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Considerations, constraints and strategies for drilling on Mars

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Abstract

The effect of the environmental conditions on Mars—low temperature, low pressure, the uncertainty in the nature of the formations to be penetrated and the possibility of encountering ice —imply that a successful drilling system will have to be able to cope with a wide range of conditions. Systems using continuous drill pipe or wireline both offer attractive features and disadvantages, and the preferred choice may depend on the target depth. The drill bit will have to cope with a range of terrain, and we offer some suggestions for making a bit that will be able to drill in both hard and soft formations, and also be able to resist choking if it encounters ice or ice-bound materials. Since it will not be possible to use a liquid to remove the drilled cuttings on Mars, the cuttings removal system will probably use some form of auger, although it may be possible to use continuous or intermittent gas blasts. The sublimation of ice resulting from the heat of drilling in ice-containing formations may help in removing the cuttings, particularly as they are expected to be very fine as a result of the low power available for drilling. Drilling into ice bound soils was also found to be akin to drilling into ice-bound sandstones.

Keywords: Mars; Drilling; Drill bit; Auger

1. Introduction

Landed Mars exploration missions aim to carry out in situ analysis and eventually return samples to Earth. While sample acquisition and analysis are presently limited to surface materials, there is growing interest in acquiring sample from below the surface. Samples can be acquired by drilling in the form of a solid core or fine cuttings. Choosing the physical form of the sample to suit the particular mission at hand is decided by the requirements of the scientific mission. Note also that useful information may be obtained from instruments placed in the borehole even if no material is recovered at the surface.

Because drilling will take place in a remote location under extreme conditions of low temperature and pressure, there exists a number of constraints that must be factored into the design of an effective drilling system. If any of the constraints is disregarded, the success of the entire mission will be compromised.

Other workers (Blacic et al., 2000; Briggs and Ross, 2002; Mars Exploration Payload Assessment Group, 2001) have already looked at various constrain and requirements that the Martian drill should have. These constraints include for example power and mass limits and the astrobiology requirements that called for uncontaminated or unaltered sample. In addition, previous workers looked at various methods of subsurface access and drilling technologies and looked at advantages and disadvantages of each of the drilling methods.

Based on our drilling research under Martian conditions (Zacny et al., 2005a,b; Zacny and Cooper, 2005a,b; Zacny and Cooper, 2004), it became apparent that new constraints need to be factored into the drill design. Thus, the main purpose of this paper was to summarize the current state of knowledge in the field of Mars drilling. In this paper, we first discuss how the Martian atmosphere will affect drilling and the three drilling scenarios that are a direct result of the Martian environment. Next, we give pros and cons of various drilling systems. This is followed

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by a more detailed discussion of the possible drill bits and cuttings removal systems, which form an integral part of the drill system. In particular, we present a design of a new hybrid bit, which is capable of penetrating various formations. In addition, we present new drilling data obtained from coring in water-saturated frozen soils. Fig. 1 shows a graphical representation of how various factors need to be taken into consideration for selecting a Martian drill system.

2. Environment constraints on the drill system

In this section we describe how various environmental conditions on Mars affect the selection and final choice of a drill system.

2.1. The effect of temperature and thermal fluctuations

Mars is cold, with surface temperatures typically reaching −100 °C. The atmospheric pressure ranges from approximately 0.1–1.5 kPa (Smith and Zuber, 1998; Hess et al., 1980; Tillman et al., 1993). Since the density of the Martian atmosphere is very low, the temperature of the surface is controlled mainly by solar heating and infrared cooling to the atmosphere and space, whereas on Earth, heat exchange with the atmosphere occurs. The temperature of the Martian atmosphere is, in turn, controlled by convective heat exchange with the surface, the absorption of infrared radiation from the sun and surface and re-radiation to the surface, space, and the rest of the atmosphere (Wilson, 2005). For this reason, Martian atmospheric temperatures can be as low as −133 °C at the poles during winter (Clancy et al., 2000; Martin et al., 2003) and thermal fluctuations of over 100 °C within 6 h can occur (Martin et al., 2003).

The coldest surface night temperature recorded by the thermal emission spectrometer (TES) instrument on the Mars Global Surveyor (MGS) was −120 °C, while the warmest temperature was −65 °C (Christensen, 2005). The coldest regions are areas of very fine grains (dust), while the warmest regions are areas of coarse sand, gravel, and rocks (all capable of greater heat retention). A maximum surface temperature of 27 °C was recorded during summer on the equator.

The low temperatures on Mars preclude the use of many materials, such as metals with a body-centered cubic structure (e.g. ferritic steels, Dutta, 1988) that may become brittle at low temperatures. In addition, large thermal fluctuations can cause thermal fatigue in composite materials that have large differences in the coefficients of thermal expansion of their different components. One such composite material could be a cutting segment in a diamond impregnated bit. Cutting segments on these bits are made of diamonds embedded inside a metal matrix. Since the coefficient of thermal expansion of diamond is much smaller than that of metals, continuous expansion and contraction of the metal around the diamond could lead to debonding. The risk of debonding will become

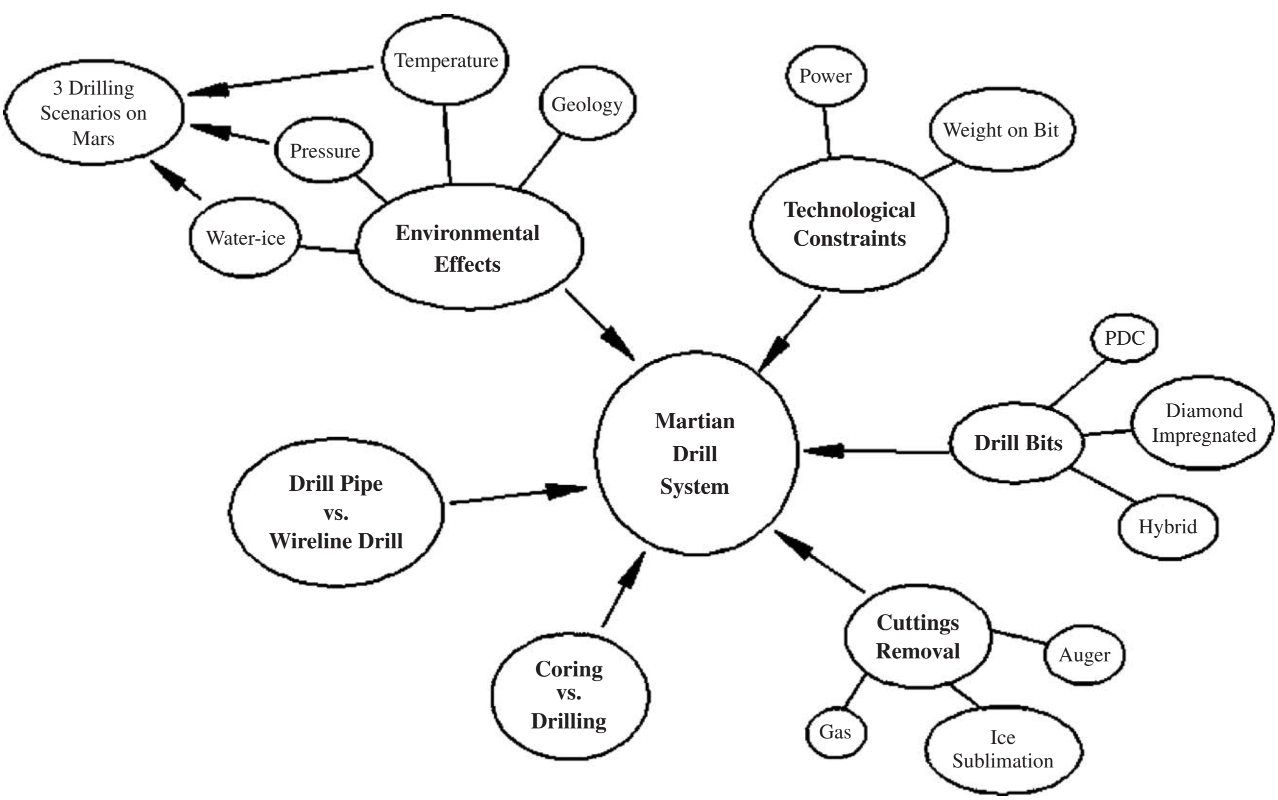

Fig. 1. Items affecting Martian drill system design.

Fig. 2. Diamond pull out due to weak mechanical locking inside the matrix.

much larger if the diamonds are not held in place by chemical means but only by mechanical locking (Konstanty, 2000; de Chalus, 1994; Dwan, 1998). If the gaps between the metal matrix and diamonds become large enough, the diamonds could easily become dislodged and fall out prematurely as shown in Fig. 2.

2.2. The effect of low pressure

As well as being cold, Mars has a low atmospheric pressure, ranging from 0.1 kPa (1 mbar) to 1.5 kPa (15 mbar) (Smith and Zuber, 1998; Hess et al., 1980; Tillman et al., 1993). These pressures are significant because they bracket the triple point of water, located at 0.63 kPa and 0 °C. If ice is present in the subsurface, and the atmospheric pressure is above the triple point, frictional heating resulting from the drilling process may cause liquid water to be formed in the borehole; but, if the pressure is lower, any liquid water will immediately be transformed into vapor. This is important from the point of view of removing cuttings from the borehole, (Zacny et al. 2005a) and also because of the risk of melting followed by re-freezing that may lock the drilling equipment in the hole.

The low atmospheric pressure will also reduce heat transfer from the bit by convection. This will no doubt require a drilling strategy that not only uses appropriately modest values of rotary speed and down force on the bit (weight on bit or WOB) but also includes intermittent stops during the process to allow the bit to cool off (Zacny and Cooper, 2005a).

The reduced atmospheric pressure also causes dust to settle quickly. On Earth, fine dust becomes airborne and covers large distances from its source before settling down. On Mars, however, the fine dust produced by the drilling or coring of rocks will settle more rapidly. In our experiments on drilling under reduced pressure (Zacny et al., 2005a) we have noted that even very fine dust with particle sizes in the 10 μm range settles at only a few centimeters from the hole. As a result, instruments and cameras on the Mars Lander or Rover may not require additional dust covers, although some sort of deflector shield at the top of the hole may be advantageous. Similarly, missions utilizing solar arrays should not require brushes or gas jets to clean their surfaces periodically.

2.3. The effect of geological uncertainty

The geology of the surface of Mars is still incompletely understood. Some parts of the surface appear to consist of blocks of hard rocks, typically basalt, distributed in soil or dust that may or may not be well consolidated. Such a terrain was encountered by the "Spirit" Rover on the slopes of Bonneville crater. In other locations, for example at Eagle crater, "Opportunity" found sedimentary terrain that may contain evaporites (Soderblom et al., 2000). Such formations would be expected to be much softer and more uniform, and thus much easier to penetrate than basalt. The drilling environment may thus be variable on a large scale and also on a centimeter-by-centimeter basis. Some environments may be particularly difficult. An example would be if the drill encounters blocks of hard rock dispersed in loose soil. Such terrain is notoriously difficult to penetrate, with problems of hole collapse while traversing the loose soil and problems of uneven running and hole deviation when the drill bit makes glancing contact with the blocks of hard rock.

Additional problems are posed by the possible presence of ice, either as lenses of solid ice or dispersed in ice-bound soils or rocks (permafrost). There is considerable evidence of water ice at the Martian poles (Titus et al., 2003; Mitrofanov et al., 2003), but it is not certain whether ice-bound terrain will be found at lower latitudes (Murray et al., 2005). At present, there appears to be no evidence of ice in the immediate subsurface where Spirit and Opportunity are working, but that does not exclude the possibility of ice being found at some depth. Solid ice is difficult to penetrate by conventional drill bits as partial melting and re-freezing tend to cause ice to fill into the spaces between the bit teeth and produce a smooth, slippery surface on the bit face that prevents it penetrating further. In terrestrial drilling, a solution that is often used to prevent re-freezing is to pour a low melting point liquid such as glycol or methanol into the hole (Ueda and Garfield, 1969), but this will not be an option on Mars because of the difficulty of transporting the liquid to Mars and because the temperature will be too low.

2.4. The combined effect of water saturation and low temperature

Since southern and northern polar regions on Mars contain ice, it was decided to investigate the effect that ice-bound rocks have on the drilling process.

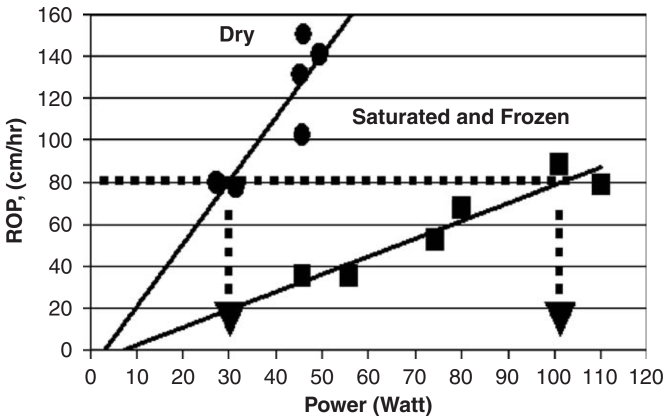

Fig. 3. Rate of penetration vs. power for a dry and water-saturated frozen sandstone under Martian pressure.

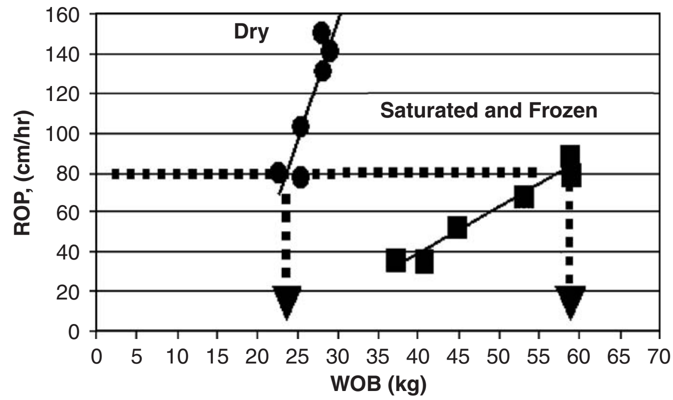

Fig. 4. Rate of penetration vs. weight on bit for a dry and water-saturated frozen sandstone under Martian pressure.

The effect of temperature on the rock-breaking process itself was found by others (Heins and Friz, 1964; Mellor, 1971) to be quite significant. Heins and Friz (1964) found that the strength of basalt is a function of temperature. In particular, the strength of oven-dried basalt increases by 50% when cooled down to $-80\,^{\circ}$C. This temperature dependency of the strength of rocks was also confirmed for other rock types by Mellor (1971).

Mellor (1971) found that the strength of the rock is not only a function of temperature but also of water content. The unconfined compressive strength of Berea Sandstone when water saturated and froze down to $-80\,^{\circ}$C increased by three times. In our drilling experiments we found that the power required for the same rate of penetration also increased by a factor of three. Fig. 3 shows the rate of penetration as a function of the weight on bit for oven-dried Briar Hill Sandstone and for water-saturated (100% saturated) frozen Briar Hill Sandstone under Martian pressure. At a rate of penetration of 80 cm/h, the power usage was around 30 W for dry rock and 100 W for the water-saturated frozen rock. Since the rate of penetration is approximately proportional to the rock strength, it appears that the strength of the water-saturated rock may be about three times larger than the strength of the dry rock. This observation is consistent with the experimental findings reported by Mellor (1971). The exact strength increase is not only a function of the rock properties but also the degree of water saturation and the temperature. This finding is of particular importance to the Martian drill design as it is expected that the Martian hole will be drilled in water-saturated areas (where the probability of finding life is highest).

When the best fit lines in Fig. 3 are extrapolated to the x-axis, they intercept the axis at a value of around 5 W. This power (when the rate of penetration is zero) can be attributed to the frictional resistance of the bit rotating on the bottom of the hole and to the auger conveying the cuttings out of the hole.

The specific energy (energy required to drill unit volume of rock) for the dry sandstone was calculated to be 210 MJ/m^3 and for the 100% water saturated and frozen sandstone was 770 MJ/m^3.

Fig. 4 shows the rate of penetration as a function of the weight on bit for the dry and the water-saturated frozen Briar Hill sandstone. Fig. 4 shows that dry rock requires much lower weight on bit values than ice-bound rocks to achieve the same rate of penetration. In particular, the weight on bit required for the rate of penetration of 80 cm/h is 25 kg for the dry rock and 60 kg for the water-saturated frozen rock.

It was also found that the approximate values for the threshold weight on bit required for the cutters to penetrate the rock were 15 and 40 kg for the dry and the water-saturated rocks, respectively. From the cutter geometry, the total surface area of cuter pressed against the rock was 3.5 mm^2. Using these threshold weight on bit values, the pressure exerted by the cutters on the face of the rock was 43 MPa in the case of dry rock. This is in the range of the unconfined compressive strength of the dry rock, reported to be 48 MPa (Briar Hill Stone Co,). The pressure exerted by the cutters on the face of the water-saturated frozen rock was approximately 110 MPa. This higher threshold pressure requirement was presumably a result of the rock strengthening effect due to the presence of the frozen pore water.

2.5. Three drilling scenarios on Mars—a direct result of Martian environmental conditions

The choice of a drill system will be influenced by the drilling location on Mars. Factors such as atmospheric pressure and the possible presence of water are major considerations. There are three possible scenarios:

Scenario one: Drilling may take place in a water-rich location with pressures below the triple point of water, as found in Southern Polar Region of Mars (Titus et al., 2003). In such a case, all or a portion of the heat generated by the drilling process (depending on the amount of water) will be used up by the latent heat of fusion and vaporization. Since liquid water is not stable at pressures below the triple point of water, the risk of a thaw followed by refreezing that locks the drill in the hole seems much reduced. In addition, the risks of cross-contamination of core samples will be reduced. At the same time, the drilling power will be reduced and hole cleaning will be improved as the subliming water will blow the drilled cuttings from the bottom of the hole (Zacny et al., 2005a).

Scenario two: Drilling may occur in water-bearing formations with pressures above that of the triple point of water as found in Northern Polar Region (Smith and Zuber, 1998). Water could then exist in its liquid form. Liquid water not only increases the chances of contaminating the core with organisms already existing on the drill, but could also refreeze, trapping the bit inside the hole. Thus, the temperature of the drill bit must be monitored very closely to avoid the melting of water ice. Since water on Mars may contain salts, the freezing point could actually be lower than 0 °C. Therefore, using the bit's temperature to monitor the state of the ice will not necessarily be the best method. An alternative approach, using an electrical resistivity measurement would be more accurate (Zacny and Cooper, 2005a) as the resistance of the formation changes depending on the amount of liquid water. Hence, a sudden change in resistance indicates water ice melting.

Scenario three: Drilling may take place where there is no water present. In this case, the low atmospheric pressure will not be a significant factor any longer. It will, however, affect the rate of heat dissipation. Therefore, the drill's temperature will necessitate careful monitoring since overheating of the cutting elements could be detrimental to the structure of the bit. In addition, low atmospheric pressure coupled with elevated temperature enhances desorption and dissociation of surface oxides and films (Bowden and Hanwell, 1964). This poses serious problems at the cutters' surface (Zacny and Cooper, 2005b). Once oxide films are removed through mechanical abrasion (cutters sliding on the rock surface), they will not be replaced. This loss of surface films results in higher friction and in turn higher frictional heating. Higher temperatures in turn promote further desorption and dissociation of chemical species, which in turn result in a larger 'un-contaminated' surface areas and further increase in friction. This situation carries on until complete seizure or welding of two surfaces occurs. On Mars, having no drill bit temperature data, it will be impossible to determine whether an increase in drilling torque is caused by higher friction or by an increase in the strength of the drilled formation. Thus, the Martian drill must be instrumented with a thermocouple reading the bit temperature, unless, drilling will be performed for short time durations only.

3. Technological constraints on the Martian drill system

In this section we investigate how technological constraints will affect drilling on Mars.

3.1. Power

The main source of power for the present and near-future Mars surface missions (including the 2007 Phoenix Lander mission) comes from multi-panel solar arrays. Mars Exploration Rovers have solar arrays that can generate up to 140 W for 4 h per sol but they do have some disadvantages. First, they only work when exposed to direct sunlight, varying their efficiency with the time of the day. Second, solar panels gradually become covered with dust, which, in turn, lowers their efficiency. Third, since Mars' rotational axis is tilted at approximately 24°, the angle at which the panels face the sun varies from season to season and this affects their efficiency. Lastly, since the orbit of Mars is elliptical, the intensity of the incoming sunlight will vary from season to season.

Future Mars Landers, particularly the 2009 Mars Science Laboratory rover mission, will use a Radioisotope Thermoelectric Generator (RTG) that can provide an uninterrupted power supply for many years. With RTGs, drilling can become independent of the time of day or positioning of the planet with respect to the sun. In fact, drilling could be conducted at night, which would be ideal to minimize overheating of the core (night time temperature can be 100 °C lower than the day time temperature. Martin et al., 2003). Although RTGs are more compact than solar panels, they are heavier and also generate a large amount of heat energy that needs to be dissipated via radiators. The science community is highly concerned that if such an RTG powered Lander or Rover crashes (instead of landing) in ice-bearing regions (Southern or Northern polar regions Titus et al., 2003; Mitrofanov et al., 2003), it could potentially sublime or melt and vaporize the ice underneath and contaminate the surrounding ice with bacteria brought from Earth. In the presence of water–ice and possible liquid water, bacteria could grow and spread over large areas (Palluconi, 2004). In addition to solar panels or RTGs, any power system will include rechargeable batteries that are re-charged by the solar arrays during daytime or continuously by the RTG. In all probability, the drill will be powered by the batteries, as was the case with the Apollo Lunar drill.

At this stage a distinction needs to be made between the energy content of the battery (reported in units of Watt-hour) and the power (Watts) that can be delivered by the batteries (voltage × current). The 2003 Mars Exploration Rovers (MER) have two lithium ion batteries with an energy content of about 300 W-h per sol each or 600 W-h per sol total. Thus, they could theoretically deliver 600 W for 1 h or 60 W for 10 h. The Rock Abrasion Tool currently on the MER uses approximately 50 W-h (10 W for 5 h) to grind a 40 mm in diameter and 5 mm deep hole in strong basalt. Assuming that only 25% of the energy content could be used by the drill, in intermittent drilling, therefore, such batteries could provide 150 W for an hour or 300 W (comparable with a hand-held home handyman's drill) for half an hour. Thus, specifications that call for the drilling equipment to be limited to 50 W of power are probably unduly conservative (2004 Centennial Challenges Workshop Report, 2004).

3.2. Weight or force on bit

The maximum force that can be applied on the drill bit while on Mars is a function of the weight of the Martian Lander or Rover for a system that applies weight from surface via a drill pipe, or for a cable-deployed system as long as the gripper system is still in the launch tube unless some positive anchoring system is provided against which the lander can pull (this seems unduly complicated to build).

The 2009 Mars Science Laboratory Rover will have a mass of approximately 500 kg (Mars Science Laboratory, 2005). Assuming that the Mars 2011 WildCat Drilling Rover will have the same mass, then the maximum force that should be applied on the bit while testing the drill bits on Earth is

$$\mathrm{WOB} = 0.3 \times 500 \times 9.8 \approx 1500\,\mathrm{N}. \tag{1}$$

The effect of the lower Martian gravity must therefore be borne in mind when carrying out drilling test experiments on Earth, and it must also be remembered that the entire weight of the Lander will not be available unless the drill is situated directly under its center of gravity. In the more likely event that the drill is placed so as to drill over the side of the Lander, the available weight will be typically a half or less of the total Lander weight.

Thus, the available WOB will be actually:

$$\mathrm{WOB} = f \times 0.3 \times M_{\mathrm{lander/rover}} \times 9.8\,\mathrm{N}, \tag{2}$$

where

- f is the fraction of the dead mass of the lander available for applying of WOB.

PDC and other discrete cutter bits are normally supplied with sharp cutting edges, and when new are very aggressive. If the maximum available weight is applied to such bits in this condition, they can easily be damaged by the excessive depth of cut that results. However, as they wear, progressively more weight must be applied. Conversely, diamond-impregnated bits tend to have a much more constant behavior because of the regular loss and replacement of the diamonds. The drilling control system will have to account for these differences according to the bit type selected.

3.3. Rotational speed

For most rock types, changes in rotary speed do not change the rock destruction mechanism significantly, so the drilling torque is approximately constant while the rate of penetration and the power required become proportional to the rotary speed. For cuttings removal using the auger, higher rotational speeds is however beneficial. Since power is directly proportional to rpm, higher rpm will also mean higher power requirements.

Note that an increasing input power due to higher rotational speeds results in increased heat generation and this may have undesired effects both as regards the wear of the bit and the heating of the core being cut. For diamond-impregnated bits, too high a speed at low weight can for example cause diamond glazing (the diamonds become polished flat and cease to cut) while too low a speed can cause excessive vibrations, which might lead to diamond fracture. Excessive vibrations at low rpm are also observed when drilling with PDC bits. In this case, PDC cutters are much more susceptible to micro and macro fractures at their cutting edges.

4. Selecting a drill system

In this section we describe various drill systems that could be used on Mars. The drill system could be divided into two general categories based on the required target depth and the sample shape. In the first category, if the depth of the required hole is shallower than around 20 m, a continuous drill pipe will suffice. However, if the hole will be much deeper, a drill suspended on a wireline will be more advantageous. In the second category, the sample shape will dictate whether the sample will be acquired in the form of a powder or a solid core. If a core is required, the drill will be in the form of a coring bit. If a powdered sample is required, the drill may be in the form of a full-faced bit. Note that the powdered sample could also be obtained from the solid core. We now consider some advantages and disadvantages of each of the systems.

4.1. Drill pipe vs. wireline

Two candidate styles of drilling are being investigated. In the first, the system that applies rotary motion and downward force (weight on bit) to the drill bit is located out of the hole on the surface. It is connected to the bit and coring assembly by a string of drill pipes that are screwed or otherwise connected together to form a rigid connection between the surface equipment and the bit. Such a system has the advantage that the drive mechanism is placed out of the hole where its size is not constrained by the diameter of the hole and where maintenance may be easier. Further, if the bit gets stuck in hole, it may be possible to unscrew the drill pipe and, while the bit and a number of lengths of pipe may be lost, if spares are available, the equipment may be moved to another location and a new hole started.

On the other hand, the drill pipes will be heavy, and a substantial mass of surface equipment will be needed to store unused pipe, then to bring it to the drilling equipment and connect it to the pipes already in hole. Similarly, when recovering core, changing the drill bit or removing the drilling assembly in order to log the hole, it will be necessary to remove and store the drill pipe. Alternatively, the drill could use a center wireline for lifting the core out of the hole. In this case, there will be no need for pulling the drill out of the hole and in turn, the drill string could serve as a casing.

An additional inconvenience of having a continuous drill string may also occur if it is desired to instrument the drill bit or make measurements down hole while drilling is under way. This is because it will be difficult to maintain electrical connections between successive sections of drill pipe and it will be necessary to provide a means of transferring information from the rotating drill pipe to the fixed equipment on surface. If an auger system is used, the drill pipes will probably all have to be provided with auger flights (unless there is provision for down-hole cuttings storage), and the torque required to bring the cuttings to surface may quickly limit the depth of hole that can be drilled.

An alternative system uses a drilling assembly that consists of a bit, drive motor and cuttings catch basket that are located in the hole, suspended from the surface on a cable that brings electrical or possibly pneumatic power to the drive motor. The same cable can be used to return drilling information to the surface. Weight on bit is provided by a gripper system that braces itself against the hole wall. No drill pipe is used and the cuttings are stored down hole in a catch basket that is periodically returned to the surface to be emptied when the core is recovered or a bit change is required.

Such a system dispenses with the need for drill pipes and the handling equipment that is required to run them into and out of the hole. Instead, the cable that attaches the drilling equipment to the surface can be stored on a simple cable reel. Of course, a launch tube will be needed to allow the gripper system to obtain an initial purchase until the hole has been deepened enough to allow the grippers to enter the hole, but this may well be combined with the guidance system that will in any case be needed to change drill bits, recover core and empty the cuttings catch basket. Once in the hole, if the gripper system is powerful enough, the maximum weight on bit that may be applied will not be limited by the dead weight of the spacecraft. In such a system, it will not be necessary to auger the cuttings all the way to the surface, as they only have to get to the cuttings catch basket. Disadvantages to this system may include the possibility that the hole wall may be damaged by the action of the gripper, and that if the drilling assembly becomes stuck in the hole, unless there is a back-up set of down-hole equipment, it will not be possible to drill another hole.

4.2. *Drilling vs. coring*

The benefits of acquiring a core rather than a small powdered rock sample are much higher from the point of view of obtaining valuable scientific results. However, the choice of coring vs. full face drilling also affects the drill system design. From the drilling point of view, the main benefit of coring is that a much smaller volume of rock needs to be excavated to reach the desired depth (during coring only the annular space is removed inside the rock). A full-faced drill will require much more energy to achieve the same depth. Conversely, the coring bit requires smaller values of WOB than a full-faced bit. Both of these features reduce the heat generation and removal problems for coring bits.

There is also an additional challenge in designing a full-faced bit as the cutters located at the axis of rotation have only vertical motion (only cutters that are away from the axis of rotation have translational motion). This complicates the choice and placement of cutters.

The main advantage of a full face bit is that no additional core handling equipment needs to be built. This makes the design of the drill much simpler and the diameter of the hole could be made smaller (reducing the amount of necessary rock excavation). In addition, since there is no core, the space inside the drill could be used for downhole logging devices.

5. Drill selection

Any drill consists of two integral parts, which are a drill bit and a cuttings removal system. The final choice of these components will depend on many inter-related factors. However, in view of the uncertainty concerning the formations that are to be penetrated, it will be more prudent to build a drill that can make adequate progress in a wide range of terrains, rather than doing superlatively well in some conditions and being unable to advance in others. Related to this requirement is that all precautions should be taken to prevent the drill becoming stuck in the hole. Stuck drilling tools not only prevent the hole being deepened, but also prevent access by logging instruments. We now discuss various elements of the equipment with these considerations in mind.

5.1. *Drill bits*

The drill bit will have to be able to penetrate a variety of formations, including ice and ice-bound soils, sedimentary rocks including evaporites, sands (more or less cemented) and hard volcanic rocks such as basalt. In view of the expected small diameter of the borehole (about 30 mm or so), and the requirement to be able to cut and recover cores, a fixed-cutter bit is indicated.

For terrestrial applications of this type, the choice is for either a diamond-impregnated bit or a bit having larger discrete teeth that are made, usually, of cemented tungsten carbide or polycrystalline diamond compacts (PDC).

5.1.1. *Diamond-impregnated bits*

Diamond-impregnated bits are provided with cutting elements in the form of blocks or segments of relatively soft metal such as bronze, impregnated with small diamonds dispersed throughout the body of the block. As drilling proceeds, the bronze is worn away, exposing the diamonds that then cut the rock. Further abrasion of the bronze matrix by the drilled cuttings erodes the bronze away at a rate that allows the surface diamonds to be lost as they become worn, and new, sharp diamonds to be exposed (Fig. 5). For optimal effect, the hardness of the bronze matrix must be matched to the hardness of the rock to be drilled, with harder rocks being matched to softer bronzes (since there is more wear of the diamonds and less cuttings are produced when drilling hard rocks). If the matrix is made too hard, the diamonds can be worn down to a condition in which they no longer cut (Fig. 6), (Zacny and Cooper, 2004) (note that Figs. 5 and 6 are of the same area). At this point, no more cuttings are formed, no further erosion of the matrix occurs and the worn diamonds are not lost and replaced. The result is that the bit stops drilling. If a very soft matrix is chosen, the risk is that the overall rate of wear of the bit will be high. Thus, the total distance drilled may be limited, but at least the bit will not be stopped. For Martian drilling, therefore, it would be prudent to err or the side of choosing a matrix that is soft, in order to be able to advance at least until the impregnated segments have been completely consumed.

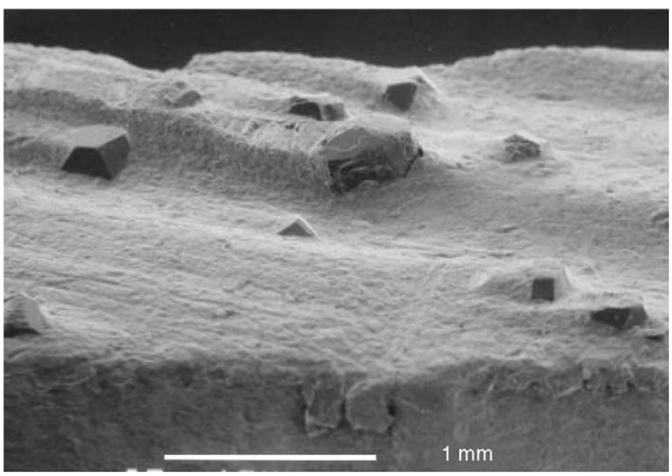

Fig. 5. Scanning electron micrograph of a diamond-impregnated segment in good condition.

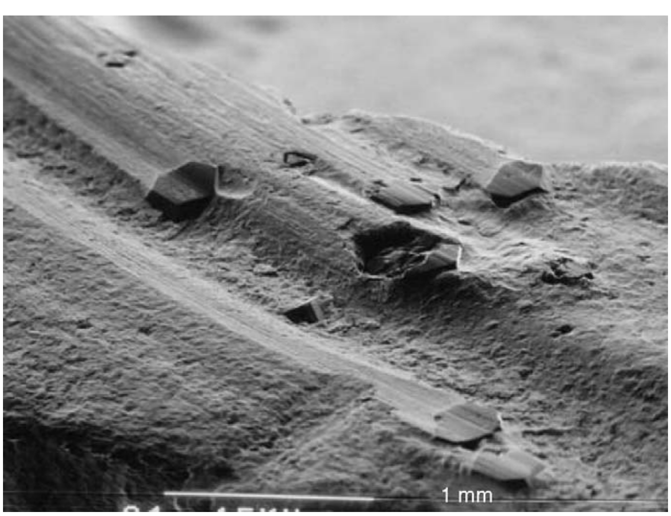

Fig. 6. Scanning electron micrograph of an ineffective diamond-impregnated segment (note polished and flattened diamonds).

5.1.2. Discrete-cutter bits

Discrete-cutter bits have relatively few, large teeth usually made of cemented tungsten carbide or cemented tungsten carbide provided with a layer of polycrystalline diamond on the forward edge of the cutter (PDC). Such bits are generally much more aggressive than diamond-impregnated bits and give rates of penetration that are typically an order of magnitude greater for equivalent weight on bit and rotary speed. However, the sharp edges of the cutters can be worn down by exposure to hard, abrasive rocks, and they can also be chipped by impact with hard rocks or when drilling in uneven terrain where impact against hard inclusions occurs. In contrast to diamond-impregnated cutters, once the sharp edges of a discrete-cutter bit have been worn or chipped, there is usually no way of re-sharpening the bit without removing it from the hole and returning it to the factory. If such wear were encountered on Mars, the bit would have to be removed and exchanged for a new one.

Both bit types have difficulty in drilling ice and ice-bound soils, since ice tends to melt and re-freeze between the projecting bit teeth, resulting in the formation of an ice-glazed surface on the bit. One solution is to make the bit teeth extremely sharp, and to provide them with a positive rake angle with respect to the direction of cut. (A positive rake angle is defined as being when the plane of the front face of the cutter is inclined so that it makes a positive clockwise angle with respect to the normal to the hole bottom, i.e. the cutter face slopes upward and backwards with respect to the direction of cut like the blade of a wood plane.) In such a case, the cutters operate very efficiently and the cuttings are lifted off the work surface with minimal opportunity to lodge between the bit teeth. Unfortunately, such very sharp cutters are easily damaged. Thus, they work well in clean ice or snow, but are quickly chipped and cease to cut if stones or even sand or silt are encountered. For normal rock drilling, the cutters are usually set with a negative rake angle to reduce the chance of cutter fracture.

5.1.3. A hybrid bit

Since neither of the bit types described above is likely to be successful under all conditions on Mars, we have considered the possibility of building a hybrid bit type that may be able to make progress in all formations. This will have a combination of both PDC (discrete cutter) and impregnated elements.

Some hybrid bits (Tomlinson and Clark, 1992; Sheppard and Dolly, 1993) have been described that allow for rapid rates of penetration in soft rocks, but for which the cutting structure is protected in some way if very hard rocks are encountered. Although these designs are intended to drill in soft rocks with occasional bands of harder material, they are not suitable for drilling soils, ice, ice and soil mixtures and rocks of variable strength, since they tend to choke and clog with drilling debris when run in very soft materials.

Fig. 7 shows the proposed self-sharpening cutting segment for drilling in any geological formation. It comprises two cutting elements. The first is a plane diamond table set at a positive rake angle with respect to the cutting direction. The diamond table is conveniently made of PDC, but may be made of single crystal diamond, chemical vapor deposited diamond, reaction bonded diamond composite or other hard material such as cemented tungsten carbide. The second part of the cutter is placed immediately behind and in contact with the diamond table and supports it so as to prevent it from being bent backwards and broken. It is composed of a regular diamond-impregnated material. The impregnated elements may contain diamonds of different sizes and quality, and the matrix metal may be varied.

Unlike the cutters used in bits described elsewhere (Tomlinson and Clark, 1992), in which the PDC cutters are separate from the diamond-impregnated studs, the present cutter combines both elements. This is so that the impregnated element can support the diamond table, and so that the diamond table can protect the impregnated element from undue abrasive wear.

In operation, the cutters operate in one of two ways. In very soft material, such as ice, ice-bound soil, soft clay, etc., it has been found that it is important that the cutter have a positive rake angle. The cutter then acts much like a chisel

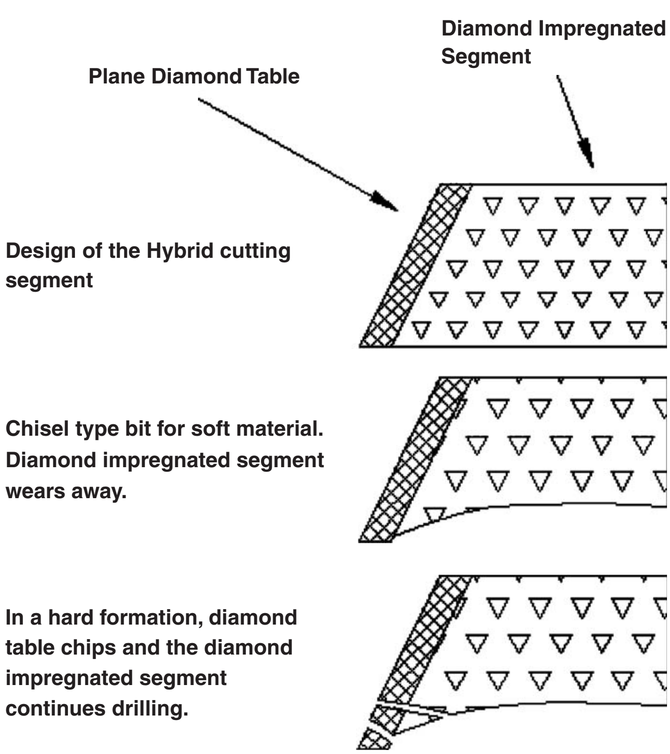

Fig. 7. A hybrid, self-sharpening cutting segment for drilling in any geological formation.

or plane to peel the material to be drilled away from the substrate. During drilling of this type, the abrasive action of the undrilled rock and the cuttings wears away the matrix of the diamond-impregnated segment behind the table. The segment thus takes no part in the cutting action. It does, however, have a very important function in limiting the depth of penetration of the diamond table so that the forces on the table are kept low enough to prevent it from being broken.

When drilling in hard material, however, it is expected that the cutting edge of the table will either be chipped or rapidly worn away. Under these circumstances, the diamond-impregnated metal segment is exposed to the rock and will continue the drilling action as the exposed diamonds make contact with the rock. A judicious selection of the abrasion resistance of the metal matrix will ensure that the matrix is worn away, allowing the diamonds to fall out, at just the rate that causes the diamonds to be lost when they have become blunt and cease to cut. In particular, use of a soft matrix is indicated when the abrasivity of the drilled cuttings is low. In the absence of clear knowledge of the terrain to be drilled, it is advisable to use a soft matrix to be sure that the segments will be worn down adequately.

When the bit, having been drilling in hard material, now encounters a softer layer of rock (or soil), the material being drilled will no longer be able to wear or break the diamond table, but the drilled debris will still be able to wear away the (much softer) matrix of the impregnated element. Thus, the original cutting structure, with the table standing proud of the impregnated element, will be re-established. At this time, the major contribution to drilling will once again be from the table. In this way, the cutter adjusts its behavior to suit the material being cut. By the same token, it is self-repairing if damaged by accidental overload.

The advantage of this design is that the bit should be able to drill in most formations. It should also be self-sharpening and, to a degree, self-repairing if damaged.

5.1.4. *Cutting sizes as a function of bit types*

Although specific energy is the most frequently used indicator of the drill bit efficiency, other indicators such as the sizes of the resultant drilled cuttings can also be used to establish the relative efficiencies of various bits. This is because the most efficient drilling process produces the coarsest particles.

Fig. 8 shows the particle size distribution of cuttings produced by PCD, hybrid and diamond-impregnated bits. The particle size distribution varies quite extensively as a result of the different rock destruction mechanisms employed by the bits under consideration. In particular, $d_{50} = 100\,\mu\text{m}$ for the PDC bit, $45\,\mu\text{m}$ for the hybrid bit and $25\,\mu\text{m}$ for the diamond- impregnated bit.

The PDC bit relies on a chisel cutting action and thus it produced the coarsest particles. The hybrid bit, although it utilized mainly PDC cutters, produced finer cuttings.

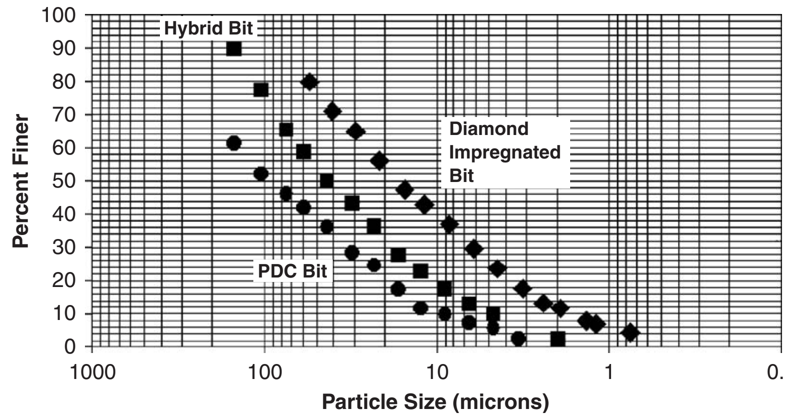

Fig. 8. Particle size distribution of cuttings produced with PDC, hybrid and diamond-impregnated bits.

This is because the bit also had diamond-impregnated segments which re-ground previously cut rock. The segments in addition ground extra rock. The finest cuttings were produced by the diamond-impregnated bit. The rock drilling action of such a bit relies on the localized cutting and grinding of the rock by small (300 μm or so) diamonds. Thus, particle size distribution successfully confirmed the mechanisms of rock destruction by various bits.

5.2. *Choosing a cuttings removal system*

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. Thus, the next question concerns the means for removing the cuttings from the workfront. Because of the combination of low temperature and low pressure on Mars, there is no liquid that can be used to flush the cuttings out of the hole.

5.2.1. *Auger methods*

Currently, the method for removing the cuttings that is receiving the most attention is by the use of augers. A typical arrangement envisages the use of a hollow-stem auger allowing the cutting and recovery of a core, with a drive tube surrounding the coring assembly. 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.

The use of augers in drilling is well known, although there is still a lot of empiricism in their design (Carleton et al., 1969). From the practical point of view, a major concern is to keep the cuttings flowing freely up the auger and preventing them from choking the auger flights. Augers generally work well when conveying dry, powdery materials but choke when required to handle wet or sticky materials. In our experiments, we have found that the presence of liquid water is very damaging to auger performance, and that once an auger fills with sticky cuttings, it is extremely difficult to clear. For the various reasons advanced above, however, it may be that drilling under Martian conditions will be easier than drilling under terrestrial conditions because the ground to be penetrated will either be dry, or if ice is present, the ice may be sublimed away by the heat of drilling before it can clog the bit and auger.

In our experiments on drilling under Martian conditions we have found that once the auger has choked and become clogged with cuttings, it is almost impossible to clear it, in spite of, for example, lifting off bottom while rotating or even applying reverse rotation. It is thus extremely important to determine the maximum lifting capacity of the auger under the operating conditions that are anticipated 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 in "easy" drilling formations.

5.2.2. *Blasts of gas*

One possibility for removing the cuttings out of the hole would be to use a gas stream, either from a supply of compressed gas brought to Mars on the spacecraft, or else generated by compressing the Martian atmosphere. A supply of compressed gas might also be generated by the decomposition or burning of a suitable chemical, as in an automobile air bag. This would reduce the need for a heavy container for the supply of compressed gas.

In some recent work we have shown that when drilling under simulated Martian conditions, it is possible to use, a relatively modest gas flow to remove the cuttings (Zacny et al., 2005b). This is for two major reasons. First, because we expect the drilling operation to be carried out at low energy levels, the cuttings will be very fine. In our experiments with either diamond-impregnated or PDC bits, we have found that the typical cuttings particle diameter is a few tens of microns (see Fig. 8). In the lower gravity of Mars, such cuttings will be relatively easily lifted. Second, we have 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 surface in the annular space between the drilling assembly and the hole wall. For example, we have found that for an ambient pressure of 0.6 kPa (6 mbar), typical of Martian conditions, the majority of the cuttings can be blown out of the hole by a gas flushing pressure of 4 kPa (40 mbar). It should not be very difficult or require an excessive amount of power to compress the Martian atmosphere to this degree. Further, it appears that intermittent blasts of gas may be as effective as a steady gas flow. Lifting the cuttings by this method may have an important further advantage insofar as the gas flow will help to cool the bit.

5.2.3. *Cuttings lift by sublimation of ice*

A very interesting related possibility for lifting the cuttings occurs if the formation being penetrated contains water ice. In experiments on ice-containing rocks and soils (Zacny et al., 2005a), we have found that, when drilling under conditions of low pressure, the heat generated by the drilling process causes the ice to melt and then immediately to boil to vapor. At a pressure of 0.6 kPa (6 mbar), 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 thus generate enough water vapor to blow the cuttings out of the hole. Since the water is converted to vapor at the drill bit, the cuttings being blown out of the hole are, in effect, freeze dried, and so they do not stick to the drilling equipment or to the hole walls as they leave the hole.

6. Conclusions

While it is clear that much still remains to be discovered about the properties of the Martian surface, and in particular how easy it will be to drill into it, it is already possible to sketch out some of the likely conditions that are to be encountered and how they will affect the drilling process. Most importantly, the combination of low pressure and low temperature will make it impossible to use liquids to remove drilled cuttings from the hole. This leaves the choice for cuttings removal between the use of an auger and, perhaps, the use of continuous or intermittent gas blasts to clear the cuttings. Various choices of drill bit are possible; these will be constrained by the probability that a wide range of formations may be encountered and so a multi-purpose bit capable of drilling in many rock and soil types is indicated. We propose a bit with a hybrid cutter type, having a positive rake leading edge formed of PDC, backed by a supporting element made of diamond-impregnated material. Further, there is a high likelihood that ice or ice-bound soils or rocks may be encountered. The ice is likely to increase the strength of the terrain being penetrated, and may also choke the bit. This will require a bit that is engineered to discourage the packing of ice between the bit teeth. The positive rake angle of the hybrid cutter is intended to reduce the likelihood of this packing effect.

Two possible advantages may be afforded by the expected operating conditions. First, since the available drilling power will be low, the drilled cuttings will likely be very fine and easily removed. Second, because of the combination of low temperature and pressure on the Martian surface, any ice encountered may be sublimed by the heat of drilling. The resultant flow of water vapor out of the hole may be sufficient to blow the fine cuttings out of the hole, thereby materially assisting the hole cleaning process.

This note has only set out some of the constraints and indicated a few of the possibilities for building a drill to work on Mars. It is evident that much further work needs to be done before a drill is developed that can be expected to drill reliably in that environment. Equally, since it is becoming clear that the special conditions of the Martian environment cause the drill to respond in ways different from those experienced on Earth, it will be necessary to carry out extensive testing of candidate drills in a test facility that duplicates the Martian environment as closely as possible.

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