Drilling Systems for Extraterrestrial Subsurface Exploration

K. Zacny,1 Y. Bar-Cohen,2 M. Brennan,3 G. Briggs,4 G. Cooper,5 K. Davis,1 B. Dolgin,3 D. Glaser,1 B. Glass,4 S. Gorevan,1 J. Guerrero,6 C. McKay,4 G. Paulsen,1 S. Stanley,7 and C. Stoker 4

Abstract

Drilling consists of 2 processes: breaking the formation with a bit and removing the drilled cuttings. In rotary drilling, rotational speed and weight on bit are used to control drilling, and the optimization of these parameters can markedly improve drilling performance. Although fluids are used for cuttings removal in terrestrial drilling, most planetary drilling systems conduct dry drilling with an auger. Chip removal via water-ice sublimation (when excavating water-ice–bound formations at pressure below the triple point of water) and pneumatic systems are also possible. Pneumatic systems use the gas or vaporization products of a high-density liquid brought from Earth, gas provided by an in situ compressor, or combustion products of a monopropellant. Drill bits can be divided into coring bits, which excavate an annular shaped hole, and full-faced bits. While cylindrical cores are generally superior as scientific samples, and coring drills have better performance characteristics, full-faced bits are simpler systems because the handling of a core requires a very complex robotic mechanism. The greatest constraints to extraterrestrial drilling are (1) the extreme environmental conditions, such as temperature, dust, and pressure; (2) the light-time communications delay, which necessitates highly autonomous systems; and (3) the mission and science constraints, such as mass and power budgets and the types of drilled samples needed for scientific analysis. A classification scheme based on drilling depth is proposed. Each of the 4 depth categories (surface drills, 1-meter class drills, 10-meter class drills, and deep drills) has distinct technological profiles and scientific ramifications. Key Words: Drilling—Coring—Sampling—Subsurface exploration—Drill bits. Astrobiology 8, XXX–XXX.

Glossary

A bailer is a small bucket suspended by a tether that is used to remove drilled formation from the bottom of a hole. Bit chatter is a strong vibration of the drill bit during drilling. Choking is a phenomenon that occurs when cuttings fail to move up the auger flutes or flights; the torque increases dramatically, and the drill jams. A core is a cylindrical piece of subsurface formation (e.g., solid rock, ice, or compacted regolith) that is formed by a coring bit after making a borehole. A coring bit is a drill bit that excavates an annular part of a hole, leaving a central, solid core of a subsurface formation. The cut per revolution is the amount of penetration that a drill bit achieves in a single revolution. The overall rate of penetration is equal to the cut per revolution multiplied by the rpm of the bit. Cuttings, also known as chips and fines, are the pulverized remains of the formation that the bit has excavated from the formation. Diamond-impregnated cutters consist of randomly placed, very small diamonds imbedded in a softer matrix. If designed
correctly, the matrix wears away just when the exposed layer of diamonds becomes dull, thus exposing a new layer of sharp diamonds.

Drilling power, measured in Watts, is the sum of the power consumed by the bit as it breaks down the formation and the power used by the cuttings-removal system. It represents some fraction of the energy consumed by the drill system and is calculated by subtracting the total system power while drilling into air from the total system power while drilling into a subsurface formation. Total drilling power, measured in Watts, is the total power consumed by the drill system while drilling. It includes the power to break down the formation and move the cuttings to the surface, as well as any mechanical losses (e.g., drill motor) associated with the drilling system.

The drill string consists of the bit and cuttings-removal structures (usually an auger) in subsurface drills. In drills longer than about 1 m, the drill string is usually made of more than one segment.

Dry drilling is drilling without the benefit of the injection of a fluid into the hole. It is more challenging than wet drilling because of less efficient cooling and cuttings removal.

Flutes (or flights) are the spiraling surfaces on an auger that convey cuttings from the bottom of the borehole region (just above the bit) toward the surface.

The formation (short for geologic formation) is the volume of material in which a drill makes a hole.

A solid-front or full-faced bit is a drill bit that excavates the entire area of the hole (as opposed to a coring bit that excavates an annular region or solid segment).

Polycrystalline diamond compact (PDC) cutters consist of a thin layer of polycrystalline synthetic diamonds lying on a thicker layer of cemented tungsten carbide.

A rotary drill, as the name implies, uses simple rotation, combined with weight on bit, to excavate a hole.

A rotary-percussive drill combines rotation of the bit with high-frequency (perhaps 50 Hz) downward hammering. The hammering results in much higher peak forces than can be achieved with a rotary drill and is most suitable for brittle materials. Rotary-percussive drill bits have to be designed so that they themselves don’t fracture or deform due to the hammering.

A slipping assembly is a device that allows electrical signals to pass between stationary and rotating structures in a drill, including, for example, a sensor or sampling actuator that is located inside the rotating drill string.

The unconfined compressive strength (UCS) of a material is the stress needed to cause fracture when a sample of the material is subjected to a compressive force with no support on the lateral surfaces.

Weight, in this paper, is quoted in units of force (Newton), while mass is in kilograms.

The weight on bit (WOB), measured in Newtons or pounds, is the downward force applied to the drill string, and hence to the bit.

A wireline drill is a drill that is suspended from a tether. The tether cannot exert any downward force, so WOB is provided by reaction against structures that press against the hole walls. Cuttings are stored in the drill until the drill penetrates to its maximum stroke, whereupon the entire drill is pulled up to the surface to remove the cuttings.

1. Introduction

The objectives of planetary exploration missions increasingly involve in situ sampling and analysis. In cases where sampling below the surface is desired, drilling is often the method of choice (Bar-Cohen and Zacny, 2008). On Earth, drilling into geologic formations is a mature technology, but extraterrestrial drilling entails challenges that are significantly more complex (Briggs and Gross, 2002). Because the task of drilling a hole on a distant planetary body is non-trivial and, in many respects, adds a lot of risk to a mission, a case must be made that the need for drilling justifies the added risk and expense.

The act of drilling a hole on a faraway planetary body is somewhat analogous to driving a planetary rover in complete darkness, with no view of the road ahead. There is a limited amount of information available from the drilling process to indicate what is being drilled or where the drill is in relation to the medium that is being penetrated. This requires addressing challenges that are significantly more complex than on Earth. The important scientific discoveries to be made by extraterrestrial drilling are what motivate the planetary science and engineering community to tackle this daunting task.

Most exploratory drilling operations on Earth are intended to search for mineral resources and are motivated by financial returns (Bar-Cohen and Zacny, 2008). In these cases, a continuous core that represents the formation is obtained and analyzed to determine the grade and depth of a metal ore or crude oil. Such cores, especially when drilled to great depths, are also used for scientific purposes. Examination of these cores can provide information about Earth’s past climate and biota as well as solar activity, since a lot of scientific information is trapped inside the geologic formations (e.g., rocks and ice).

The geologic record is created by material emplacement; and, generally, any feature that is being sought is buried by more recently emplaced material. On Earth, where erosion rates are high, material accumulates rapidly; resurfacing is a constant process, and most surfaces are geologically young. On Mars, however, without liquid water to provide high erosion rates, the average resurfacing rate is very low. Herkenhoff et al. (1997) estimated it to be \( \sim 10^{-9} \text{ m/yr} \). Golombek and Bridges (2000) suggested that these erosion rates decreased from \( 10^{-7} \text{ to } 10^{-5} \text{ m/yr} \) in Noachian terrains to \( 10^{-11} \) to \( 10^{-10} \text{ m/yr} \) during the Hesperian and Amazonian epochs. This is why ancient features such as ancient river- and lake beds can be easily seen or reached. In principle, access to very ancient terrains might be afforded on much of Mars even with relatively shallow drilling. However, in those locations where active resurfacing processes occur, such as the annual snowfall at the martian polar caps, accumulation rates of entrained dust can be much higher. This is the plausible source of the polar layered terrains and may indeed be locations where evidence of recent past life might be found (McKay, 1997; Smith and McKay, 2005). We say “recent” because these sites are expected to be young on the geological scale. Of course, the dust that accumulated in these locations has been transported through the atmosphere, and it is not clear how well signs of life would be preserved during transport. On the other hand, as we discuss elsewhere in the paper, the northern polar deposits may have locations where
summer ground temperatures exceed melting under favorable orbital conditions; thus, these locations may have been recently habitable.

Geologic examination of the subsurface will increase understanding of the formation and history of a planet or moon and, by extension, the history of the Solar System. Examination of the subsurface will also aid future human exploration by allowing the characterization of possible resources, as part of the In Situ Resource Utilization approach to planetary exploration (i.e., “living off the land”). The same applies for knowledge of the mechanical properties of the soil (necessary for human construction and transport projects). Data from drill telemetry can also be helpful for material characterization and may be used to identify changes in stratigraphy in order to flag regions of scientific interest.

The goals of planetary drilling are to obtain samples for in situ analysis, achieve sample return mission objectives that include geology, geochemistry, and geophysics, and provide an access hole for borehole measuring instruments such as a neutron probe (for water detection). A borehole will also allow assessment of the stratigraphy of the formation and, in turn, a look back into the geologic past of the planet or moon. A drill may also be integrated with thermal and electrical probes for in situ measurements.

The present assertion about the potential importance of drilling is echoed in many publications of the planetary science community. The NASA Solar System Exploration Roadmap (NASA, 2006) lists drills as one of the major tools required for future planetary exploration. The same document lists “advanced drilling, coring, or boring devices, carrying scientific sensors and tethered to a surface platform” as key technologies for in situ exploration. The Mars Exploration Program Analysis Group (MEPAG), in its written statement of scientific goals and objectives for Mars, lists access to the subsurface with drilling as one of the most “crucial technical abilities that need development.” (MEPAG, 2005).

This paper focuses on drilling methods that are applicable to extraterrestrial bodies. It covers the basic principles behind drilling excavation processes and offers examples of mechanisms that use these processes. Also, 3 methods of cuttings removal are described: (1) the use of augers, (2) chip removal via water-ice sublimation (when excavating water-ice–bound formations at pressure below the triple point of water), and (3) pneumatic systems that use the gas or vaporization products of a high-density liquid brought from Earth (gas provided by an in situ compressor) or the combustion products of a monopropellant. Throughout this paper, many examples of past, existing, and future drill systems are presented. The drilling systems are classified according to their reachable depth as surface drills, 1-meter class drills, 10-meter class drills, and deep drills. A distinction is made between coring and drilling mechanisms. The uses of percussive and rotary-percussive methods of drilling are also described.

2. Past, Present, and Future Extraterrestrial Drills

Extraterrestrial drilling dates back to the 1970s, when Apollo 15 astronauts (Commander David Scott and Lunar Module Pilot James Irwin) drilled a hole on the Moon to a depth of approximately 2 m. The drill they used, the so-called Apollo Lunar Surface Drill, was a 500-Watt rotary-percussive drill, with a coring bit capable of acquiring a continuous 1-inch-diameter core, and an auger for moving cuttings to the surface (Fig. 1). Even with this powerful drill and a human operator, several problems were encountered. If it had not been for the persistence of the astronauts, the drill would still be on the Moon. The final depth of ~2 m was a meter short of the target depth. The main problem with the drill was misalignment of auger flutes between consecutive drill segments, which caused the auger to choke and locked the entire drill inside the hole. It took both astronauts an extra 15 minutes of EVA time, working at the limits of their strength, to pull the drill out. Astronaut Scott sprained his shoulder.

The drill was brought back to Earth and inspected and redesigned for subsequent missions. The Apollo 16 and 17 Lunar Surface Drills included redesigned drill tubes and a jack for lifting the drill string out of the ground. With this new design, both the Apollo 16 and 17 missions were able to reach the target depth of 3.5 m. The jack also proved to be extremely useful, though it did not make the extraction of the drill tubes effortless. In the low lunar gravity, Jack Schmitt of Apollo 17 had to apply his full weight on the jack handle to remove the drill from the ground (NASA, 2007a).

The first fully autonomous drilling operation on an extraterrestrial body was done by the Soviet Union on Luna 24 in 1976. The drill was mounted along the side of the lander...
The lander mass was almost 6 tons on Earth (60 kN), 10 kN on the Moon, and thus was able to provide ample reaction thrust for the drill. The drill itself had a very clever mechanism for delivering drilled cuttings from a depth of around 1.6 m: the powdered sample was coiled as it was deposited inside the return craft. A 170-gram sample of lunar regolith was successfully returned to Earth on 22 August 1976 (Luna 24 Sample, 2007).

A drill on the Soviet Venera 13 and 14 landers also managed to penetrate a few centimeters into the venusian rock and deliver a sample (via vacuum suction) to an X-ray fluorescence spectrometer (Barmin and Shevchenko, 1983). This drill weighed 26.2 kg, and the drill motor could provide 90 Watts of power. The total drilling and sampling operation took no more than 200 seconds. Considering the extreme pressure (84 Earth atmospheres) and temperature (457°C) on the planet, this was indeed a great achievement. The Venera 13 and 14 landers survived for 127 minutes and 57 minutes, respectively (the planned design life was 32 minutes) (NASA, 2007b).

Technically, the Rock Abrasion Tool (RAT) on each of the 2 Mars Exploration Rovers cannot be defined as a drill, since it is a grinder. Nevertheless, its job is to create a shallow hole, in martian rocks, 45 mm in diameter and several mm deep (Fig. 3). The RAT has a mass of 489 g, is slightly larger than a soda can, and uses ~10 Watts of power (Gorevan et al., 2003a). As opposed to other drills, for which the goal is to acquire a sample or deploy sensors beneath the surface, the requirement of the RAT is simply to remove the weathered exterior of rocks and expose the pristine interior for examination by a suite of scientific instruments. Both RATs have been successfully operating on the surface of Mars since 2004.

There are also other forms of excavation that should be noted. Viking Landers 1 and 2, for example, had scoops mounted at the end of robotic arms and created a number of deep trenches as part of the surface-composition and biology experiments on Mars. The digging tool on the sampling arm could scoop up samples of material and deposit them into the appropriate experimental equipment. Some holes were also dug deeper to study soil that was not affected by solar radiation and weathering, both of which are important factors in the search for potential biomaterial. Surveyor 3 was the first lunar-landed mission to carry a surface soil-sampling scoop; it was used to dig 4 trenches up to 180 mm deep. Samples from the trenches were placed in front of the spacecraft’s television cameras for image transmission back to Earth.

The Mars 2007 Phoenix Lander will also have a scoop, or Icy Soil Acquisition Device (ISAD), shown in Fig. 4, mounted at the end of an arm (Bonitz et al., 2007). To aid in acquiring icy samples from the frozen regolith of northern martian plains, the ISAD possesses a number of features, including a small rasp-style cutting bit, which will plunge into the icy soil while rotating at high speed. The carbide rasp protrudes at an angle through a slotted load plate in the scoop floor.
and may pivot about a spring-loaded hinge line so that the force applied at the bit is dictated by the spring. After the ISAD’s blade features have been used to prepare the surface, the robotic arm preloads the rasp against the surface. At this point, a DC motor is energized to spin the rasp at approximately 5000 rpm. As it penetrates the surface, cuttings are thrown into the ISAD’s rear sampling chamber. A series of robotic arm wrist articulations, combined with vibration from a cam-impact feature on the bit’s shaft, transfers the powdered cuttings from the rear sampling chamber to the front open chamber where they can be imaged by a camera and transferred to science instruments. The ISAD sample acquisition performance was tested with frozen soil mixtures that had an unconfined compressive strength (UCS) of 45 MPa. With a new bit, four 15-second rasp operations will produce 1–4 cc of powdered cuttings, depending on surface conditions. One parameter that greatly affects the amount of sample acquired is the gap between the ISAD’s slotted load plate and the surface. Ideally, no gap would occur if the surface were perfectly prepared and there were no robotic arm–positioning error. However, there will most certainly always be some measurable gap. While the exact sensitivity is still being studied, gaps of 1–2 mm have been shown to cause at least a 50% drop in the volume of material acquired. Also, rasping with the current ISAD rasp bit design has been shown to remove a significant fraction of H2O in permafrost samples (Peters et al., 2007). It is hypothesized that a different cutting bit design would likely mitigate water loss.

The Mars Science Laboratory rover, pictured in Fig. 5 and to be launched in 2009, will have a small drill capable of penetrating a few cm into rocks and acquiring powdered cuttings samples. At the time of this publication, it is being designed and fabricated by NASA’s Jet Propulsion Laboratory.

FIG. 4. Phoenix Icy Soil Acquisition Device (ISAD) consists of a scoop and a small drill called the RASP at the back of the scoop. As the RASP plunges into the icy soil, its rotational motion throws the soil into the scoop.

FIG. 5. NASA Mars Science Laboratory rover scheduled to launch in 2009 will have a dust-removal tool and a small drill at the end of its robotic arm (indicated with an arrow). Note a radioisotope thermoelectric generator at the back of the rover. Photo courtesy of NASA/JPL.
The Sampling Drilling and Distribution system (SD²) of the European Space Agency’s (ESA) Rosetta mission, which is en route to a comet (arriving in 2014), has a drill that is designed to penetrate 25 cm into the subsurface of the comet and collect samples at predetermined or known depths. SD² will then transport samples to a carousel that will feed them to different instruments or stations, such as a spectrometer, a volume check plug, analytical ovens with medium and high temperatures, and a cleaning station. SD² designers had to solve a number of challenges as they pertain to operation in microgravity, such as autonomy (due to communication time delay), the unknown formation making up the comet, low temperatures in the range of $-200^\circ$C, and a requirement for little or no sample contamination (Mugnuolo et al., 1997).

As part of ESA’s planned 2013 Exomars rover (Fig. 6), an astrobiology mission, the Pasteur science payload is expected to have a sampling drill called DIBS (Drill-Integrated Package for Borehole Sciences). The drill’s full 2 m extension is to be achieved by assembling 4 sections (1 drill tool rod with 3 extension rods). The system’s goal would be to provide pristine subsurface samples to study the mineralogy of soil and rocks with a spectrometer inside the drill. The spectrometer package is expected to include the optical head of the spectrometer, a lamp to illuminate the borehole walls, and an optical fiber that brings the signal to the spectrometer. The multispectral images are expected to be acquired by means of a sapphire window placed on the lateral wall of the drill tool. (Coradini et al., 2007).

3. Principles of Drilling

Borehole excavation by drilling consists of 2 processes: the first is the breaking of the rock by the drill bit, and the second is the removal of cuttings from the bottom of the hole to the surface (e.g., using an auger or fluid) (Maurer, 1968; Clark, 1987; Karanam et al., 1998, Devereux, 1999). These processes can occur simultaneously or separately (e.g., drilling followed by use of a bailer to remove cuttings). If the cuttings removal is done with an auger, it is possible that the power required to auger the cuttings to the surface is orders of magnitude larger than the power required to break the rock. Figure 7 shows data from a test conducted in a very abrasive lunar regolith simulant. Note that the power due to drilling and auger operation can easily be decoupled. The drilling power of 25 Watts at the beginning of the test can be attributed almost entirely to the cutting process. Once the drill penetrated deeper into the sample, the cuttings removal by the auger started to consume power as well. The increase in auger power was linear with depth, and it is indicated as a straight line with a gradient of 1.5 W/cm. With extrapola-
tion of this gradient to a deeper hole, the same drill reaching 1 m into the sample would use 150 Watts to auger the cuttings out of the hole, or 6 times as much as the power consumed by the bit only. Note that, if cuttings removal is done via compressed gas (which in fact may be feasible on Mars or the Moon), there would be no need for an auger and, in turn, there would be no auger power.

Breakage of rocks is generally done by subjecting rocks to stresses that are above their tensile, shear, or compressive strength. Tension and shear failures are primarily involved with the destruction of intergranular bonds, whereas compression failure involves mostly grain crushing and breakage. Drilling processes consist of inducing all 3 types of stresses at different locations within the rock under the drill bit. In rotary drilling, the cutter first penetrates into the rock medium, and the bit crushes and fractures the rock. Crushing is caused by impact forces imparted by axial thrust from the weight on bit (WOB), while fracturing is caused by the shear cutting force. On the other hand, in percussive drilling, high-velocity impact is induced by the bit causing fractures that extend much deeper and wider than the depth and width of the bit itself. One of the key challenges to efficient drilling is to optimize not only the type of energy input (relative amounts of compression and shear loading) but also the drill bit geometry for a given rock type. Rock deformation is a nonlinear and inelastic behavior, and its analytical modeling is complex. No unified optimization approach is available that provides a predictive model to determine the behavior of a given rock under specified load characteristics and bit geometry.

In the design of extraterrestrial drills, there is a tendency to focus on bit design; but cuttings removal is just as important, as will be described below. This is because the cuttings, if they are not removed in time, will be ground into progressively smaller particles without extending the hole. In addition, poor removal of cuttings adds to the thermal issues, as cuttings trap approximately 75–80% of heat generated during the drilling process (Uhlmann et al., 2003). The remaining heat balance goes to the tool (10–20%) and the drilled formation, i.e., rock (5–10%). Finally, an inadequately designed cuttings-removal system can also increase the torque demands on the drill.

3.1 Breaking the formation

The action of the drill bit is a very complex process that has been studied both theoretically and empirically for centuries. Basically, an external force is required to fracture or shear the drilled formation in the most efficient manner possible. Bit design focuses on the shape, orientation, and type of material of the cutting surfaces. Since different types of formations have distinct fracture behaviors, bit designs are often tailored to the material they will be cutting. For strong brittle materials, rotary-percussive drilling is most efficient in terms of required weight on bit and specific energy. The drill bit in this case uses somewhat dull tungsten carbide cutters assembled in such a way as to form a footprint of a bit in the shape of an X. These bits are used every day in the construction industry for drilling holes in concrete. The rotary-percussive drilling method does not work very well in permafrost because of the more plastic nature of the formation at temperatures near the freezing point of water. For this type of formation, rotary drilling with a drill bit that has discrete cutters made of tungsten carbide or the harder, but more brittle, polycrystalline diamond compact (PDC) would be required. For situations in which it is required to recover a core of the material being drilled, the usual procedure is to use a bit that cuts an annulus around the core to be recovered. Since recovery of an undamaged core is important, rock cutting is usually achieved by rotation without percussion, with the use of a bit with discrete cutters (Fig. 8), or one whose cutting structure is formed of small diamonds impregnating a bronze matrix (a so-called diamond-impregnated bit). In an impregnated bit, the cutting action is precise and vibration free, which minimizes the risk of breaking the core, although rates of penetration are lower than with the more aggressive discrete cutter bits.

3.1.1. Operational parameters in rotary drilling. A general view of a drill bit is shown schematically in Fig. 8. The bit-cutting elements are shown at the bottom, while an auger

FIG. 8. A drill for extraterrestrial applications includes a cutting bit for breaking up the formation (in this case a coring bit is shown) and an auger for moving drilled cuttings to the surface.
with flutes for powdered cuttings removal is shown on the cylindrical surface. In addition to bit-design considerations, there are 2 operational parameters that affect rotary drilling progress: the rotational speed, usually measured in revolutions per minute (rpm), and the WOB, measured in Newtons (Fig. 9).

Drilling power and, in turn, the temperature rise of the bit and formation (and the core sample if one is present) are directly proportional to the rotational speed of the drill for a given WOB (Eq. 1). The higher the rotational speed, the more heat will be generated. Note that for all practical purposes, it can be assumed that drilling power is converted entirely to heat. This is because the energy of creating two new surfaces, \( 2\gamma \) (where \( \gamma \) is surface energy), is a minor fraction of the energy actually put into breaking the rock material.

\[
\text{RPM} \times \text{Power} \times \text{Heat}
\]  

(1)

If it is assumed that the cut per revolution is constant, the penetration rate is also directly proportional to rotational speed, and a faster speed will result in faster drilling. Lower rpm may result in higher auger torques, due to poor cuttings removal and possible choking (Section 3.2.1), and, to some extent, higher bit torque. Conversely, at higher rpm, the cutting action of the bit may be smoother, which results in a more efficient cutting process and a disproportionately faster rate of penetration. Rotational speed can also affect the removal of cuttings from the bottom of the hole and their efficient transfer to the auger flutes. Finally, certain rotational speeds can cause bit chatter (if the rpm is too low) or bit vibration (if a harmonic of the rpm is at a resonant frequency). Thus, in practice, there are rotational rates that are better than others; and many factors, such as auger diameter and allowable power, have to be taken into consideration when determining what rpm to use.

The stress exerted on a formation by the bit cutters is a direct function of the WOB. Since different formations have different mechanical behaviors, the UCS of a formation is often used to determine the required WOB. For example, basalt with a UCS of 200 MPa would require twice as much WOB as another basalt with a UCS of only 100 MPa. As such, \( \text{WOB}_{\text{threshold}} = \text{UCS} \times \text{Area}_{\text{cutter}} \) where \( \text{Area}_{\text{cutter}} \) represents the area of the cutters actually in contact with the rock. Since the cutter area increases as the bit wears due to the formation of a wear flat, bit life is directly proportional to the available WOB and, in turn, the weight of the spacecraft on the extraterrestrial body. Bit life is also a strong function of the cutter material. For example, if the WOB is already at its maximum and the cutter material is hard, the cutter will remain sharp for much longer; in turn, the drill bit will be able to drill deeper.

If the cutter material is soft, however, the cutter will prematurely dull, and the penetration rate will drop to zero. Figure 10 illustrates an example where a cutter edge became dull because of the development of the wear flat during the drilling process. In this case, the WOB was kept constant, and the drill penetration rate went to zero. Only with an increase of the WOB, to compensate for bit dulling, would the penetration rate have been maintained. This phenomenon is better illustrated in Fig. 11 for a diamond bit drilling 280 MPa basalt rock. Initially, at a WOB value of 500 N, the rate of penetration was 40 cm/hr. However, as the wear flat developed, the rate of penetration dropped and so did the power (since the bit was cutting less rock). At the 241 second time mark, the WOB was increased to 750 N, which resulted in a temporary increase in the rate of penetration and power. Soon, however, the rate of penetration dropped again due to bit wear, and the WOB had to be increased one more time to 950 N (time mark: 661 seconds). Note, for example, that for a martian lander/rover to provide this kind of reaction force to the bit, it would have to weigh at least 3 kN (~300 kg on Earth). The maximum depth that can be effectively drilled in a rock of given strength will thus be limited by the mass of the lander or rover or the maximum force that an actuator can provide to a drill. It follows that, if a mission requirement is to drill deeper, several bits would have to be taken along, as well as a robotic mechanism for changing them.

In softer formations, such as soil, a high WOB can also excavate material at a rate that exceeds the capacity of the cut-
3.1.2. Drilling energy vs. formation strength. As mentioned before, any drilling excavation process consists of 2 stages that can occur either simultaneously or separately. The first stage is breaking the drilled formation into small particles (cuttings), and the second stage is the extraction of cuttings from the hole. Thus, the total drilling power can be divided into the power required to extend (drill) the hole and the power required to lift the cuttings out of the hole. Normally, a drill system measures the drill motor current and converts this measurement into the combined drilling and augering power consumption. However, it is possible to measure the auger power and the drilling power separately, and this is already being done in the Drilling Automation for Mars Exploration (DAME) drill (Section 5.4.2).

By isolating the power consumed by the drill bit, it may be possible to infer the strength of the formation from the power consumed and the rate of penetration. These 2 variables can be combined into a single term known as specific energy (SE) of drilling (Eq. 2). The SE, measured in MJ/m^3, is the energy required to excavate (drill) a hole per unit volume. For example, drilling sandstone (i.e., cutting/crushing sandstone by a drill bit) might require 100 MJ per cubic meter of rock.

\[
\text{Power} \ (\text{Watt}) = \frac{\text{Rate of Penetration} \ (\text{cm}^3/\text{s}) \times \text{Hole Area} \ (\text{cm}^2)}{\text{Hole Area} \ (\text{cm}^2)} = \frac{1}{\text{cm}^3} \text{ or } \frac{\text{MJ}}{\text{m}^3} \quad (2)
\]

The SE is a function of many variables, such as the strength and abrasiveness of the formation, the drill bit design, and the aggressiveness of the drilling method. Note that some of these variables are inherent physical properties of the material being drilled, while others are products of the drilling method. Because so many variables affect SE, it is usually determined empirically and calculated by way of the above equation. SE can be conveniently used to compare different bits that are drilled into the same material under identical conditions. However, if all the drilling variables are held constant and only one of the inherent physical properties of the drilled material (such as UCS) is changed, then the SE could be used as a measure of this particular property.

The following example illustrates this case. The same drill bit was used to drill 3 different sandstones of known strength and ice-bound lunar simulant, FJS-1 (Kanamori et al., 1998) of unknown strength. In each case, the SE was calculated from the drilling data. The SE for the 3 sandstones and their corresponding UCS were plotted along with the SE of the lunar simulant as shown in Fig. 12. By extrapolating, the UCS for the lunar simulant was estimated to lie near 50 MPa, between soft- and medium-strength sandstones. To confirm the strength value of the simulant, a UCS test was performed, and data was tabulated (see Table 1). The average of the three tests was 42.6 MPa with a standard deviation of 11.4 MPa, which is very close to previously estimated 50 MPa from the drilling data.

A drill bit that will be eventually sent to the Moon or Mars could then be tested in a variety of formations to obtain a database of formation strength (measured from the laboratory strength tests) and the corresponding SE for each material. In turn, the SE data acquired from a planetary mission could then be compared to the database to estimate the strength of the drilled formations.

3.1.3. Drill diameter vs. drill power. The total power is a sum of the power required to drill a rock with a bit (i.e., the bit or drilling power) and the power required to auger the cuttings to the surface (auger power). In rotary drilling, the drilling power has 2 sources: the power to overcome the sliding friction and the power required to actually cut the rock (Zacny et al., 2005b; Zacny and Cooper, 2007a). The power equation is, therefore,

\[
\text{Power}_{\text{drilling}} = \text{Power}_{\text{cutting}} + \text{Power}_{\text{sliding}} \quad (3)
\]

The contribution of the friction to the total power is

\[
\text{Power}_{\text{sliding}} = (\text{Torque}) \times \left(\frac{2\pi}{60} \times \text{RPM}\right) = (\mu \times \text{WOB} \times \text{R}) \times \left(\frac{2\pi}{60} \times \text{RPM}\right) \quad (4)
\]
where \( R \) is the radius of the center of pressure of the cutting elements of the bit, which depends on the bit geometry and the distribution of cutters in the bit. For a core drill bit, because of the small difference between the inner and outer radius of the cutters, \( R \) can be approximated by the average radius, i.e., \( R = (R_{\text{inner}} + R_{\text{outer}})/2 \). For a full-faced bit, \( R \) is \( 2/3R \). Note that in Eq. 4 the only unknown is the coefficient of sliding friction, \( \mu \).

The energy required to break a rock in rotary drilling is commonly taken to equal the UCS of the rock (work per unit volume = force per unit area), which amounts to supposing that a force corresponding to the UCS acts so as to sweep through the entire volume of rock to be destroyed. Thus, the contribution of cutting (i.e., rock destruction power) to the total power budget is

\[
\text{Power}_{\text{cutting}} = \text{Work per revolution} \times \left( \frac{2\pi}{60} \times \text{RPM} \right)
\]

\[
\approx (\text{UCS} \times \text{Area} \times \delta) \times \left( \frac{2\pi}{60} \times \text{RPM} \right) \tag{5}
\]

where

- \( \text{Area} = \frac{\pi}{4} (D^2_{\text{outer}} - D^2_{\text{inner}}) \) for a core bit or \( \text{Area} = \frac{\pi}{4} (D^2) \) for a full-faced bit
- \( \text{UCS} = \) Unconfined Compressive Strength.
- \( \delta = \) depth of cut per revolution.
- \( \text{RPM} = \) rotational speed in revolutions per minute.

Thus, the final power equation is

\[
\text{Power}_{\text{drilling}} = \text{UCS} \times \text{Area} \times \delta \times \left( \frac{2\pi}{60} \times \text{RPM} \right)
\]

\[
+ (\mu \times \text{WOB} \times \overline{R}) \times \left( \frac{2\pi}{60} \times \text{RPM} \right) \tag{6}
\]

Equation 6 shows that the drilling power is directly proportional to the strength of the drilled formation, the area of a hole (and, in turn, drill bit diameter or the difference between outer and inner diameters for a core bit), depth of cut per revolution and rotational speed (which is in effect the rate of penetration), as well as coefficient of sliding friction, which on Mars is lower (Zacny and Cooper, 2007), and WOB.

Thus, it follows that smaller drill bits would require less power to drill. Note also that to break the rock, the rock’s strength, \( \sigma \), has to be exceeded as shown in Eq. 7. Thus, for a given rock strength, smaller-diameter drill bits would require smaller WOB than larger-diameter drill bits.

\[
\sigma < \frac{\text{WOB}}{\text{Area}} \tag{7}
\]
the hole by air drawn in from the outside of the chamber. 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 caused the bit to “skid” on the surface of the rock powder and the rate of penetration to drop 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, which allowed the clearing of the cuttings from the bottom of the hole and the bit to penetrate the rock. The result was an immediate increase in the rate of penetration. This experiment showed that it is imperative for any successful drilling apparatus to have a very effective cuttings-removal system. It also shows that dry drilling will inherently be less efficient than drilling with gas flushing.

3.2.1. Cuttings removal via augers. There are 3 critical areas that need to be considered when designing a bit for a rotary drill for efficient cuttings removal. These areas, indicated in Fig. 14, include the cutting tooth geometry and placement (1), “junk” slots (2), and the auger (3). The cuttings removal starts at the bit itself (Number 1 in Fig. 14); the cutter is responsible for sweeping the cuttings to the outside of the bit. For example, this can be enhanced by placing the cutters at a side rake angle to achieve an action similar to that of a snowplow pushing snow to the side of a road. Once cuttings are pushed to the outside, further movement of cuttings up the hole will progress through so-called “junk” slots (Number 2 in Fig. 14). If junk slots are misaligned with the edge of the auger flute or are too narrow, they will slow—and may even stop—the flow of cuttings and, in turn, the drilling process. Once cuttings have passed through the junk slots, they are passed on to the auger (Number 3 in Fig. 14).

The use of augers in drilling is well known, though there is still a lot of empiricism in their design (Carleton et al., 1969). Augers generally work well when conveying dry, loose granular material over short distances and at high rpm; in turn, they do not work well at low rotational speeds and for small-diameter drills (~a few cm) (Mellor, 1981), i.e., parameters that are considered for extraterrestrial drilling.

Auger efficiency and throughput are complex functions of many interrelated parameters, such as pitch angle, number of flutes, flute width, auger diameter, type of surface coat-

![FIG. 14. The areas that need to be considered when designing a drill for efficient cuttings removal include (1) tooth geometry and placement, (2) junk slots, (3) and auger.](image)

![FIG. 15. Experimental data showing Auger torque in N m 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 (Zacny and Cooper, 2007b).](image)
soil) at a lunar base at lunar gravity conditions on NASA’s KC-135 aircraft (Sullivan et al., 1994). They found that the choking velocity (in the vertical transfer) and the saltation velocity (in the horizontal transfer) required at lunar gravity were reduced to $1/2$ to $1/3$ of the velocity required at 1 g. (Choking and saltation velocities are minimum velocities that keep particles aloft.) This means that with 1 kg of gas 6–9 tons of regolith can be lifted at $[1/6] g$ (surface gravity on the Moon). Since the amount of gas necessary to provide this sort of pressure is fairly modest, it could be brought from Earth in pressurized canisters, or in the case of Mars, it could potentially be obtained by an in situ compressor.

Another possibility is to use combustion products from a small rocket engine as the cuttings-removal fluid (Zacny et al., 2007c). Analogous to terrestrial pneumatic drilling that uses chemical fuel (i.e., gasoline and air), a pneumatic drill, which has been proposed 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 could 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 could be tapped for carrying out pneumatic tool operations, including drilling. Gas generation for a pneumatic drill, for example, can be provided by partial decomposition of a new, high-specific impulse, non-toxic, low-freezing point, monopropellant called NOFB developed by Firestar Engineering under the NASA Mars Advanced Technology program (Mungas, 2007, personal communication). Hydrazine, a commonly used monopropellant for the maneuvering thrusters of spacecraft or in terminal descent of spacecraft (e.g., used in both Viking landers as well as the Phoenix lander launched 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 descent stage of a lander, would make interpretation of organic analysis more difficult (Chyba et al., 2006).

There are also a number of significant benefits to using a pneumatic system, as opposed to a more conventional electro-mechanical planetary drill. As already mentioned, gas circulation can be very effective in lifting the drilled cuttings to the surface. Clearing the cuttings from a drill hole has many advantages that include significantly lower operating power and cooling of the drilled formation. In addition, since there is no need for an auger to remove the cuttings, the drill can be made to extend telescopically, which reduces its mechanical complexity, volume, and mass.

Figure 17 shows a concept of such a pneumatic drill. There are several advantages in this type of design. Since the drill doesn’t require an auger, as mentioned earlier, it can extend

![FIG. 16. Gas jet produced by releasing $1 \text{ dm}^3$ of gas at 30 torr differential pressure successfully clears particles from the bottom of a 15 cm deep hole. The ambient pressure was 5 torr (Zacny et al., 2005b).](image1)

![FIG. 17. Pneumatic Telescopic Drill Concept. Gas may be used to provide downward drill thrust and to extend the telescopic drill. As the gas exits the drill, it would blow cuttings out of the hole (Zacny and Mungas, 2006a).](image2)
telescopically, which makes the drill system simpler, smaller, and lighter (there are no drill string manipulation mechanisms with joints and locking mechanisms). In addition, an auger accumulates cuttings at the rim of the hole; and, once the drill is pulled out, these cuttings tend to fall back into the hole. With a pneumatic system, the cuttings will be ejected at a distance from the hole. However, to prevent dust from settling on the surface of the lander or rover, a deflection plate will have to be installed (shown just below the drill drive in Fig. 17). Since cuttings removal will be achieved very effectively via gas flow, the rate of penetration (for the same power input) will be higher. Of course, having no auger will make the drilling process much more efficient, since an auger requires high torques to operate effectively. A pneumatic system can provide rotation as well as drill thrust; the NASA Ames wireline pneumatic drill uses pneumatics to engage the WOB mechanism and electric motor to provide rotation (Briggs and Brown, personal communication). In addition, the pneumatic drive can be designed to provide percussive motion in addition to rotation (the most efficient hammer drills on Earth use pneumatics). The biggest advantage of using a pneumatic drill is a faster penetration rate at reduced thrusts in hard and brittle formations, which translates into less heat input into the formation. In addition, pneumatic drills have a more robust design and, in turn, are less susceptible to fracture. Note also that, with an auger, a small deflection of the drill head off vertical can cause large torques due to the rubbing of the auger against the side of the hole. The telescopic drill string, which will have a smaller diameter toward the top (Fig. 17), will avoid this problem.

3.2.3. Cuttings removal via water-ice sublimation. A very interesting related possibility for lifting cuttings out of a hole (and, in turn, making an auger unnecessary) occurs if the formation being penetrated contains water ice. In experiments on ice-containing rocks and soils, it was observed that, when drilling under conditions of low pressure, the heat generated by the drilling process caused the ice to sublime immediately into a vapor (Zacny et al., 2004). At low ambient pressures (~4 torr), the volumetric expansion that occurs in converting ice to vapor is on the order of 150,000 times. Thus, even relatively small concentrations of ice in soils or in the pore spaces of rocks can generate enough water vapor to blow the cuttings out of the hole (Fig. 18). The effect of cuttings removal on the rate of penetration and power is quite substantial (Fig. 19). Since the water is converted to vapor at the drill bit, the cuttings being blown out of the hole are, in effect, freeze-dried, so they do not stick to the drilling equipment or to the hole walls as they leave the hole. In addition, heat removed through the latent heat of sublimation helps to keep the formation and the core (if present) cold. Also note that if it is a mission goal to obtain water or to measure the water fraction in drilled cuttings (as opposed to a core), sublimation should be avoided. This could be achieved by keeping the drilling power low and intermittently stopping the drilling process to allow for the formation and the drill to cool down.

Figure 19 shows that, when the pressure was raised above the triple point under experimental conditions, boiling ceased and cuttings were removed only via the auger. During this time, the power tripled, while the rate of penetration dropped by 50%. In addition, the temperature of the drill bit and the formation increased. This is because the latent heat of sublimation that would have consumed the heat produced during the drilling process (friction heat) was absent at higher pressures.

Thus, for the process of water-vapor flushing to take place, it is important that the ambient pressure is below the triple point of water so that no liquid water can be formed. (Note, also, that the process will only be effective if ice is present in the formations being drilled.) While many parts of Mars have atmospheric pressures that are below the required limit, some of the lower-lying areas have pressures above the triple point. This must be taken into account when deciding whether the sublimation of ice is likely to help the drilling process. Additionally, even if an insufficient amount of 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.
4. Coring vs. Solid Front or Full-Faced Drilling

In general, drill bits can be divided into coring bits and solid front or full-faced bits. Coring bits, as the name suggests, acquire a sample in the form of a core (mostly in cylindrical shape), while a full-faced bit excavates the entire volume of the hole (Fig. 20). As described below, the tradeoffs between these 2 methods of drilling are multifaceted, and the decision as to which to use in a particular application requires careful consideration.

From a science standpoint, a core provides much more information than do drilled cuttings. A core can be split in half to reveal an uncontaminated, virgin surface. It can be photographed or viewed under a microscope to determine the morphology of the sample and even search for fossilized evidence of life (e.g., fossils). A thin section for petrographic analysis could be more easily made from a core than from ground-up cuttings (Anderson, 2007, personal communication; Dreyer et al., 2007). Other instruments (X-ray fluorescence, for example) can also be used to determine the elemental composition of a core simply by taking a reading from the core surface. A core may also be crushed to a desired particle size and the powder analyzed by, for example, X-ray diffraction to identify minerals. Thus, there is no doubt that a core is much more useful than cuttings.

Note, however, that cores are often fractured when they are retrieved. Sometimes they are fractured because the drilled formation was already fractured. (If a formation is consolidated, then an intact core is more likely.) Other factors include core diameter (a smaller-diameter core is more likely to fracture mainly because it is weaker in shear), drilling method (rotary is better than rotary percussive), drill bit design (excessive rubbing of cutters against the core surface is detrimental), and methods of cuttings removal (dry drilling as opposed to pneumatic generates a large amount of cuttings that wedge between the rotating drill and the core, which tends to shear the core).

From the drilling power and torque standpoint, drilling for a core is also much more efficient than drilling out the entire volume of a hole. Since a core bit cuts only an annular space in the ground, the power and WOB (i.e., thrust applied on the bit) are much lower.

Figure 21 and Fig. 22 show the rate of penetration and the drilling power plotted as a function of the rotational speed (rpm) for the full-faced bit and the core bit pictured in Fig. 20, respectively. The diameter of the full-faced bit was 38 mm, while the core bit had an outside diameter of 38 mm and an inner diameter of 25 mm. The full-faced bit required twice the WOB (150 N as opposed to 60–80 N); and the rate of penetration, as well as the drilling power, were at least twice as large as for the core bit.

From the mechanical design and robotics perspective, however, obtaining a core is a much more complex endeavor. It requires a core break-off mechanism inside the drill, a core catcher, and a pushrod inside the drill string to push the core out. To achieve this, electrical leads have to be passed through a slipring assembly and into the drill string, and if the drill is deep and requires a number of separate drill segments, each segment would also need to have electrical connectors on each end. For deep drilling, the making and breaking of segments multiple times can be very time consuming and also risky. In most of the coring drill designs for extraterrestrial applications, the drill is designed only to acquire a core of relatively short length. Thus, after drilling to a depth equivalent to the core length, the drill string must be pulled out of the hole and, after delivering the core to the sampling tray, lowered into the hole again, which adds still more complexity to drill operations. If the drill is deployed from an arm, getting the drill back in the same hole might be tricky if the arm-positioning accuracy is limited. For example, if the hole diameter is 10 mm and the positioning accuracy of the arm is only 5 mm, the drill might easily be placed to the side of the hole and not in its center. Another problem with pulling the drill out of the hole is that cuttings accumulated on the surface of the auger might fall back into the hole. From the cross-contamination viewpoint, this might be an issue.

From a drilling standpoint, a full-faced bit requires more power and higher WOB than a coring bit of the same diam-

![FIG. 20. Examples of a full-faced bit (top left) and the resultant hole (bottom left) as well as a core bit (top right) and the resultant core inside the hole (bottom right) (Zacny et al., 2007a).](image-url)

![FIG. 21. Drilling data for a 38 mm full-faced bit.](image-url)
eter. In addition, it has to solve a problem associated with the excavation of the hole center. At the center of the hole, the drill bit does not rotate and, thus, relies exclusively on downward pressure to break the formation. It is therefore critical to make the center cutter from the hardest possible material (e.g., diamond). If this center cutter gets dull, it becomes a load-bearing member of the bit and, in a practical sense, can limit or even halt the advancement of the drill. A benefit of having a full-faced bit is that the drilled hole may be made smaller than for a core drill (the diameter of a core drill is limited by the smallest core diameter that can feasibly be obtained, while for a full-faced drill, no such requirement exists), and this of course would translate into lower power and WOB. However, it is doubtful that a full-faced bit can match the performance of a coring bit, in terms of longevity and reliability, mainly because of the center bit issue. In spite of the lower scientific payoff and lower performance, the greater simplicity of full-faced drilling is often the driving factor in designing extraterrestrial systems.

Since there is no core sampling with a full-faced bit and, in turn, the drill segments are hollow, they may house down-the-hole instruments for in situ analysis. For example, the Honeybee Robotics CRUX drill was designed to accommodate a neutron probe, shown in Fig. 23, for in situ identification of lunar hydrogen (Elphic et al., 2006). A borehole IR spectrometer, made to fit inside a 25 mm drill stem, has also been developed by Smythe (Smythe et al., 2007). The spectrometer/IR combination is intended to be used in reflectance spectrometer mode to monitor H2O and CO2 content, as well as iron and carbonate mineralogy.

A full-faced drill system may also be instrumented with a sample acquisition chamber. In its simplest form, this may be nothing more than a small internal space that can open, acquire a sample of a known volume, and close. A benefit of this method is that the sample is obtained from a known depth. The “Sniffer” drill concept put forward by Paul Mahaffy of NASA’s Goddard Space Flight Center, shown in Fig. 24, can collect a sample at a known depth and heat it up inside the sample chamber with a semi-permeable ceramic heater until vapor is released. The vapor can then travel through a tube embedded in the non-rotating part of the drill stem to a mass spectrometer on the drill base where analyses can be performed.

5. Constraints on Extraterrestrial Drilling Systems

As mentioned in the introduction, extraterrestrial drilling is an extremely challenging endeavor. This section explores some of these challenges. Constraints on drill systems can be divided into those imposed by the planetary body itself and those imposed by the mission, such as engineering, budget, and science requirements. The sections to follow will address these issues in greater detail. Note that some of the drilling constraints as they pertain to Mars have been dealt with before (Briggs and Gross, 2002; Guerrero et al., 2005b; Zacny and Cooper, 2006c; Bar-Cohen and Zacny, 2008; and other authors of this paper).

5.1 Constraints imposed by the drilled media

One of the most important parameters that determines the speed of drilling, the required power, the durability of the drilling bit, and the ability to acquire and deliver the produced sample is the type of medium that is being drilled. In addition, the type of formation, as well as its hardness and abrasivity, will dictate the method of excavation, as well as the cutter tooth material and drill bit geometry (e.g., Liu et al., 2007). Extraterrestrial media that can be encountered when penetrating the surface of various planets include rocks, ice, permafrost, regolith, and others. The medium can be distinguished by its hardness, level of consolidation, and many other physical and chemical characteristics that are dependent on the temperature, pressure, gravity, and other factors. Rocks are solid, cohesive aggregates of one or more...
types of minerals that have formed as a result of various geologic processes. Rocks are classified not only according to their mineral content, but also in accordance with their mode of formation (igneous, sedimentary, metamorphic), chemical composition, grain size, and physical appearance. Other forms of media can be unconsolidated loose rock fragments of various sizes and may be embedded in soil that resulted from weathering effects and bombardment by meteorites. For example, regolith (from the Greek: “blanket rock”) is a layer of loose, heterogeneous material covering solid rock. Note also that permafrost or permafrost soil is soil at or below the freezing point of water (0°C or 32°F) for two or more years, and ice does not necessarily have to be present for soil to be termed permafrost. Rocks vary in hardness; one of the hardest rocks is basalt, which reaches hardness levels that are well above 100 MPa.

In the search for life in the universe, one may prefer to sample certain media over others. Rocks with some degree of porosity are more likely to contain biological materials, and in areas with extreme environments on Earth, microorganisms often live within the pores of rocks. Oxidation, UV exposure, and meteorites, however, actively damage such formations, and the use of rock abrasion tools can be helpful in exposing pristine areas of rocks and other media. Permafrost presents another important class of materials of astrobiological interest. Field observations on Earth indicate that pure ice is not as likely to contain biologically interesting materials as mixed ice and sediment. However, sampled media that consist of permafrost can be very hard, and they pose some challenges when using drills.

One of the characteristics of drilling exploration boreholes on Mars or other extraterrestrial locations is that the choice of drilling sites will be limited and the nature of the ground to be penetrated will be uncertain. Under such circumstances, it is more important to have a drill that can make progress in any terrain rather than one that is optimized for a particular material. As for all drilling situations, choice of drill bit and drilling system will be based on a need to satisfy 3 criteria simultaneously: to be able to advance at a reasonable rate under a likely limited feed force (WOB), to have an acceptably long life before wear stops progress, and to avoid getting stuck. The nature of the terrain being penetrated alters the relative importance of each of these criteria.

The hard rocks, such as basalt, place demands on tool life and the ability to penetrate under limited WOB. In most cases, having a very sharp-toothed and aggressive bit allows for penetration even at low feed force. Even modest amounts of wear, however, generate wear flats on the cutter teeth that spread the load on the rock until the pressure exerted at the tooth-to-rock contact is no longer sufficient to exceed the crushing strength of the rock, and penetration ceases. For a rock such as basalt, with a strength under the highly constrained compressive stress field that occurs under a drill bit tooth that may easily reach 40,000 psi (280 N/mm²) and an available feed force from the drill of, say, 200 N, the allowable wear flat area will be 0.7 mm²; for a core cutting bit with inside diameter of 25 mm, outside diameter of 37 mm, and 4 teeth made from sharpened “tiles” of PDC, the width of the wear flat will be only 29 microns—the width of a hair—before drilling stops. Even moderately abrasive rocks can produce this degree of wear in a short distance. If the hard material exists in discontinuous form, as pebbles in a more easily drilled matrix, considerable damage may be done in the form of chipping damage as the cutter teeth pass from the soft to the harder material. Indeed, the wear can be more severe under these conditions than if the hard material had been continuous.

To deal with this problem, 2 general approaches are available. The first is embodied in the concept of the “diamond-impregnated bit” in which small diamonds are embedded throughout a softer matrix (usually a bronze). In operation, the bronze wears away so that the diamonds are exposed and cut the rock. However, the stream of abrasive cuttings wears away the bronze, and so the diamonds are undermined and fall away, ideally just as they are becoming blunt and cease to cut. Further erosion of the bronze exposes new, sharp diamonds. Clearly, there is a balance to be found between the hardness of the rock being drilled and the wear resistance of the bronze (i.e., the harder the rock, the softer the bronze). Because of the steady loss and replacement of the diamonds, the rate of penetration of such bits is relatively constant until the entire volume of diamond-impregnated bronze is worn away.

The second approach is to use an impacting or hammering action at the bit. This effectively increases the force available at the bit without increasing the average support force applied to the drilling machine. Since it is the overall impulse applied to the bit that must be balanced by the impulse applied by the support system to the drilling machine, an impacting mechanism that supplies (for example) a pulse of 2000 N for 100 milliseconds to the rock every second can be balanced by an average feed force of 200 N. The effectiveness of this approach will be appreciated by anyone who has used a consumer power drill to drill masonry using the “hammer” option after using rotary motion only.

Soft rocks or soils do not pose as severe difficulties from the wear point of view as do the hard rocks, though, as noted above, “pebbly” deposits can cause chipping damage to the cutters. Problems can arise if the material is so easy to penetrate that too many cuttings are produced and the bit and cuttings-removal system choke. The best means of preventing choking is to control the drilling machine so as to limit

FIG. 24. The purpose of the “Sniffer” drill is to acquire a sample at given depth and then heat it until vapor is released to be collected up the drill string.
the maximum rate of penetration; attention to making the cuttings evacuation path as smooth as possible is also important. In many cases, the greatest problem is hole stability and hole straightness, both of which can lead to the bit and drill stem becoming stuck. Sticking arises from several causes. In very soft ground, such as sand, the hole can collapse as it is being drilled; and even if the sand is not sufficiently cohesive to prevent the bit from being pulled out of the hole (with a sample that may simply fall out of the core barrel before it is recovered), it may be impossible to re-enter the hole again. The presence of mixed hard and soft materials (basalt blocks or pebbles in sand or clay) causes the bit to skate sideways and to produce a crooked hole if the contact surface is even slightly oblique; this again can cause the drill to get stuck. In such circumstances, limiting the feed force is effective in maintaining hole straightness, and providing a bit with a flat face and side-cutting ability on the flanks is helpful. In any case, to combat the risk of getting stuck in one or all of the above-mentioned scenarios, it is strongly advised to make the drill stem with as smooth a surface as possible and to provide the bit with an array of backward-facing teeth at its largest diameter so that it can drill its way back out of the hole.

Finally, there is the possibility on Mars, in places where the atmospheric pressure is above the triple point of water, that the subsurface contains a significant proportion of ice, either as ice-bound soil or as ice in the pore spaces of harder rocks. The greatest challenge in drilling ice-containing materials is that the temperature at the bit may rise until the ice melts. This causes a variety of undesirable effects. The first is that, once melting has occurred, any reduction in the power applied to the bit may allow the temperature to fall below freezing again, in which case the bit will become stuck by becoming frozen in place. If the material being drilled contains any clay-like material (or even finely ground cuttings from hard rocks), the material will become sticky and resist being removed from the hole. Under such circumstances, it is almost impossible to clear sticky, but re-frozen, cuttings from around the drilling assembly. A further consequence of the thawing and re-freezing phenomenon is that a mixture of ice and cuttings can fill the spaces between the bit teeth that normally serve to allow cuttings to flow away from the bit face. The bit face then becomes coated with a smooth, low-friction surface of ice and cuttings that completely covers the bit face and prevents the cutting teeth from reaching the work front. Penetration then ceases completely, and the problem is almost impossible to clear without removing the bit from the hole and warming it to melt the ice.

Several of the phenomena described above may occur in combination and be very difficult to handle. Unfortunately, the range of possibilities is very large, and it cannot be emphasized too strongly that any bit and drill system combination should be tested in a wide range of conditions to try to identify difficulties and find solutions before committing to a particular design.

5.2. Constraints imposed by the environment

The planetary environment in which a drill system will operate is the main driver in the design of a drill system. Extreme temperatures, as well as large daily thermal fluctuations, require the selection of materials with similar coefficients of thermal expansions. Under low pressures, cooling via convection will be much reduced. Under low gravity, the WOB provided by lander reaction force will be limited and, in turn, limit the maximum depth of hole possible (Section 3.1.1). The low gravity on comets and asteroids is an extreme case. Here, the weight of a drill system would be minuscule, and the only way to achieve sufficient WOB for drilling would be to anchor the drill platform to the surface. Two other important environmental factors are dust and operation under vacuum; of which the former requires the development of very capable mechanical seals, while the latter creates difficulty for moving/sliding mechanisms.

5.3. Mission and science-driven constraints and criteria

Some mission constraints are internally imposed by project managers, system engineers, and budget, while others are required for the acquisition of appropriate samples; constraints may include allowable levels of cross contamination between 2 different samples or the maximum temperature a sample can reach during sample acquisition. Constraints imposed by mission design may include the maximum energy a drill process can use and the time allotted to acquire a sample or to reach the target depth. The average power and maximum power, torque, mass of the drill, and size of the drill in the stowed position also need attention. In general, very little power is available to an extraterrestrial robotic drill system when compared to its terrestrial counterparts.

Scientists require a sample with no forward contamination from Earth, minimal cross contamination between samples taken from different sites, no thermal alteration, and sometimes no physical alteration (i.e., powdered cuttings). Samples must be taken from various depths below the surface of the ground or a rock. It is important for the acquired sample to be chemically unaltered, even if physical alteration (from a solid rock to powder) occurs. Chemical alteration might occur when the sample reaches very high temperatures. In the simplest example, it could be water ice changing its phase from solid to liquid or vapor. Since planetary drilling will be dry, the only means of sample alteration will be through temperature increase (if water were used, chemical reaction between water and drilled rock could take place). Thus, it is important that the temperature of the sample is kept within a certain range.

As previously mentioned, cuttings trap approximately 75–80% of the heat generated during the drilling process (Uhlmann et al., 2003), and it can be assumed that all the power delivered to the bit and used to drill the formation is converted to heat. Therefore, if it takes 25 W to drill a rock, approximately 19 W will be used to heat up the cuttings. On Earth, gaseous convection is the largest contributor to heat transfer between granular materials and their surroundings (Presley and Christensen, 1997). On extraterrestrial bodies with low atmospheric pressure (Mars) or vacuum (the Moon and asteroids), there is little or no gaseous convection; therefore, the temperature of the cuttings can reach very high values. Thus, if the sample thermal alteration is a critical issue, the mission probably would call for acquiring a core rather than cuttings. Even a core, though, heats up.

5.3.1. Temperature increase of a core. To determine the exact temperature increase of a core, the fraction, $f$, of heat...
that flows into the core needs to be determined. To determine the fraction, \( f \), a number of tests were conducted in limestone and basalt rocks at both Earth atmospheric pressure (760 torr) and martian pressure (4 torr) conditions. A thermocouple was first embedded inside that portion of the rock that would become the core. In Fig. 25, the thermocouple was placed in such a way that it measured the temperature some 2 mm from the core’s outer surface during the drilling operation. The peak temperature recorded was then subtracted from the initial rock temperature to determine the change in the core temperature due to the cutting action of the bit. The results are plotted in Fig. 26 and Fig. 27.

Figure 26 shows the change in the core temperature as a function of power for the same core bit drilling limestone and basalt rocks at 760 torr and 4 torr atmospheric pressure. The general trend shows that the \( T_{core} \) increases as the drilling power increases. However, when the same temperature data are plotted as a function of the SE, the data form almost a straight line. This indicates that the SE term should be used to evaluate thermal effects during a drilling process rather than just the power.

Specific energy is the energy required to drill a volume of rock, and it takes into account the rate of penetration and the cross section of the drilled hole (for a full-faced bit, it is the entire cross section of the hole; whereas for the core bit, it is the annular area cut out by the bit). This relationship is shown in Eq. 2. Consider, for example, 2 cases. In the first case, it takes 1000 seconds to drill a 1 m deep hole with a power of 10 Watts, while in the second case, it takes 10 seconds to drill a 1 m deep hole with a power of 100 Watts. Assuming the area of the hole to be 1 cm² in both cases, the SE is 100 MJ/m³ in the first case, while in the second it is 10 MJ/m³, or 10 times lower. Thus, 100 MJ of heat flows into each 1 m³ of formation in the first case, while in the second only 10 MJ of heat flows into 1 m³ of formation (note, though, that in the first case the power is 10 times lower).

Equation 8 shows the relationship between the change in the core temperature as a function of rock properties and drilling parameters. It assumes that a fraction, \( f \), of the total power input into the formation flows into the core. The fraction, \( f \), is very difficult to determine theoretically; however, it is much easier to obtain it empirically. Thus, using the data from Fig. 26 and Fig. 27, taking into account rock physical properties, and substituting into Eq. 8, we calculate the \( f \) to be approximately 5%. Thus, 5% of total drilling power in the form of heat flows into the core.

\[
\Delta T_{core} = \frac{f \cdot Power}{c \cdot \rho \cdot A_{core} \cdot ROP}
\]

where

- \( f \) = fraction of energy flowing to the core
- \( c \) = specific heat capacity of rock
- \( \rho \) = rock density
- \( ROP \) = rate of penetration

One way to make sure the core does not exceed a certain temperature is to stop drilling temporarily. This could be achieved by lifting the drill off the bottom of the hole while reducing the rpm. This is illustrated in Fig. 28. If a maximum core temperature raise cannot be higher than, say, 30°C, the drilling needs to stop when that \( \Delta T \) of 30°C is reached. It is, however, possible to start drilling again once the \( \Delta T \) of the core has decreased to below 30°C (for example 20°C). In this particular example, a duty cycle of 50–50 might work. That is, drill for 50% of the time until \( \Delta T \) reaches 30°C and then stop drilling for 50% of the time until \( \Delta T \) drops to 20°C (and then commence drilling again). These intermittent stops would also need to be taken into account when considering the time required to reach a target depth. For example, if a mission allocates 4 hours for a drill to reach a depth of 10 cm and, in addition, puts a \( \Delta T \) limit on a core of 30°C, then the actual drilling time would be only 2 hours, since the required duty cycle of 50–50 would call for 2 hours of cool-down period.

5.4. Autonomy imposed by distance

Probably the biggest challenge to robotic planetary drilling is the one imposed by the sheer distance from Earth and, in turn, the unavoidable light time delays. Large communication time delays require autonomous operation of the drill. As mentioned earlier, the first autonomous drilling was
achieved by the Soviets in 1976 on the Moon (with a light time delay on the order of 1–2 seconds). The drill essentially executed a number of preprogrammed commands (Barmin and Shevchenko, 1983).

5.4.1. Rock Abrasion Tool (RAT) on Mars Exploration Rovers. The Rock Abrasion Tool (RAT) on the Mars Exploration Rovers, described previously in Section 2, is a good example of the current level of autonomy for a mechanical system operating on the surface of another planet (Fig. 29 and Fig. 30).

The RAT employs 3 actuators to affect grinding in a planetary arrangement. Rotation of the bits about their centers, orbiting of the bits about their common center, and plunging of the bits into the rock are each independently actuated. The grind operation may be divided into several steps. These include selecting the target rock, selecting the area on the rock to grind, and performing an actual grind. Initially, scientists decide which rock would be the most interesting based on spectral data. Once the target rock is selected, engineers on Earth locate the safest area on the rock to grind. Upon selecting the correct location, the rover’s robotic arm positions the RAT over the rock, and the grind operation begins. These 2 operations are done autonomously.

On Mars, the light time delay is on the order of 20 minutes. In a fashion similar to the Soviet approach, the RAT instruments on Mars have a number of programmed routines such as calibration, “seek-scan,” and grinding (Gorevan et al., 2003a). The seek-scan is the most elaborate routine, whereby the grinding bit, while rotating at very low rpm, slowly approaches the surface and stops when it encounters resistance. The bit then revolves 360 degrees to determine whether indeed this is the highest point on the rock. If it is not, the bit moves back and revolves again until it finds the highest point. If it is the highest point, the RAT then executes a grind, whereby the bit spins at 3000 rpm and revolves at 2 rpm, and upon completion of a single revolution it steps down 50 μm, as shown in Fig. 31. During this time, electric current from the grinding motor is closely monitored (along with the current from other actuators). As this current approaches some initial threshold, the revolve speed slows from the 2 rpm rate to try to prevent the grinding motor from approaching a stall. Additionally, if this current were to reach an even higher threshold, the bit would back off 50 μm to relieve the pressure on the grinding wheel. This automation system relies entirely on the feedback from the RAT actuators (e.g., torque, power, position, and the rate of penetration). Thus, the more sensors and feedback data there are, the better drill automation will be.

Note that, since the RAT performs a mechanical operation on a rock, deductions can be made about the rock’s physical properties. The energy consumed by the RAT’s primary actuator while grinding a given rock, apart from losses such as frictional drag in the mechanism, is normalized to provide a representative specific grind energy in terms of Joules per cubic millimeter for each grinding operation. The calculation is performed over the last 0.25 millimeter of a grinding operation, where it is possible to make an accurate estimate of the volume of rock removed. The resulting specific grind energy is considered an index of grindability of a rock. An index such as grindability describes the performance of the device on the given material in a given environment (Metzger, 1986). Decoupling device and environment characteristics leaves a bulk description of the given material’s physical properties, with respect to a grinding operation (Bartlett et al., 2005). Deconvolving indications of separate standard rock physical property values, such as that of shear strength or hardness, from this bulk property is non-trivial. This is because rocks are not homogenous; they have different porosities and are comprised of multiple materials of different physical properties, especially with variation on spatial scales relevant to grinding. Figure 32 shows RAT grind history in the Meridiani Planum region of Mars, with values of specific grind energy of “RATed” rocks. It could be said that Lion Stone rock, with specific grind energy of 18 J/mm³, requires more energy to grind than, for example, Manitoba rock with the SE of 0.36 J/mm³. For a more thorough investigation of rock physical properties from RAT data, please refer to Myrick et al. (2004).

5.4.2. Drilling Automation for Mars Exploration (DAME) drill. As successful as the RAT has been, actual autonomous

FIG. 27. The change in core temperature as a function of specific energy for the same core bit drilling limestone and basalt rocks at 760 torr and 4 torr atmospheric pressure.

FIG. 28. Change in the core temperature (ΔT) as a function of time. It is possible to keep the core temperature below a certain ΔT by stopping the drilling process and allowing the bit and formation to cool down. The duty cycle (drilling-stopping) will be based on the allowed ΔT and drilling power.
drilling with a bit that penetrates more than a few mm below the surface is considerably more complex and challenging. For example, take the case of managing drilling torque. Drill torque is the sum of bit torque that arises from the resistance of the formation to the breaking action of the bit and auger torque from the resistance of cuttings as they move up the auger flutes. If the total torque increases on a drill system, the cause may be that the bit is encountering a harder formation or the auger is becoming choked with cuttings. Only by decoupling the 2 torques from each other is it possible to determine whether the problem is caused by the auger or the bit.

The DAME drill, shown in Fig. 33, is a system designed specifically to investigate methods of automated drilling for Mars. This 10-meter-class drill was built with a bit torque sensor integrated inside the hollow auger, with the purpose of measuring the bit reaction torque (Glass et al., 2006). The auger torque could then be calculated by subtracting the bit torque from the total torque measured from the current of the rotation motor in the drill head. Figure 34 shows the bit torque, the auger torque, and total torque as a function of depth in a DAME drilling test conducted on Devon Island, in the Arctic, in the summer of 2006 (Zacny et al., 2007e). From the graph, it can be clearly seen that, at a depth of close to 300 cm, the auger contribution to the total torque was 5 times greater than the bit contribution. Thus, it was concluded that the auger was becoming clogged with cuttings, and the drill rotational speed had to be increased to improve the flow of cuttings.

The DAME project built upon the experience of its predecessor, the Mars Astrobiology Research and Technology Experiment (MARTE, Section 6.3.3) drill control software (Stoker et al., 2004). The main improvements in DAME were the addition of diagnostic, monitoring, and control elements for operating the DAME planetary-prototype drill. Humans troubleshoot and control drills by tracking and logging sensors and parameters, by monitoring sound and vibration of the shaft, and by using established fail-safe limit checks. The diagnostic approach used in DAME created software modules that mirrored each of these complementary methods. A rule-based system simply reacted to changing sensor values, just as in the RAT control example above. A hybrid model-based reasoning system compared the actual drill system response to the response of a parallel software-simulated model of the drill, in real time. Laser vibrometers were also used to measure the deflection and dynamic response of the drill, with a neural net used to interpret the observed changes in natural vibrational frequencies and modes. These diagnostic modules themselves continuously monitored the state of the DAME drilling system, receiving data from the drill server and “reasoning” about this data in order to provide state estimates. Figure 35 shows the non-interfering laser vibrometers trained on the DAME drill during Arctic field testing.
For the DAME rule-based and model-based software to be effective, the drill was outfitted with sensors located near the drill bit to measure the WOB, bit torque, bit temperature, and bit vibrations. In addition, other sensors located at the surface measured the total torque and total downward force required to auger the cut material and penetrate the formation. The sensors also measured the rotational speed and rate of penetration. Only with this suite of sensor information available to the drill could certain failure modes such as auger choking, auger jamming, and bit wear be detected. Once detected, these new drilling states or failure modes were addressed and corrected automatically by changing drilling parameters or drill vertical motion.

6. Depth: Challenges and Solutions

Reaching to greater depths in subsurface planetary exploration translates into greater knowledge of geologic history; the deeper we reach, the more we learn about a planet (and even the entire Solar System). In fact, drilling will help to answer all high-level goals for the scientific exploration of Mars, which include

Goal I: Determine whether life ever arose on Mars
Goal II: Understand the processes and history of climate on Mars
Goal III: Determine the evolution of the surface and interior of Mars
Goal IV. Prepare for Human Exploration (Miller et al., 2004; Taylor et al., 2004)
However, with depth also comes greater risk and cost, which must be weighed against the prospective science returns. For example, in the case of both Mars (biomarkers) and the Moon (water ice), there is much debate among scientists about how deep it will be necessary to drill to obtain the desired data. The difference, say, between 1 m and 10 m can be enormous in terms of cost and risk. For the purposes of mission planning, it is useful to categorize drill systems by their maximum drilling depth. We suggest the following classification scheme: surface drills, 1-meter class drills, 10-meter class drills, and deep drills. The following sections describe each category along with innovative examples.

### 6.1. Surface drills

Surface drills can penetrate only a few centimeters into rock or soil. Examples of these are the Soviet Venus drills (Barmin and Shevchenko, 1983), the drill currently proposed for the Mars Science Laboratory Rover (Anderson, 2007, personal communication), and the 2 examples described below. A major benefit of a surface drill is that it can be deployed on a robotic arm and thus drill at very steep angles into rocks or the ground. For example, such a drill could acquire a sample from the side of a large boulder that has never been exposed to solar or cosmic radiation.


Access to the top meter of the subsurface does not always require a drill. Indeed, the Viking arm, the Pathfinder wheels, and even the Mars Exploration Rover (MER) wheels could access tens of cm in unconsolidated material. In hard materials such as rock and permafrost, however, a drill would be required to reach any appreciable depth. A core from a solid rock would be interesting for studies of weathering reactions. Such reactions include oxidation by atmospheric oxidants as well as mechanical weathering of the rock by salt and ice. The upper cm of ice-cemented permafrost is also most easily sampled with a drill and is of science interest for investigations that relate to the nature of formation of the ice-cemented ground and its vapor equilibrium with the atmosphere (e.g., Mellon and Jakosky, 1995; Schorghofer and Aharonson, 2006; McKay et al., 2007). The upper surface of ice-rich ground may also preserve a record of past epochs of high obliquity that may have resulted in surface melting. Such epochs may be as recent as a few million years ago and are most likely in the northern polar regions (McKay et al., 2007).

#### 6.1.2. The Low-Force Sample Acquisition System (LSAS).

The Low-Force Sample Acquisition System (LSAS) shown in Fig. 36 is a 440 g percussive drill with integral sample acquisition capability developed by Alliance Spacesystems, LLC. It uses 15–20 Watts to drill 19 mm into rocks and acquire a 1.5 cc powdered sample (Table 3). LSAS is intended to drill into a wide variety of rocks and frozen soils while supported by lightweight platforms; its primary design goals were to minimize force, mass, envelope, and power. This simple and elegant mechanism uses a single motor to acquire samples by drilling into the surface of a target material. The drill bit (made of very specific materials to ensure life and...
minimize contamination issues) is driven by a space-qualified brushless DC motor. The drilling action is hammer-driven, which allows the mechanism to acquire a sample with the minimum amount of force necessary. The hammer is actuated by a spring / free mass system driven by the motor and a cam-follower. As material is removed from the target surface or hole, it is fed into the mechanism by the bit flutes, which deposit the sample into a storage bin via holes for later delivery to the support platform’s instruments. Further details of mechanism operation are shown in Fig. 37.

LSAS operation is straightforward and readily autonomous as shown in Fig. 38. First, the sampling tool is placed against a target. Preload is set and maintained by compressing an internal spring that supports the hammer drill system. Redundant contact sensors indicate whether the bit has been depressed to the correct position, which automatically results in the tool’s being placed against the target with the correct amount of force. Once in position, the motor spins the bit at approximately 800 rpm, and the bit begins to drill into the surface of the target up to 19 mm deep. Hammering action is the primary drilling effect and occurs 3 times per revolution. The hammering action is driven by the same motor and is accomplished via the cam-follower, which forces the hammer up as it rotates and compresses a spring. Then the stored energy is released very quickly and drives the bit into the target. As material is removed, it is carried into the mechanism by the fluted bit. Material travels up the flutes and is forced into the sample bin by brushes riding along the side of the gaps between the flutes. The sample bin gradually fills to the desired volume (maximum 1.5 cc), and any excess material simply travels past the bin and out of the mechanism.

Once the required amount of sample has been acquired, it can be delivered to any instrument on the support platform. To allow for sample delivery, the LSAS incorporates a passive clamshell storage bin. Features on each instrument (also developed as part of this effort) force the clamshell open as the tool comes into contact with the instrument. A simple scraper ensures that all material is removed from the bin as it is opened; actuating the hammer a few times helps remove particularly cohesive material and minimizes cross-contamination between samples.

6.1.3. Mini-Corer. The Miniature Rock Coring and Rock Core Acquisition and Transfer System (Mini-Corer) was designed as a portion of NASA’s Mars Sample Return Athena Payload, which was originally scheduled for launch in 2003 (Myrick et al., 2000). It was developed as a rover belly-mounted system that acquires rock cores for in situ examination by other instruments and caches cores for sample return. The drill fared well during a harsh desert environment test. An engineering model of the Mini-Corer was installed on the Jet Propulsion Laboratory’s field test rover, FIDO, to facilitate basic mission operations testing as shown in Fig. 39.

The Mini-Corer is capable of obtaining two 25 mm long and 8 mm diameter cores from a single hole of a strong rock. The Mini-Corer mass (not including pitch-translate system) is 2.7 kg, and the dimensions are 29.8 cm × 14.51 cm × 9.64 cm. The Mini-Corer employs 5 brushed DC motors equipped with incremental encoders.

The compact, low mass Mini-Corer can drill 25 mm into strong basalt in less than 6 minutes, while consuming fewer than 10 Watt-hours of power. The Mini-Corer’s carbide cutting teeth penetrate 30 cm in basalt (compressive strength of 100 MPa) at a penetration rate of more than 20 cm/hr (Fig. 40).

A key feature of the Mini-Corer is its ability to break off the core from the base rock and retain the core. A pushrod internal to the core tube provides for a controlled and positive ejection of the core. This same pushrod is used to stabilize the target rock during the initial coring action.

Should the target rocks be hard enough to dull the bit before the required number of cores are acquired, the Mini-Corer is designed with a quick-change bit acquisition capability. Using the z, break-off, and push-rod axes, a dull bit is removed from the Mini-Corer tip, and a new one is acquired. Employing the same quick-change subsystem used for changing drill bits, the Mini-Corer drill can be commanded to acquire a soil acquisition end effector. This gripper utilizes the pushrod and drill drive train for its operation; no additional actuators are required.

6.1.4. Coring and Abrading Tool (CAT). The integrated Coring and Abrading Tool (CAT) is a hybrid of Honeybee’s existing Rock Abrasion Tool (RAT) and Mini-Corer (MC) designs (Table 4). The CAT is an arm-mounted, stand-alone device that requires no additional arm actuation once positioned and preloaded (Fig. 41 and Fig. 42). The CAT is a precision robotic device capable of acquiring, retaining, and transferring cores and unconsolidated material. It can also abrade and brush rock and soil surfaces and change out bits and end effectors to perform the coring/abrating operations efficiently.
A low mass and compact transmission internal to the tool housing provides all the actuation of the tool mechanisms. A “butterfly” surface contact and tool stabilization assembly is attached to the bottom of the tool housing. This mechanism allows the arm to load up the CAT for stiffness and stability, and react torque and side loads created while coring or abrading into the rock rather than the arm.

The coring bit is essentially a hollow tube with custom-designed tungsten-carbide cutting teeth and flutes along the outside of the bit for cuttings transport. The abrader func-

### Table 2. Summary of the Different Drilling Systems Discussed in This Paper

<table>
<thead>
<tr>
<th>Depth range</th>
<th>Drill name/type</th>
<th>Company</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface drills</td>
<td><strong>LSAS (Percussive)</strong></td>
<td>Alliance Spacesystems</td>
<td>Acquires 1.5 cc powdered sample Depth of penetration: 19 mm Mass: 440 g TRL: 6</td>
</tr>
<tr>
<td></td>
<td><strong>Mini-Corer (Rotary drill)</strong></td>
<td>Honeybee Robotics</td>
<td>Acquires an 8 mm core Depth of penetration: 25 mm Mass: 4.3 kg TRL: 6</td>
</tr>
<tr>
<td></td>
<td><strong>CAT (Rotary drill) (Rock grinder)</strong></td>
<td>Honeybee Robotics</td>
<td>Acquires an 8 mm core/grinds rocks. Depth of penetration: 100 mm Mass: 4 kg TRL: 6</td>
</tr>
<tr>
<td></td>
<td><strong>USDC (Ultrasonic)</strong></td>
<td>JPL</td>
<td>Acquires fine powdered cuttings and 10 mm diameter by 100 mm long core. Mass: 0.2–1.5 kg TRL: 5</td>
</tr>
<tr>
<td></td>
<td><strong>Subsurface Sampler (Rotary-hammer/USDC)</strong></td>
<td>Honeybee Robotics/JPL</td>
<td>Penetrate regolith to a depth of 0.5 m Mass: 9 kg (full system including z-slide and cables) TRL: 5–6</td>
</tr>
<tr>
<td></td>
<td><strong>Venus drill</strong></td>
<td>Honeybee Robotics</td>
<td>Designed for 460°C, 90 bar, and CO₂ atmosphere Depth of penetration: 25 cm TRL: 5</td>
</tr>
<tr>
<td>1-meter drills</td>
<td><strong>SAS (Rotary)</strong></td>
<td>NORCAT</td>
<td>Acquires a core 15 mm diameter and 100 mm long Depth of penetration: 1 m (base), up to 15 m TRL: 5</td>
</tr>
<tr>
<td></td>
<td><strong>SATM (Rotary)</strong></td>
<td>Honeybee Robotics</td>
<td>Acquires a 0.1–1 cc powdered sample Depth of penetration: 1 m TRL: 5</td>
</tr>
<tr>
<td></td>
<td><strong>CRUX (Rotary and Rotary-Percussive)</strong></td>
<td>Honeybee Robotics</td>
<td>Instrumented research drill Depth of penetration: 1–2 m TRL: 4–5</td>
</tr>
<tr>
<td></td>
<td><strong>SCAD (Rotary)</strong></td>
<td>ATK Space Systems</td>
<td>Acquires a 10 mm diameter core Depth of penetration: 1–2 m TRL: 4</td>
</tr>
<tr>
<td></td>
<td><strong>USDC Penetrator (Ultrasonic/sonic)</strong></td>
<td>JPL</td>
<td>1 m deep low axial load penetrator of packed regolith Mass: 0.5–1.5 kg TRL: 4</td>
</tr>
<tr>
<td>10-meter drills</td>
<td><strong>MARTE (Rotary)</strong></td>
<td>Honeybee Robotics</td>
<td>Acquires a core 2.5 cm diameter and 25 cm long Autonomous core capture, transfer and ejection TRL: 5–6</td>
</tr>
<tr>
<td></td>
<td><strong>DAME (Rotary)</strong></td>
<td>Honeybee Robotics</td>
<td>Full-faced drill Emphasis on drill automation TRL: 4–5</td>
</tr>
<tr>
<td></td>
<td><strong>Gopher (Ultrasonic)</strong></td>
<td>JPL</td>
<td>Acquires a 45 mm diameter core TRL: 4</td>
</tr>
<tr>
<td></td>
<td><strong>SPECES (Rotary)</strong></td>
<td>ATK Space Systems</td>
<td>Acquires a 10–15 mm diameter core TRL: 5</td>
</tr>
<tr>
<td>Deep drills</td>
<td><strong>ATC (Rotary)</strong></td>
<td>Raytheon-UTD</td>
<td>Acquires a 25 mm diameter and 100 mm long core TRL: 4–5</td>
</tr>
<tr>
<td></td>
<td><strong>JSC (Rotary)</strong></td>
<td>JSC</td>
<td>Acquires a 25 mm diameter core TRL: 5</td>
</tr>
<tr>
<td></td>
<td><strong>MPDS (Rotary)</strong></td>
<td>ATK Space Systems</td>
<td>Acquires 10–20 mm cores (by exchanging bits) TRL: 5</td>
</tr>
</tbody>
</table>

TRL, Technology Readiness Level.
tions essentially the same as the MER RAT to create an abraded diameter much larger than the size of the grinding bit, which allows for low power, force, and torque operation. The abrader is not hard-mounted to the CAT housing. Rather, it is a passive end effector that includes the transmission for its rotate and revolve axes, and the grinding bit and brushes, but no motors. The abrader end effector uses the motors within the CAT housing to drive the rotate and revolve axis transmission when attached. The corer bit and abrader end effector are attached and locked onto the center tube of the CAT, which allows for the efficient transfer of force and torque to the bits while cutting.

For both coring and abrasion operations, the CAT is placed on a rock or soil target by the rover arm. Contact is sensed when the switches on the “butterfly” assembly fire. The arm then establishes preload for structural stiffness, the tool extends toward the rock to find the surface via its internal z-axis, the coring or abrasion actuators are activated, and the tool continues, under torque and force-feedback control, to extend the bit into the rock. With the abrasion end effector, the tool penetrates the rock surface to a commanded depth or for a commanded duration, then retracts and cleans the abraded surface with its brushes. With the coring bit, the tool penetrates the rock to a commanded depth, breaks off and cleans the abraded surface with its brushes. The coring bit, the tool penetrates the rock to a commanded depth, breaks off and retains the core, retracts from the hole, and then, after it is positioned by the robotic arm, ejects the core into a sample storage bin.

All else being constant (same rock, coring bit, WOB, and speed), drilling in a low-pressure environment yields a significantly different penetration rate and cumulative depth (Fig. 43). Coring bit tests at Earth standard temperature and pressure yielded maximum penetration rates between 40–60 cm/hr and a cumulative depth drilled of 20–25 cm before the penetration rate dropped below 5 cm/hr. When these tests were repeated in a 5 torr, CO₂ environment, maximum penetration rates above 120 cm/hr were observed and a single coring bit achieved 117 cm before tests were stopped due to time constraints. Assuming a linear decline and excluding catastrophic failures, the bit might have achieved ~200 cm before the penetration rate dropped below 5 cm/hr, marking the end of life.

This phenomenon is thought to result from trace amounts of water that remained trapped within the test basalt, despite efforts to remove it (prior to testing, the basalt specimens underwent a 110°C bake-out, non-vacuum, for 2–4 days). As the trapped moisture was exposed by the coring process, it instantly transitioned to a gaseous phase. The resulting volumetric expansion contained enough energy to loft the fine cuttings from the drill hole—in the relatively low atmosphere the fine particles experience less drag and, therefore, travel farther. A constant plume of cuttings (~10–15 cm) was observed during all 11 tests at 5 torr. With such efficient chip removal, the coring bit’s cutting elements are free to exert all their pressure onto the rock, and the drilling process becomes much more efficient (refer also to Zacny et al., 2004).

Obviously, phase transition of trapped water cannot be counted upon on Mars; this phenomenon should be eliminated in future test setups, either by raising the atmospheric pressure to the point where instantaneous evaporation does not occur or (preferably) with the use of a completely dry test sample. Nevertheless, the results of these tests are encouraging insofar as they suggest the potential benefits of chip-removal optimization (Section 4.2.3). Previous bit development programs focused predominantly on material selection and geometries designed to concentrate stress on the rock, while chip-removal features went largely unexplored. If future improvements to coring bit design increase the efficiency of chip removal even incrementally, these tests show that the increase in penetration and life performance could be significant.

### 6.1.5. Ultrasonic/Sonic Driller/Corer (USDC)

To address restrictions imposed by the limited WOB that can be provided from a small lander or a robotic arm, the Jet Propulsion Laboratory’s Advanced Technologies Group and engineers from Cybersonics, Inc. jointly developed the Ultrasonic/Sonic Driller/Corer (Fig. 44) (Bar-Cohen et al., 1999; Bao et al., 2003). The USDC requires only a very low axial force and, thereby, overcomes one of the major limitations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>LSAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>g</td>
<td>440</td>
</tr>
<tr>
<td>Length</td>
<td>mm</td>
<td>229</td>
</tr>
<tr>
<td>Diameter</td>
<td>mm</td>
<td>33</td>
</tr>
<tr>
<td>Drill diameter</td>
<td>mm</td>
<td>6.35</td>
</tr>
<tr>
<td>Drill depth</td>
<td>mm</td>
<td>19</td>
</tr>
<tr>
<td>Sample volume</td>
<td>cm³</td>
<td>1.5</td>
</tr>
<tr>
<td>Power</td>
<td>W</td>
<td>15–20</td>
</tr>
<tr>
<td>Penetration rate</td>
<td>cm/hr</td>
<td>up to 10 in basalt</td>
</tr>
<tr>
<td>Hold-down force</td>
<td>N</td>
<td>35</td>
</tr>
<tr>
<td>Operational temperature range</td>
<td>°C</td>
<td>-120°C to +35°C</td>
</tr>
<tr>
<td>Survival temperature range</td>
<td>°C</td>
<td>-135°C to +110°C</td>
</tr>
<tr>
<td>Pressure range</td>
<td>torr</td>
<td>0–760</td>
</tr>
<tr>
<td>Life</td>
<td>samples</td>
<td>75 min</td>
</tr>
</tbody>
</table>
of planetary sampling with conventional drills in low-gravity environments. This capability offers the advantage of performing difficult tasks of drilling and coring in hard rocks, ice, and packed soil with relatively small force and relatively lightweight hardware. The capabilities that were developed include collecting various forms of samples (including cores and powdered cuttings), as well as sampling long cores of hard basalt with low power and hosting sensors for measuring various properties.

The USDC is made of 3 key components as shown in Fig. 44: actuator, free-mass, and bit (Bao et al., 2003). The actuator operates as a hammering mechanism that hits the free-mass; and, in turn, the bit is hit to fracture the rock that is in contact with the bit. The USDC is actuated by a piezoelectric stack that is driven in resonance and held in compression by a stress bolt that prevents its fracture during operation. In the basic design, the piezoelectric stack has a resonance frequency of about 20 kHz. Unlike typical ultrasonic drills, where the bit is acoustically coupled to the horn, the actuator in the USDC drives a free-flying mass (free-mass), which bounces between the horn tip and the drilling/coring bit, converting the ultrasonic impacts to hammering at sonic frequencies. The impacts of the free-mass create stress pulses that propagate to the interface of the bit and the rock onto which the USDC is placed in contact. The rock is fractured when its ultimate strain is exceeded at the rock/bit interface.

At shallow depths of less than 2–2.5 cm, the produced powdered cuttings travel along the shaft, partially due to the air pressure from the vibrating bit and the induced vibration. To enable greater depth of penetration, pressurized gas was introduced from the center of the bit. With this technique, a basalt core approximately 10 cm long was produced. To further increase the rate of penetration and avoid the use of pressurized gas, the USDC was integrated with a rotation capability to create a rotary-hammer drill. This new percussive-rotary design uses decoupled actuation mechanisms and has shown significant improvement in removal of the powdered cuttings and the speed of drilling. This drill, when...
### Table 4. Differences between the Mini-Corer and Coring and Abrading Tool

<table>
<thead>
<tr>
<th>Mini-Corer (MC)</th>
<th>Coring and Abrading Tool (CAT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core dimensions</td>
<td>8 mm diameter 25 mm long</td>
</tr>
<tr>
<td>Required WOB in Keweenaw Basalt</td>
<td>70–80 N</td>
</tr>
<tr>
<td>Bit change-out capabilities</td>
<td>Y</td>
</tr>
<tr>
<td>Surface Abrasion Attachment</td>
<td>N</td>
</tr>
<tr>
<td>Mass</td>
<td>2.7 kg</td>
</tr>
<tr>
<td>Deployment</td>
<td>Rover belly mounted</td>
</tr>
<tr>
<td></td>
<td>8 mm diameter 25 mm long</td>
</tr>
<tr>
<td></td>
<td>120–130 N</td>
</tr>
<tr>
<td></td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>4 kg</td>
</tr>
<tr>
<td></td>
<td>Arm mounted</td>
</tr>
</tbody>
</table>

**FIG. 40.** ROP and WOB vs. Accumulated depth Athena Mini-Corer–drill bit life tests for a single bit in 100 MPa Keweenaw Basalt (left) and test basalt and coring bit (right).

**FIG. 41.** The CAT being tested in Indiana limestone.
operated at a 20% duty cycle with a 25 N preload, reached a depth of approximately 8.5 cm in limestone. The total continuous drilling time was 5 minutes. To reach a depth of 0.5 m in regolith, Honeybee Robotics and the Jet Propulsion Laboratory (JPL) developed, in a joint effort, a sampler that combines a USDC mechanism and bit rotation. The objective was to produce an all-in-one type drill with the capability to produce, retain, and transfer samples. A photograph of the drill is shown in Fig. 45.

6.1.6. Venus Drill. Future Venus missions, including New Frontiers Venus In Situ Explorer and 3 Flagship Missions—Venus Geophysical Network, Venus Mobile Explorer, and Venus Surface Sample Return—all focus on the search for evidence of past climate change on the surface as well as in the composition of the atmosphere and the interior dynamics of the planet. To achieve these goals and objectives, many key technologies need to be developed for the venusian extreme environment. These key technologies include sample acquisition systems and other high-temperature mechanisms and mobility systems capable of extended operation when directly exposed to the venusian surface or lower atmosphere environment. Most existing motors and actuators are not designed to survive in the harsh venusian environment, with temperatures as high as 460°C, pressures on the order of 90 bar, and a mostly CO₂ atmosphere. In response to the need, Honeybee Robotics has developed 2 types of high-temperature motors: a switched reluctance motor and a brushless DC motor. All the materials and components in both motors were selected based on the requirement to survive temperatures above a minimum of 460°C, at earth atmosphere.

The prototype switched reluctance motor, which is approximately 2 inches in diameter and 2 inches in length, has been operated non-continuously for over 20 hours at Venus-like conditions (460°C temperature, mostly CO₂ gas environment), and it remains functional. The prototype, controlled by a custom controller (still optimizing), has generated promising test data comparable with a Maxon RE25 motor that has been used in actuated flight systems (see Table 5).

A drilling system, actuated by 2 switched reluctance motors, was also tested in Venus-like conditions, 460°C temperature and mostly CO₂ gas environment, for more than 20 hours (see Fig. 46). The current configuration of the drill volume is 7 inches × 4.5 inches × 19 inches with drill stroke up to 25 cm (10 inches). The drill successfully completed 3 tests by drilling into chalk up to 15 cm (6 inches) deep in each test.

Prototype brushless DC motors and a high-temperature resolver were also tested, and the feasibility of the designs was demonstrated by the extended operation of both devices under Venus-like condition.

Scalable high-temperature motor, resolver, and bearing developments allow for the creation of long-lasting sample acquisition systems, booms, robot arms, and even mobility systems that operate outside of an environment-controlled landed platform on the surface of Venus. The SR and prototype brushless DC motors are no longer expected to limit the life of venusian surface operations. With the accompanying high-temperature bearing and other mechanisms development, surface operations will be limited only by available power. Therefore, the capability of the motor and resolver to survive for hours (and potentially longer) in the environment is a major benefit to future venusian science missions and will also allow time for communication ground loops to optimize sample target selection and the possibility for acquiring multiple samples from the surface. The extreme temperature motors, resolver, and other high-temperature mechanisms, therefore, will revolutionize the exploration of Venus.

6.1.7. The Sampling, Drilling, and Distribution system (SD²). The only drill in a present planetary mission is found...
on Philae, which is the lander portion of ESA’s Rosetta mission to comet 67P/Churyumov-Gerasimenko; Rosetta is scheduled to arrive in 2014. This Sampling, Drilling, and Distribution system (SD2) is intended to drill down to a depth of 25 cm, collect ice samples, and distribute them to science instruments. The SD2 has the autonomous capability to adjust drilling parameters based on real-time telemetry from integrated force and torque sensors (Mugnuolo et al., 1997).

6.2. One-meter class drills

A 1-meter class drill can fully fit into the payload envelope of a lander/rover protective aeroshell (in the case of Mars). A major benefit of this compactness is that the drill can be preassembled on Earth and would not require any robotic assembly once deployed on the surface of an extraterrestrial body. One-meter full-faced drills can also be integrated with down-the-hole logging instruments to obtain in situ data while drilling. These instruments might include, among others, an infrared spectrometer, a neutron spectrometer (Fig. 23), and remote sample preparation for topside analysis by a mass spectrometer. In this case, full-faced drill bits would be required. Thus, 1-meter class drills have significantly greater scientific capabilities than surface drills, yet they entail significantly less cost and risk than drills in the 2 deeper categories.

Having a mass significantly larger than surface drills creates new challenges for deployment and stability. A 1-meter class drill could potentially be deployed from a robotic arm on a stationary lander. However, such an arm would have to be significantly stronger and more stable than those used on present-day missions. Alternatively, a 1-meter class drill could also be fix-mounted on a rover, but again, this would place stability demands beyond the capabilities of present-day rovers. In terms of Mars and the Moon, the current state of research and development of this class of drills is still not quite ready for flight missions. One exception to this is the use of a drill on a body with very low gravity, where the weight of the drill system is small regardless of its mass (see the SATM drill in Section 6.3.2).

6.2.1. Science rationale. Access to depths of one or a few meters opens up new science questions for permafrost studies. Searching for a record of life on Mars will require getting beneath the surface oxidants that would destroy any such record (McKay et al., 1998). Given the lack of organics at the Viking landing sites at the ppb level, some sort of active destruction mechanism must be present—presumably reactive oxidants (e.g., Klein, 1978; Zent and McKay, 1994). These oxidants need only be present at the ppm level (Zent and McKay, 1994) to explain the reactivity seen by the Viking Biology Experiments. Bullock et al. (1994) showed that the diffusion of atmospherically produced $\text{H}_2\text{O}_2$ through the pore spaces of the soil could explain the lack of organics at the Viking landing sites, even under rocks and in trenches. They also showed that this oxidant decreases with soil depth and drops to zero in a few meters’ depth.

Similar levels of reactivity and lack of organics were seen at both Viking lander sites, which were in vastly different geographic locations on Mars, so it appears that finding an organic record of life will require getting beneath the oxidant or finding a location where the organics are prevented from reacting with the oxidants, such as inside rock or possibly an ice matrix where organics may reside.

It has been suggested that the impermeable nature of ice-cemented ground on Mars may preferentially preserve organic material against destruction by atmospheric oxidants (e.g., McKay et al., 2007). Samples obtained for this sort of analysis must not be heated such that the organics decompose; and, preferably, samples would include specimens in which the contact between organics, ice, and soil particles...
remains intact and can be imaged. The nature of this contact could help elucidate the source of the organic material. Organics found at these shallow depths would probably be of recent origin a result of meteoric inflow. However, it is also possible that, during periods of high obliquity, surface liquid water in the north polar regions results in biological production of organics.

6.2.2. The Sample Acquisition System drill. In conjunction with Electric Vehicle Controllers Ltd., the Northern Centre for Advanced Technology (NORCAT) is developing dry drilling technology for subsurface sample acquisition at depths from 1–15 m on Mars or the Moon. NORCAT’s current technology enables capture of a consolidated or unconsolidated continuous core (from the surface to the bottom of a hole) without the use of down-the-hole electric components and incorporates autonomous control that requires little or no operator intervention. The basic unit, capable of drilling to 1 m, is designed to accept additional modules, such as components for rod handling for depths beyond 2 m (Fig. 47). It weighs less than 25 kg and uses a nominal 40 W of power. Laboratory testing and frozen field testing of the technologies have been conducted.

6.2.3. The Sample Acquisition and Transfer Mechanism (SATM) drill. The Sample Acquisition and Transfer Mechanism (SATM) is a 1-meter class drill system that features sample-handling abilities, sample-return containers, and compatibility with in situ science instruments (Fig. 48). A prototype was developed and successfully tested by Honeybee Robotics to demonstrate the performance requirements for the (cancelled in 1999) NASA ST/4 Champollion mission goals. The Champollion mission was to land on a comet and use the SATM drill to collect subsurface samples. The extremely low gravity of a comet would have made this fairly large drill weigh very little, and in fact, the greatest challenge would have been to create a large enough WOB for the drill to penetrate successfully. Although the mission was cancelled, many of the technologies developed on the SATM prototype could be applicable to a martian or lunar sampling mission. For example, the SATM was designed to acquire samples at 20 cm and at 1 m below the surface with little or no cross-contamination. Depending on the scientific sampling needs, the system can also accommodate sample volumes that range from 0.1–1.0 cc (Fig. 49).

6.2.4. The Construction and Resource Utilization Explorer (CRUX) Drill. The Construction and Resource Utilization Explorer (CRUX) project addressed technology development associated with a modular, drilling based payload as a means of prospecting for future in situ resource utilization efforts. To demonstrate that drilling into the frozen lunar surface was possible, a drill platform was developed, which could be tested in frozen lunar simulant at the Cold Regions Research and Engineering Laboratory. The drill platform was designed to accommodate a downhole neutron spectrometer for measuring the amount of hydrated material in the area surrounding the borehole (Elphic et al., 2006), as well as downhole temperature sensors and accelerometers.

The CRUX drill system was designed to penetrate 2 m below the surface and has 3 different drilling modes: rotary, rotary-percussive, and percussive (Fig. 50). The rotary-percussive motion was specifically designed to break down the hard, ice-bound lunar soil simulant and transport the drill cuttings up and out of the borehole. The drill has a total linear stroke of 1 m, and each drill segment is 0.75 m in length. The drill was designed to produce as much as 45 N m of torque at a rotational speed of 200 rpm via two coupled DC servo motors. A maximum downforce of 1000 N can be achieved by the linear drive system. The percussive mechanism consists of a piston and mass-based pneumatic system.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>Maxon RE-25</th>
<th>SRM Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied voltage</td>
<td>V</td>
<td>4.5–48</td>
<td>20–48</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>rpm</td>
<td>5500</td>
<td>7500</td>
</tr>
<tr>
<td>No-load speed</td>
<td>rpm</td>
<td>4790–5500</td>
<td>7000–7500</td>
</tr>
<tr>
<td>No-load current</td>
<td>mA</td>
<td>7–80</td>
<td>1000–1200</td>
</tr>
<tr>
<td>Stall torque</td>
<td>mN·m</td>
<td>119–144</td>
<td>200–250</td>
</tr>
</tbody>
</table>

SRM, switched reluctance motor.
powered by a brushed DC motor and is driven independently at a frequency up to 25 Hz. This allows the frequency of percussive impact to be varied if needed, while other drilling parameters are held constant. To control the WOB during the drilling process, a load cell is axially aligned with the drill segment to provide accurate feedback of drilling loads to the control system. Drilling torque is controlled by monitoring the motor current of each servo motor.

As part of the CRUX program, 2 designs of drill bits were tested: one with Tungsten Carbide Cutters (WC) and the other with serrated cutters made of PDC, as shown in Fig. 51. Both bits had a central point made of WC and cutters held in place by screw-clamped wedges. Thermocouples were imbedded in thermally conductive epoxy next to the leading edge of each cutter. The WC bit had the cutters placed at a rake angle of $+5^\circ$, while the PDC cutters were placed at a rake angle of $-15^\circ$.

Initial tests were conducted in FJS-1 Lunar Simulant (manufactured by the Shimizu Corporation of Japan). The simulant was mixed with water at a concentration of 10 wt%, compacted to a density of 2 g/cm$^3$ by the Modified Proctor Method (ASTM D1557) into 15 cm deep and 10 cm diameter stainless steel cylinders, and frozen to $-85^\circ$C. This sample preparation represents somewhat of a “worst case” scenario for drilling, with the water completely mixed in the soil before freezing, and the water concentration and total density at the high end of the estimated values for the Moon (Zacny et al., 2006b, 2007b). The results are shown in Fig. 52. The results of this preliminary study indicate that it is possible to drill into simulated, worst-case, ice-bound lunar soil with low drilling power (i.e., less than 40 W).

6.2.5. The Segmented Coring Auger Drill (SCAD). The Segmented Coring Auger Drill (SCAD) is a 1 to 2 m class research drill and sampling system developed in 1998 by ATK Space Systems for the Jet Propulsion Laboratory’s Robotic Sampling and Containerization Technology Program (Fig. 53). The features of SCAD consist of a custom diamond-impregnated bit, exchangeable drill bit joints, a pure auger (dry cuttings-removal system to transport fines to the surface), and a mechanism with an internal sample container that collects core samples continuously while drilling. The SCAD drilling and segment mating/de-mating operations are controlled by a LabView custom program computer interface. In addition, the internal sample mechanism can accommodate downhole instruments. In 1999, the first breadboard was completed and was demonstrated to drill 12 inches into solid rocks that varied in Moh’s hardness scale from 1-Talc to 6-Basalt. In 2001, SCAD was successfully used to drill 2.24 m (88 inches) deep while continuously obtaining sample cores in an 8-day laboratory demonstration test (Fig. 53). The first formation layer was comprised of a 0.91 m thick limestone and a 1.32 m thick Bishop tuff. With the use of a custom dry-drilling method, the risks involved with dry drilling down to 1–2 m deep were mitigated so as to allow for the acquisition of pristine core samples with minimum cross-
contamination. Laboratory test results indicate that a dry pure auger drill system will dramatically increase drag friction at depths beyond 1 m, depending on subsurface material composition (Guerrero et al., 2005a, 2005b). The increased drag friction can eventually lead to limited depth and higher mission risk of getting permanent jamming inside the borehole (Guerrero et al., 2005a, 2005b). Drag friction combined with subsurface formation layers that contain rock materials with high cuttings expansion can quickly fill the volume capacity of the auger flute and cause the phenomenon of choking (Guerrero et al., 2005a, 2005b).

6.2.6. One meter USDC-based penetrator. At JPL, a USDC-based penetrator was developed for reaching in packed soil and regolith as deep as \(1 \text{ m}\) (Fig. 54). This penetrator is driven by the ultrasonic/sonic mechanism that was described earlier (Bar-Cohen et al., 2007). The penetrator was developed in 2004 for Sandia National Laboratory to meet the need for a means of measuring the content of toxic chemicals in the vicinity of buried barrels (Bao et al., 2003). Due to concern of damaging the barrels when using conventional penetration techniques, only minimal preload could be tolerated. The bit of the constructed penetrator was made of a steel rod that was 91 cm long and 3.2 mm in diameter. The dimensions of the ultrasonic/sonic actuator were 15.2 cm long and 3.3 cm in diameter. For packed soil that required \(>68 \text{ kgf} \) insertion force, a thrust force of 3.2 kgf was used with the penetrator, and it was driven by an average power of \(\sim 14 \text{ W}\). Data of the thrust force and penetration distance were recorded for a total penetration depth of 91.4 cm, and the graph of the depth vs. time is shown in Fig. 55. As can be seen in this figure, a depth of 82.5 cm was reached in 22 minutes. An effective drilling time of 5–7 minutes was also shown in subsequent tests.

6.3. Ten-meter class drills

6.3.1. Science rationale. There are many science benefits of getting significantly deeper than one, or a few, meters. For example, samples from several meters’ depth from martian permafrost may provide a record of the events of the last few million years, while samples gathered from shallower depths may only reflect the current atmosphere-surface equilibrium (Mellon et al., 2004; Aharonson and Schorghofer, 2006; McKay et al., 2007).

There is growing evidence that, in its early history, Mars had a much warmer climate than at present, liquid water was more common, and both flowing water and standing bodies of water (lakes and even seas) occurred. However, the presence of a thick, stable CO2 atmosphere that would be required to support such warm conditions is unlikely to have occurred more recently than 3 BY ago (based on the observed low resurfacing rates and the widespread areas where the terrain dates from these ancient times). Thus, the conditions that would have supported globally widespread life on the surface and the generation of a geologic record of that life were probably quite ancient, and evidence of such conditions would likely be deeply buried.

Environmental conditions on the surface of Mars today are also inauspicious for the survival and growth of even the hardiest terrestrial life-forms. The Antarctic cryptoendolithic microbial ecosystems and snow algae found in alpine and polar snowpacks are probably the best analogues for martian surface life (McKay et al., 1993), even that of the past. Both ecosystems can grow in environments where the mean air temperatures are below freezing; but the temperatures in the substrate (the sandstone rock and the snowpack, respectively) must be at, or near, the melting point, and liquid water must be present for growth. There are no plausible models for the growth of these systems anywhere on Mars at the present time.

Conditions at the northern polar regions, however, are the most likely to facilitate habitability in several respects. First, the low elevation of the northern plains results in atmospheric pressures that are above the triple point of water, which would allow the liquid to be stable. The second fac-

\[\begin{align*}
\text{FIG. 50.} & \quad \text{Honeybee CRUX drill head was designed for 3 different drilling modes: rotary, rotary-percussive, and percussive. The augers and drill bits are not shown.}
\end{align*}\]

\[\begin{align*}
\text{FIG. 51.} & \quad \text{Tungsten Carbide (WC) bit with } +5^\circ \text{ rake angle (left) and polycrystalline diamond compact (PDC) bit with } -15^\circ \text{ rake angle (right).}
\end{align*}\]
tor that favors habitability in the polar regions is the presence of ice near the surface. The third factor is that the polar summer solstice is an energy-rich period and can cause strong seasonally dependent melting. Because of significant secular changes in the orbital eccentricity and obliquity of Mars, the polar insolation changes greatly over timescales of millions of years. During the highest insolation periods, liquid water can form more than 50 days a year (Richardson and Michna, 2005). These high-insolation periods also enhance the hydrological cycle and may result in the evaporation of water ice from the northern cap, which may precipitate as snowfall in the winter and possibly melt this snowfall in the spring.

Drilling to a depth of a few meters could potentially provide access to ice that melted when conditions were warmer. Also, since these warm conditions occur periodically, it is possible that life, if present, adapted to that environment by thriving during the warmer periods but lying dormant when temperatures were prohibitive to growth. The organic record of that life, or even the living organisms themselves, could be sampled by drilling beneath the more modern deposits. This would require drilling to at least a meter, though it would be preferable to drill to more than 10 m. By drilling to such depths, the sampling of materials that may hold a record 10 M years or more of climate cycling would be possible. A concise list of science rationale of deep drilling on Mars was also gathered by Mancinelli (2000).

Heat-flow experiments require the placement of temperature-sensing probes deep enough to eliminate the diurnal heating cycle. The temperature and thermal-property measurements of the subsurface help to determine the rate at which heat flows out of the interior of a planet or the Moon. The heat loss can be related to the rate of internal heat production, and these measurements give information about the abundances of long-lived radioisotopes within the planet or the Moon (Heiken et al., 1991).

6.3.2. Drilling approaches. Drills that are much longer than 1 m require assembly and disassembly of drill segments—this was, for example, done on the Moon by Apollo astronauts when drilling to a depth of 3.5 m—and this increases the challenge of making the system autonomous. Also, the size and mass of 10-meter-class drills may exceed the payload capacities for the current sizes of rovers and landers. For example, the Mars Science Laboratory rover will be the size of a small car and weigh approximately 850 kg. For a good description of an end-to-end concept for a Mars deep-drill mission please refer to Beaty et al. (2004), Gorevan et al. (2003b) and Miller et al. (2004).

6.3.3. Mars Astrobiology Research and Technology Experiment (MARTE) drill. The Honeybee Robotics MARTE drill was part of the Mars Astrobiology Research and Technology Experiment (MARTE)—a Mars research platform that has investigated robotic drilling to 10 m depths (Fig. 56). The MARTE system was a collaborative effort led by NASA Ames (Stoker et al., 2004).

The MARTE project included drilling, sample-handling, and instrument technologies relevant to searching for life in the martian subsurface and demonstration of these technologies in a field test at a site with a Mars analog subsurface biosphere on Earth, exemplified by the R’o Tinto, Spain. The drill brings to the surface 25 cm core segments, which

![FIG. 52. Comparison of power and ROP for PDC and WC bits at 60 rpm and a bit temperature of −10°C. (Zacny et al., 2007b)](image)

![FIG. 53. Images of Segmented Coring Auger Drill (SCAD) showing a carousel with auger sections in the foreground (left), Swales Laboratory’s 2 m Drill Tower (center), and pristine core samples from the 2 m test (right). Photographs courtesy of ATK Space Systems.)](image)
are then passed to a suite of instruments on a lander platform via an automated Core and Sample Handling facility. Cores are then examined by remote sensing instruments, including a panoramic context imager, a microscopic imager, and a visible–near infrared hyperspectral imager (Cannon et al., 2007).

The MARTE drill is a highly automated deep-drill and core-retrieval system. The 10-axis system is designed for subsurface sample recovery and hand-off from depths of up to 10 m. For project risk mitigation reasons, the nominal core and borehole diameter dimensions were chosen to be compatible with a terrestrial wireline coring system (Boart Longyear AQT). The MARTE drill produces rock cores 27 mm in diameter and 250 mm long, while creating a 48 mm diameter borehole. The drilling mechanism utilizes dry rotary cutting techniques that include both carbide drag cutters and mono-crystal diamonds. An auger-type chip-removal system moves the cuttings away from the drill bit and into a chip reservoir located inside the lead drill tube, which is emptied upon removal from the borehole. Having the auger only occupy the end of the drill string greatly reduces the auger torque that would result from conveying cuttings all the way to the surface. The system is designed to operate at, or below, 150 Watts average during nominal drilling operations. Highly integrated sensor feedback control on all drilling axes allows for future integration of intelligent drilling algorithms and fully autonomous operation.

6.3.4. Ultrasonic/Sonic Gopher. The Gopher was developed at JPL to reach great depth with an ultrasonic/sonic actuation mechanism. For this purpose, a rod-shaped mechanism, carried on a cable, was constructed with a 6.4 cm diameter bit that is greater than the actuator and its housing diameter (Badescu et al., 2006a, 2006b). A schematic view of the Gopher cross section and its envisioned operation from a rover are shown schematically in Fig. 57, where a core is formed by drilling up to the length of the internal size of the bit. A dawg with wedges was used such that a quick pull on the cable breaks the core loose and holds the core until it is brought to the surface for removal. Once the core is removed, the process is repeated until the desired depth is reached. The field demonstration of the Gopher’s capability was done first in July 2005 by drilling glacier ice at Mt. Hood, Oregon. The lessons learned were implemented into the Gopher design, and the enhanced device was tested in Antarctica in December 2005. This field test was conducted at Lake Vida and provided an important opportunity to test its feasibility to perform deep drilling while determining the associated challenges and requirements to enhance its capability for future drilling objectives. The unit was successfully used to reach 1.76 m deep, which was a major achievement given that this is significantly deeper than the length of the whole Gopher with its support elements. The specific bit design was focused on drilling ice and silt, but it can be modified to cut rocks by adding teeth onto the bit ring shape cutters. In future studies, efforts will be made to reach as deep as 100 m, while performing the drilling autonomously.

6.3.5. Subsurface Planetary Exploration Core Extracting System (SPECES) drill. In 2002, the SPECES drill was developed and field tested to 10 m depth. This drill was developed by ATK Space Systems under funding from NASA and JPL (Fig. 58). Its mechanism effectively integrates the functions of drilling, borehole maintenance, sample coring, and cuttings removal, utilizing a novel system for the realization of these functions. This system consists of a hollow outer stem that provides borehole stabilization and access to the drill tip for continuous core and cuttings removal. In this design, individual drill segments do not have to be removed from the borehole to acquire a core. Instead, an internal bailer with cuttings and a core is lifted to the surface, and upon emptying of the cuttings and the core, it is lowered back into the hole. This approach saves time and prevents the risk of collapse of the borehole wall. This internal access mechanism also provides capability to accommodate down-hole instruments to the drill tip.

FIG. 54. View of the USDC-based penetrator with 1 m long bit inserted into packed soil.

FIG. 55. Penetration depth vs. time for hard-packed soil.
For the 2002 Arizona 10 m Sandstone field test, the bit was instrumented with a down-hole color video camera to observe the drilled medium. The SPECES drill provides automation, core samples, and effective dry drilling while generating negligible heat and prolonging bit life (Guerrero et al., 2005a, 2005b). The SPECES drill used only 1 drill bit to penetrate the entire 10 m sandstone formation layer. The custom diamond-impregnated bit showed negligible wear based on the evaluation of the JPL Review Board. The entire 10 m field test was completed in 10 days, and drilling operations took a total of 7 days to reach the target depth. Power levels were all within acceptable levels of expected planetary drilling requirements (about the power of a light bulb: 80–100 W). Images of the SPECES drill field test can be seen in Fig. 58. The figure clearly shows the average total system power of the drill system (all operational motors on during drilling process) at specific drill depth zones (1–10 m). A professional power quality logger was used to collect the power usage data. The actual drill power was the power used to destroy the subsurface material. The operational power used by the drill system to operate (without destroying any subsurface material) can be obtained by subtracting the total system and actual drill power.

6.4. Deep drills (>10 meters)

6.4.1. Science rationale. In ice-rich material deep below the surface of Mars, an organic and biological record of early life may be preserved (Smith and McKay, 2005). Deep drilling may yield samples that reflect biological conditions on Mars 3–4 BY ago, when Mars had more active hydrological activity. From an astrobiological perspective, frozen biological material acquired from deep martian permafrost may be preferable to mineralized fossils that could potentially be found in the equatorial regions. Such biological material would not only show that there was life on Mars, but it would allow a determination of the relationship of that life to life on Earth. If life on Mars represents a second genesis, such biological samples would be necessary before researchers could discern whether a second genesis occurred. The alternative is that, if life has had its day on Mars, it shared a common origin with life on Earth. Fossils cannot resolve this important astrobiological question.
It has been suggested that subsurface liquid water aquifers may exist on Mars (e.g., Clifford, 1993). If such aquifers resulted from geothermal conditions, then their depth is likely to be a km or more. However, the presence of gullies (Malin and Edgett, 2000) on Mars may be due to the discharge of relatively shallow, 200 m deep aquifers (Heldmann et al., 2005) that contain water at the present time. Accessing such aquifers would be of interest for astrobiology as well as for resource utilization for human missions.

The issues of contamination are the most severe with regard to drilling into subsurface aquifers, where any equipment that goes into the aquifer would have to be rigorously sterilized before it enters the ground. Point-of-entry sterilization has been demonstrated in Antarctica for drilling to depths of 20 m into Lake Vida (Doran et al., 1998).

6.4.2. Drilling approaches. Selecting drilling approaches for penetration beyond 10 m continues to be a debated subject among drill technology experts. On one side of the argument, subsurface-drive system advocates state that top-drive systems usage of a continuous drill string would exceed the mass, volume, and total operational time requirements for a robotic flight mission. For these reasons, a preferred subsurface-drive system solution for such depths would be a wireline or an “inchworm” drill. (Note that moles are not being considered in this section. Moles use an internal percussive system to bury themselves in loose soil. In general, moles are not very efficient at penetrating hard layers and thus are constrained to penetrating to shallow depths in relatively loose soils.)

Wireline and “inchworm” drills use the borehole wall to create WOB and thus do not need a rigid connection to the surface. The main difference between the two is that a wireline is suspended by a tether (that also is used for data and power relay), while the inchworm drill has no physical connection to the surface but has an additional anchor module incorporated in the drill assembly. Therefore, as the forward section drills and extends further into rock, the aft section remains anchored to the borehole via small pins or feet. Once drilling ceases, the forward section anchors itself to the borehole and the aft section moves further down the hole. This process is repeated for the entire length of the borehole. The nature of the inchworm mobility technique allows the device to move both up and down the borehole. Once the cuttings chamber fills up, the drill climbs up to the surface and empties it. Inchworm drills need to carry their own power source at all times, a requirement which necessarily increases mass, complexity, risk, and waste heat that would affect samples and the reliability of internal electronics (Guerrero et al., 2005a, 2005b). In addition, both wireline and inchworm drills may encounter problems in soft materials because the anchors would not hold, and the loose material may also fall onto the drill and bury it inside the borehole. The probable solution to the latter is to put another drill bit on top of the wireline system to allow it to drill itself out from the collapsed hole.

For a good description of an end-to-end concept for a Mars deep-drill mission please refer to Beaty et al. (2004), Gorevan et al. (2003b) and Miller et al. (2004).

6.4.3. The Autonomous Tethered Corer (ATC) drill. The Autonomous Tethered Corer (ATC) built by Raytheon-UTD and pictured in Fig. 59 is designed to be lowered by a winch down the borehole it creates. Lacking any drill tubes, the
mass of this device is extremely low compared to conventional drills (only 7 kg). A short auger conveys the cuttings to a reservoir in the top of the core barrel. With such a short auger, the torque on the drill segment can be much lower than that for a conventional drill; therefore, the power requirements are lower (50–75 W), regardless of the depth. To start a drill hole, the initial WOB is achieved by pressing an anchoring module against a tube held above the surface. The drill operates by gripping the sides of the borehole with an anchor module, drilling to the maximum stroke of the drill (110 mm), winching the entire drill to the surface to empty the cuttings and deposit the core sample, and then repeating the cycle over and over again. During development testing, the ATC drilled 10 m in Texas limestone with average power consumption of 74 W and a rate of penetration of 3.4 mm/minute.

6.4.4. The Johnson Space Center (JSC) wireline drill. NASA’s Johnson Space Center (JSC), in collaboration with Baker-Hughes Inc. and NASA Ames Research Center, has also been developing a coring wireline drill approach for the past few years (Briggs and George, 2005). The drill has been tested on Elsmere Island in the Canadian High Arctic since 2003 in frozen rock and ice (Fig. 60). The drill is 45 mm in diameter and approximately 2 m long and was designed to obtain a continuous 25 mm diameter core up to 15 cm long from the bottom of the hole. The coring approach minimizes the amount of rock that must be drilled, which makes the drilling more power efficient. Drilled cuttings are moved up the hole by an auger and collected in a container on top of the core barrel. Once the barrel is full, the drill is winched to the surface, where the container is emptied and the core retrieved for analysis. Laboratory and field drilling in sandstone to a depth of 2.2 m were demonstrated. Drilling rates approached 15 cm/hour with mechanical power of ~20 W. (George and Derkowski, 2007)

Building on this experience, NASA Ames Research Center has begun development of a full-faced wireline drill that will use the volumetric expansion of nitrogen gas to lift cuttings to the surface and use pressure from the same gas to provide WOB to the drill and sidewall anchoring (Briggs and Brown, personal communication). This approach does not have the scientific benefit provided by a core but represents a significant simplification because the down-hole unit does not require an auger and does not have to be retrieved to gain access to the samples. Further, by using compressed gas actuation instead of electrical motors for WOB and anchoring, the down-hole unit can be significantly shorter in length.

6.4.5. The Modular Planetary Drill System (MPDS) drill. The Modular Planetary Drill System (MPDS), developed by ATK Space Systems, is a multi-segmented drill concept designed for a maximum depth capability of 20 m (Guerrero et al., 2006a, 2006b, 2006c). MPDS research is a 3-year technology development task funded by NASA. The MPDS is based on the SPECES drill system (Section 6.3.5 and Fig. 61) and uses a custom bottom-hole assembly to minimize drilling power. The bottom-hole assembly contains the rock-destruction and sample-removal mechanisms. All subsurface samples are removed from the bottom of the hole immediately after acquisition. The cuttings and 1.5 cm diameter cores are collected and regularly brought to the surface via wireline assembly without removing the drill segments from the borehole. Both types of sample—cuttings and cores—are stored in individual, separate tubes at the surface. This ap-
proach isolates samples from different depths from each other and preserves the samples for later investigation by *in situ* instruments. The segments of the drill serve as a casing to provide borehole stability and are removed when drilling the borehole is completed and all needed samples have been collected.

While MPDS is based on the SPECES system, efforts were made during the development of the MPDS technology to address issues and reduce risks related to future space missions. For this purpose, a suite of sensors was incorporated to measure reaction force and torque, and support the control of the drilling performance and the evaluation of the operation. Several critical subsystems were designed to enhance performance and allow automation for reaching the subsurface from 0.5–20 m deep.

Top-drive systems allow for capabilities that are not available to subsurface-drive systems, including effective borehole management and cuttings-removal subsystems. Wire-line and inchworm drills cannot stabilize the borehole because they are suspended by a wire (with top-drive systems the drill sections above a drill bit are able to support a borehole). Unless methods are used to support the produced borehole, the unsupported section of the borehole above the drill would increasingly be subjected to the risk of collapse and the trapping of the drilling hardware inside the subsurface (Guerrero *et al.*, 2005a, 2005b).

A field test of the MPDS was conducted in 2006 at Idaho National Laboratory, Idaho Falls, and used to verify its capability to drill ice-soil mixtures, frozen soil, and hard basalt reaching 2.1 m deep. The goal for this initial test was 3 m. Due to weather conditions (rain and melting ice), the MPDS team stopped at 2.1 m and ran out of field test time. The 2006 Idaho Falls field test was very different from the 2002 field test. In Idaho, the MPDS drilled into ice-soil, frozen soil mixed with pebble rocks, and hard basalt rather than the homogeneous sandstone in Arizona, as was the case for the SPECES drill. New hybrid drill bits were demonstrated to penetrate ice, permafrost, and hard basalt with no visible wear. For the medium tested, results have shown that drilling ice required about 40–50 W, frozen soil 50–70 W, basalt 80–100 W.

### 7. Future Work

Although many great strides have been made in developing autonomous drill systems for space exploration, there are challenges to overcome. Mechanisms for sample capture (namely, solid core) and delivery need to be designed to be more robust in dusty environments and adaptable to a large array of materials and changes in environments. Given the primary use of dry drilling, extensive research must be performed to optimize drill bits for specific material types and to improve cuttings-removal techniques. These factors have the most significant effects on drilling efficiency for dry drilling. Ultimately, feasibility studies for using pneumatics on extraterrestrial bodies may play an important role in achieving deep drilling on these bodies. Also, control algorithms for detecting and recovering from drilling faults must continue to be developed and tested under multiple drilling conditions.

In particular, future NASA funding should support the following areas to solve the remaining drilling technology challenges.

1. **Field tests are critical and provide valuable lessons:** learned opportunities for design improvements, technology needs, and critical operational experiences. Rover mobility technology required hundreds of lab tests and several field tests to fine-tune the technology and resolve the major engineering issues. Drilling technology requires more opportunities for field test and laboratory test funds (Guerrero *et al.*, 2007).

2. **Performance testing for drill systems with similar samples:** at controlled pressure, temperature, or atmospheric conditions should be fully verified at an independent facility. These verification results should be published, and a table should be developed of the results (Guerrero *et al.*, 2007).

3. **Life and wear testing should be funded to determine maximum life of current drill system design components:** (Guerrero *et al.*, 2007).

4. **Science instrument teams should participate at each of the field tests to better develop interfaces and ideas for future integration:** (Guerrero *et al.*, 2007).

5. **Laboratory tests should be funded to complete performance tests that would improve sample-recovery percentages:** (Guerrero *et al.*, 2007).

6. **Some funding should be made available to reduce drill system packaging and envelope; this would facilitate transportation to out-of-state field test locations and improve capability and feasibility of a viable flight design:** (Guerrero *et al.*, 2007).

7. **Studies should be funded to allow our current team of experts to work together with the science community to develop system requirements and technology development priorities:** (Guerrero *et al.*, 2007).

### 8. Conclusions

Extraterrestrial drilling has seen limited use in planetary exploration missions due largely to the great challenges that are involved with its implementation. However, the scientific motivation to study the subsurface of planetary bodies is very strong and driving the exploration community to overcome the engineering challenges to performing autonomous, robotic drilling. Drilling consists of 2 separate, but equally important, processes: breaking the formation with a bit and removing cuttings to the surface. The bit is designed with cutting teeth, and it is made of a material that is both suitable for breaking the formation and wearing as slowly as possible. In most extraterrestrial drilling systems, cuttings removal is done with an auger and without the benefit of an enabling fluid (the commonly used method in terrestrial drilling). Recent research has shown promise in the use of pressurized gas to assist in cuttings removal. Also, in the special case of drilling in ice-rich formations at very low atmospheric pressure, the sublimation of the ice can create enough expanding water vapor to drive cuttings out of the drill hole. There are 2 main types of drilling: core drilling, which produces a core sample, and full-faced drilling, which excavates the entire cross section of the hole and produces only powdered cuttings. Core drilling is superior from a scientific standpoint; it consumes less power and results in greater bit longevity. However, core drilling is much more challenging roboti-
cally; therefore, drilling systems with full-faced bits are more often considered in extraterrestrial applications. Generally, extraterrestrial drilling imposes 2 categories of constraints on a planetary drilling system: the extreme environmental conditions and mission-driven constraints.

The depth to which a drill system can penetrate is one of its most salient capabilities for extraterrestrial exploration, as different depths offer distinct science “payoffs.” A useful classification of drill systems is to divide them into the following categories: surface drills, 1-meter class drills, 10-meter class drills, and deep drills. Each of these categories involves significant research and development challenges; but, logically, surface drills are at the highest state of technological development and readiness to be included in upcoming missions. One-meter class drills are not far behind and may see use during the coming decade. Ten-meter and deep drills have reached the level of field testing on Earth, but it will be some time before they can satisfy the mass, power, and automation requirements of a flight mission.

Over the years, the various drilling methods and the related designs were enhanced in technology readiness levels to the point that some are being used or are about to be used for in situ planetary missions. The focus of this paper was mostly on rotary drilling. The use of percussive action and the combination with friction in the form of a rotary-percussive drilling action was described with fewer details since the number of such drills is much smaller. Recently, there has been a growing recognition of the importance of the capability of the percussive and rotary-percussive drilling techniques, and greater attention is now being given to this technology, including the use in the Mars Science Laboratory that is scheduled to be launched in 2009. However, one of the challenges that faces mission designers today is the fact that there is no theoretical analysis or experimental data that shows what type of drilling tool is the best for given drilling constraints. Effectively, no common analysis for drilling tool types has been developed, and experimental results for different tools are not comparable due to the differing experimental setups used. Future progress in this area will significantly benefit both terrestrial and extraterrestrial drilling and allow reducing the operation cost as well as the power, mass, and volume of the systems used.

In the more distant future, most likely in the era of human exploration, sufficient mass and real-time supervision should be available to carry out truly deep penetration of the subsurface of extraterrestrial bodies.

9. Acknowledgments

Some of the research reported in this manuscript was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). Most of the drilling systems that are described in this paper were developed under funding from the National Aeronautics and Space Administration (NASA) through various grants and awards. The authors would like to express their appreciation of the many scientists and engineers who contributed to the development of the reported technology and who are from the authors’ affiliation and other partner organizations.

10. Abbreviations

ATC, Autonomous Tethered Corer; CAT, Coring and Abrading Tool; CRUX, Construction and Resource Utilization Explorer; DAME, Drilling Automation for Mars Exploration; ESA, the European Space Agency; ISAD, Icy Soil Acquisition Device; JPL, the Jet Propulsion Laboratory; JSC, Johnson Space Center; LSAS, Low-Force Sample Acquisition System; MARTE, Mars Astrobiology Research and Technology Experiment; MC, Mini-Corer; MEPAG, Mars Exploration Program Analysis Group; MER, Mars Exploration Rover; MPDS, Modular Planetary Drill System; NORCAT, Northern Centre for Advanced Technology; PDC, polycrystalline diamond compact; RAT, Rock Abrasion Tool; ROP, rate of penetration; rpm, revolutions per minute; SATM, Sample Acquisition and Transfer Mechanism; SCAD, Segmented Coring Auger Drill; SD², Sampling Drilling and Distribution system; SE, specific energy; SPECES, Subsurface Planetary Exploration Core Extracting System; UCS, unconfined compressive strength; USDC, Ultrasonic/Sonic Driller/Corer; WC, Tungsten Carbide Cutters; WOB, weight on bit.

11. References


EXTRATERRESTRIAL DRILLING

Space, Albuquerque, New Mexico, American Society of Civil Engineers, Reston, VA, pp 462–468.


Luna 24. (2007) NSSDC Master Catalog Search, National Space Science Data Center, Greenbelt, MD. Available online at http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=197 6-081A.


Address reprint requests to:

Kris Zacny
Honeybee Robotics Spacecraft Mechanisms Corporation
460 West 34th Street
New York, NY 10001

E-mail: zacny@honeybeerobotics.com
K. ZACNY

AU1
Changes to sentence OK?

AU2
Keep as written?

AU3
Keep sentence as written?

AU4
OK as written?

AU5
Author, you requested adding Beaty et al., 2002 here. But no such entry exists in the reference list. Add here and in reference list?

AU6
“actively” OK? You had “activity.”

AU7
These 2 sentences OK as written?

AU8
Sentences deleted here per your request.

AU9
Update if available

AU10
Update if available and please confirm author surnames and journal.

AU11
Update, if available.

AU12
Add publisher and city, if possible.

AU13
Please add volume and page numbers

AU14
Add vol. and page numbers, if available.