Technical Challenges of Drilling on Mars

Geoffrey Briggs and Anthony Gross
Center for Mars Exploration
NASA Ames Research Center

Reno Aerospace Sciences Meeting
January 2002

In the last year NASA's Mars science advisory committee (MEPAG: Mars Exploration Payload Advisory Group) has formally recommended that deep drilling be undertaken as a priority investigation to meet astrobiology and geology goals (1). This proposed new dimension in Mars exploration has come about for several reasons. Firstly, geophysical models of the martian subsurface environment indicate that we may well find liquid water (in the form of brines) under ground-ice at depths of several kilometers near the equator. On Earth we invariably find life forms associated with any environmental niche that supports liquid water. New data from the Mars Global Surveyor have shown that the most recent volcanism on Mars is very young so we cannot rule out contemporary volcanism -- in which case subsurface temperatures consistent with having water in its liquid phase may be found at relatively shallow depths.

Secondly, in recent decades we have learned to our surprise that the Earth's subsurface (microbial) biosphere extends to depths of many kilometers and this discovery provides the basis for planning to explore the martian subsurface in search of ancient or even extant microbial life forms. We know (from Viking measurements) that all the biogenic elements (C, H, O, N, P, S) are available on Mars. What we therefore hope to learn is whether *or not* the evolution of life is inevitable given the necessary ingredients and, by implication, whether the Universe may be teeming with life.

The feasibility of drilling deep into the surface of Mars has been the subject of increasing attention within NASA (and more recently among some of its international partners) for several years and this led to a broad-based feasibility study carried out by the Los Alamos National Laboratory (2) and, subsequently, to the development of several hardware prototypes. This paper is intended to provide a general survey of that activity.

First, a little more background on the astrobiology considerations will be provided beginning with a summary of the results of Steve Clifford's modelling of the martian subsurface (3). Clifford has concluded that near the martian equator (where the mean surface temperature is above the frost point of ~200K) the near surface regolith is likely to be substantially desiccated as a result of the internal temperature gradient and the very low water vapor pressure in the atmosphere. However, below some hundreds of meters depth ground ice can persist over geologic time scales and, as the planet, slowly cools can gradually increase in thickness. This region of ground ice is referred to as the martian cryosphere. Clifford's modelling of the thermal gradient is based on what we know about the Earth and the Moon's internal thermal gradients and it leads to the conclusion that temperatures consistent with the formation of brines are likely to be reached at a depth of a few kilometers. It is believed that substantial amounts of water vapor have been outgassed at the time of formation of Mars and over its 4.5 billion year lifetime. Estimates of the amount vary but the equivalent of some hundreds of meters of water spread over the whole planet is plausible. A major thrust of NASA's Mars exploration program is to discover where that water is today. Some has certainly escaped to space and some is locked in the permanent residual polar caps. Much probably lies beneath the surface. Today we cannot be sure that the cryosphere is saturated but plausible estimates suggest that it will be – in which case below the cryosphere there will be additional water and it will be in liquid form. Any such liquid water will find its way to a geopotential surface above impermeable basement rocks – perhaps ten kilometers yet further down. And between this postulated water table and the base of the cryosphere will be a region in which water vapor can circulate in response to the thermal gradient. It is in this region that we may plausibly find martian micro-organisms analogous to the "SliME" (Subsurface Lithoautotrophic Microbial Ecosystem) organisms that Todd Stevens and Jim McKinley have discovered in the Columbia River basalts (4). Stevens and McKinley have concluded that their SliMEs are primary producers that use chemical energy through the weathering of the basalts and derive their carbon from inorganic sources i.e. they are chemolithoautotrophic organisms.

So, some of the specific questions that can be answered by analyzing samples from the postulated martian hydrosphere are:

- Can primary production take place at depth on Mars?
    - What chemical energy sources are available?
    - Are all the biogenic elements appropriately available?
    - How much biomass can be supported
- Can such organisms metabolize fast enough to repair damage that would be caused by radiation over geologic time?
- How small and closed is the ecosystem in question
- Do microbial habitats "migrate" in concert with dynamic hydrothermal system activity?
- Can microbial life flourish for an indefinite time at the boundary between the martian cryosphere and the putative hydrosphere?

Turning now to the issue of deep drilling, some more background is called for. Most exploratory drilling is carried out by the petroleum and gas industries where time is among the most precious resources while mass and power can be more-or-less unlimited. Generally, bore-holes are drilled using diamond bits and massive amounts of drilling fluids are used to cool the bit and to flush out the cuttings. The down-hole drill is typically mounted on a segmented "drill string" where each element is individually added as the hole gets deeper (and individually taken apart when it is necessary to extract the string). When the hole is drilled in unstable formations steel casing is used to line the hole wall. Information about the strata through which the hole has been made can be provided by logging instruments attached to a cable and cores may be extracted at intervals for laboratory analysis. Drills can be steered with remarkable precision. Most drilling involves intensive human oversight given that innumerable problems can be encountered and solutions depend on the experience and skill of the operators. In recent years various advances in drilling technology are being introduced including automation so that potentially much of the drilling operation can be controlled from a remote location.

Drilling on Mars is obviously a major technical challenge, especially in the period that precedes human exploration. Firstly the martian environment is still only minimally characterized in terms of what a driller would normally expect to know before beginning operations. Jim Blacic of LANL has described the situation as the "ultimate wildcat". This will begin to change quite soon because ground penetrating radar data will be added to the lengthening list of remote sensing data sets when ESA's Mars Express orbiter arrives at Mars in 2004. NASA is also planning for the use of such instruments which can, in principle, identify changes in dielectric constant (i.e. rock/water or ice/water boundaries) to depths of several kilometers. Networks of seismic sensors will also be needed and here too ESA is taking the lead with its planned Netlander mission (albeit these landers are planned to make regional measurements rather than the local soundings that will be required to help site the first Mars deep drill).

Mass and power are also obvious major constraints. Mars drilling will have to be carried out without drilling fluids (except perhaps compressed martian atmosphere) and the total available mass will be tiny by normal standards. Hole stabilization will also have to be accomplished within the limited mass budget. Likewise we will not have massive power generators but are likely to be limited to solar array power or, perhaps, RTGs.

To minimize power use the rock comminution process will have to be very efficient and to this end it is likely that the borehole will be created by coring rather than by reducing all the material to cuttings. Coring, one piece at a time, promises to be a rather long and tedious process but from a science point of view it will be ideal since it will provide a complete record of the stratigraphy of the site. Coring will also reduce the amount of cuttings that will have to be removed to the surface – a task that is a significant challenge in the absence of drilling fluids.

Dry drilling will create problems in cooling the bit if a conventional diamond bit is used—which seems quite likely (there are many alternatives, each with their advantages and disadvantages). The rate of advance of the drill will obviously have to be very slow in comparison to normal terrestrial practice.

The application of sufficient down force on the drill (weight-on-bit) represents another challenge given the low mass system and the lesser martian gravity field. Solutions include use of a down-hole unit that anchors itself to the bore-hole wall so that down force can be applied locally using an electric motor.

And since the holes will be drilled for science purposes it is critical that contamination of the samples be avoided.

These challenges have been recognized for some time and a systematic analysis has been made by Jim Blacic and his colleagues at the Los Alamos National Laboratory to try to determine from first principles what are the most promising avenues to pursue. The range and combinations of different technical approaches examined by Blacic et al are shown in the following table which also identifies the document containing their conclusions.

Candidate Deep Planetary Drilling Technologies

Drilling Method	Rock and Soil Comminution	Drill Conveyance
rface Percussion Drills	Mechanical rotary/percussion	T&C ‡ drill steel
ble deployed Drills	Mechanical percussion	Umbilical sandline
tary Drills	Mechanical rotary	T&C drill Pipe
wnhole Motor & Rotary Hammer Drills	Mechanical rotary/percussion	Continuous tubing
ercing soil Drills	Local formation compaction	T&C push rods
erburden Drilling Systems	Coring, local compaction, erosion	Special piercing casing
bterranean Moles	Local formation compaction	Self propelled mole /umbilical
t and cavitation Drills	Hydraulic Impact/erosion	Continuous tubing with utilities
ermal Spallation Drills	Thermal stress spallation	Continuous tubing with utilities
ck Melting Drills	Thermal fusion	Continuous tubing with utilities

From *The Third Dimension of Planetary Exploration -- Deep Subsurface Drilling*
J. Blacic, D Dreesen, & T. Mockler Los Alamos National Laboratory
http://www.ees4.lanl.gov/mars/

In addition to the many mechanical engineering challenges that must be overcome there is, of course, the question of whether we can develop sufficiently reliable autonomous control systems so that the Mars drill (located at round trip light distances of tens of minutes from Earth) can complete its task without the real-time oversight that is typical for terrestrial drilling operations. The drill must be set up, the bore-hole initiated and stabilized as necessary, cores removed and analyzed, directionality maintained, and cuttings must be disposed of. At no time can the equipment become stuck (a common enough occurrence in drilling). Nor can we tolerate mechanical failures so the system must be capable of self-maintenance. Since the strata through which we are drilling will be substantially unknown the drill system must be able to anticipate failure situations and recover. And all this must be undertaken while managing a tight power budget and other consumables.

It is encouraging to note that autonomous spacecraft operations have made a major advance in the last few years with the flight of the Deep Space One mission whose goal was to demonstrate a range of new spacecraft technologies (including, especially, ion propulsion for interplanetary application). DS –1 technology demonstrations included high-level autonomous spacecraft control using "Remote Agent" software. The remote agent is model-based and goal-oriented. It consists of several modules working together with the functions of planning/scheduling; mode identification & recovery; and reactive executive. Tests were carried out by DS-1 in 1999 and showed that the remote agent functioned as planned. Specifically the remote agent was presented with three simulated failures on the spacecraft and correctly handled each event (5) . The simulations were: 1) a failed electronics unit, which remote agent fixed by reactivating the unit; 2) a failed sensor providing false information, which remote agent recognized as unreliable and therefore correctly ignored; and 3) an attitude control thruster stuck in the "off" position, which remote agent detected and compensated for by switching to a mode that did not depend on that thruster. Problems that will be encountered while conducting drilling operations will be of a quite different nature but the DS-1 experience points the way to dealing with them.

The bore-holes that space scientists wish to drill on Mars are substantially smaller in diameter that a typical industry hole. So, it is expected that miniaturization will be needed for many of the sensors that will be needed to control the drill (e.g. weight-on-bit, rate-of-penetration, rotation rate, bit torque, temperature, gas pressure) and to make down hole measurements of structure and composition (e.g. multi-spectral imager, gamma ray, neutron/density). These are all challenges that can be met.

It must also be pointed out that the drilling industry (which is understandably reluctant to publicly share information about their newest technologies) has evidently made much progress in automating drilling operations – both from the hardware and the software sides. Remotely controlled semi-autonomous drilling has become the state of the art. So, the prospects for achieving a highly capable, low mass, low power autonomous Mars drill appear excellent.

It is hoped that some of the prototype Mars drills will undertake field testing in an appropriate terrestrial environment (such as the Arctic) over the next several years and that those systems can incorporate increasing degrees of operational autonomy. Such experience combined with the results of ESA's Mars Express mission can set the stage for a major new thrust in the exploration of Mars – one with profound implications for not only astrobiologists and geologists but also for planning for eventual human exploration where access to sources of water would have obvious benefits.

References:

(1) Science Planning for Exploring Mars: Scientific Goals, Objectives, Investigations and Priorities by the Mars Exploration Payload Assessment Group, Chair Ron Greeley, *JPL Publication 01-7*, July 2001

(2) Clifford, S. M., 1993, A model for the hydrologic and climatic behavior of water on Mars. *J. Geophys. Res.* 98, 10,973 - 11,016

(3) Blacic J., Dreesen D., & Mockler T., 2000, The Third Dimension of Planetary Exploration -- Deep Subsurface Drilling, *AIAA Space 2000 Conference and Exposition, Long Beach*, #AIAA-2000-5301, http://www.ees4.lanl.gov/mars/

(4) Stevens T. O., and McKinley J. P,. 1995, Lithoautotrophic microbial ecosystems in deep basalt aquifers, *Science*, 270, 450 – 454

(5) Internet Site for the NASA ARC Information Sciences Directorate, Computational Sciences Division, http://ic-www.arc.nasa.gov/ic/projects/remote-agent/