measurement by precisely measuring the frequency of the plate, and accurately gauge the particle speed by analyzing a digital video of each trial. The frequency of the plate can be easily measured by shining a laser just above the top of the oscillating plate, and placing a photo sensor behind it. The signal of the photo sensor can then be converted into the frequency of the plate. Digital video will yield a more precise measure of velocity because each trial can be viewed at a greatly reduced speed, and compared to the time between each digital frame. This will eliminate the inevitable human error involved in timing. For our second goal, broadening the data analysis, the parameters identified as the most prominent, i.e. angle, density, and stiffness of bristles can be measured precisely along with bristle length. This will allow us to determine which of the above parameters might be optimized for maximum performance, and will yield a more thorough analysis of the data recorded.

In addition to improving our experimental methods, the plans for the future of this research include new applications for this idea. Any field that requires the transportation, primarily lifting, of fine particles could benefit from this new method. For example, the agricultural industry often moves large amounts of grain from silos. Using this method, a closed tube of concentric cylinders could convey the particles with no losses to the environment, and take up considerably less space. We are continuing to develop further ideas for applications and modifications to this simple and efficient conveyance system.

8 Outreach

The Mars Drilling Group has participated in various ways to reach out to the community. Prior to becoming a specialized entity at Berkeley, the Mars Drilling group was part of a broader research class named *Mars 2012*. Every year the class adds its own unique flair to Cal Day, a celebration of UC Berkeley's vast and varying extracurricular activities. We created interactive presentations to give visitors to Berkeley a hands-on experience of our research (Figure 13). In 2001 the class took home the 'Most Interesting Display Award' from the facilitators of Cal Day.

To reach out to the community beyond Berkeley, the Mars Drilling group participated in a science fair organized by Oakley Junior High School in Oakley, California. The fair was an exciting effort to combine the imagination of local students of all grades with the experience of area businesses and colleges. At the fair we showcased our research activities and presented interesting facts about Mars, explaining and demonstrating research items to adults and children alike. We also were able to volunteer as judges for the projects of local students.

We have also reached out to the greater scientific community for their feedback and experience. We held videoconferences (Figure 14) with both Johnson Space Center and NASA Ames Research Center, where we presented our projects to NASA scientists for input and review. These links between current and future scientists have provided a wealth of knowledge and experience not available from research alone.

Presently, our group aims to involve local high school students in our research. In an effort to give them a taste of things to come, we plan to have a few interested students from Berkeley High School come to our lab to learn and participate in our research activities. So far, we have one enthusiastic student that comes for every meeting, but we anticipate more soon. Who said that beginnings are easy?

9 Acknowledgements

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Figure 13: Outreach during Cal Day

Figure 14: Videoconference with NASA scientists.

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