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DRILLING OPERATIONS TO SUPPORT HUMAN MARS MISSIONS

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Water, both as a source of hydrogen and for life support, will be one of the most valuable commodities for Martian operations. Large quantities of water are available as ice at the Martian poles, but access to these sources will be restricted by the necessarily complex transport, mining, and solids handling infrastructure that is required. Drilling for subsurface liquid aquifers may provide a cost effective alternative large scale supply of water, will enable bases to access geothermal power, and will also be of considerable scientific interest. Although there is little data on the depth of Martian aquifers, it is expected that large amounts of water can be found at depths between 1 and 5 km. Terrestrial drilling operations reaching this depth are massive, power intensive industrial efforts, but some of the latest technological advances hold promise to reduce the equipment and power requirements to a level that would be feasible for a Martian drilling operation. This paper outlines the technical design of a proposed low mass Martian drilling mission capable of reaching depths of more than 1 km.

INTRODUCTION

Water is one of the more useful compounds on space missions, and has numerous uses. Among other applications, it is required for life support for astronauts, can be electrolyzed to provide hydrogen/oxygen bipropellant, provides a compact and easily handled material for hydrogen storage, and is required for most construction activities. On Mars, the surface environment is more arid than the driest deserts on Earth, and water collection will be one of the primary difficulties. Water supplies for early missions to Mars will undoubtedly be based on importation of water or synthesis of water from imported hydrogen and Martian atmospheric carbon dioxide. These missions will also rely on near complete closure of the crew life support system to recycle water for repeated use.

As Mars efforts expand, the expense of imported hydrogen will become prohibitive, and water will be acquired directly from the Martian atmosphere. Data returned by the Viking landers shows atmospheric water content of approximately 300 ppm by volume.[1] This is extremely dry, but water can still be extracted by using extreme desiccants as regenerable adsorbents, or by condensing the vapor on a cryogenically cooled plate. Water will also be extracted from the soil, which may in some places be as much as 1% water by weight. In terms of amount of water that can be recovered, these techniques are feasible for support of relatively large bases. However, they are extremely power intensive, requiring more than 100,000 kJ energy input per kilogram of water recovered.[2] Thus, the early bases will probably not be limited in terms of actual physical amount of water that can be recovered as much as by the amount of power available for water recovery operations.

For these reasons, it is expected that at a relatively early period in the lifetime of the Mars bases, the crews will start to look for large sources of water that will require minimal power input, yet be able to support a growing population nearly indefinitely. When faced with these restrictions, there are only two possible sources of water on Mars. The first is the ice at the polar caps. There are vast reserves of water located at the poles, and they can be recovered relatively efficiently simply by mining the ice and putting in the required melt energy. However, by definition, these reserves are highly localized. Either the bases will have to be situated near the poles, with all the attendant disadvantages, or a large mining, solids handling, and transportation infrastructure will need to be built.

The alternative to polar ice is to find subsurface water, either ice locked in permafrost reserves, or warm liquid water in deep aquifers. Drilling to the liquid water aquifers would provide Martian bases with an essentially limitless water supply and, once the borehole is completed, would require little maintenance and energy input. However, completion of a successful well is not a trivial task. On Earth, deep drilling operations are massive and power hungry heavy industrial efforts, and it would seem that this technique would have few advantages over simply scooping up polar ice and transporting it to the required locations. However, this paper will show techniques and equipment adapted from terrestrial practices that promise to make drilling to the Martian water table a manageable task, while the benefits of a well to a base or colony will make this the preferred method of large scale water acquisition.

MARTIAN WATER

Evidence that large amounts of water have existed on Mars in the past is well documented, and it is expected that huge quantities remain in the subsurface cryosphere and hydrosphere. Estimates for total inventories of water range from a low of under 10 meters of water evenly spread over the planetary surface to a high of several kilometers[3] (for comparison, the Earth water inventory is about 3 kilometers spread evenly over the Earth's surface). The lowest estimates are based on the enrichment of deuterium in hydrogen, and assume constant hydrogen loss rates and atmospheric enrichment factors.[4] Adjusting any of the assumptions in the model can dramatically increase the estimated inventory of water. Estimates based on the geological evidence, particularly from the amount of water needed to cut the deep erosion features seen on the surface near Chryse and in Elysium and Hellas, require a minimum of 400 meters of water spread evenly over the surface.[5] Based on all the available evidence, and the accuracy of the various estimates, it is generally assumed in the scientific community that the current Martian water inventory is at least several hundred meters, but probably less than one kilometer. However, the combined known reserves in the polar caps, the regolith, and the atmosphere cannot account for more than about 40 meters. The remaining 85 - 95% of the Martian water inventory is assumed to be in the subsurface cryosphere and in the underlying groundwater system.

The Martian cryosphere (also known as the permafrost zone) is the portion of the megaregolith that is permanently frozen. Based on the current Martian temperatures, the cryosphere can start very close to the surface, and is expected to penetrate to several kilometers. The depth at which the cryosphere starts is determined by how fast underground ice sublimes, and how quickly the water vapor can diffuse through the soil to the atmosphere. While much of the data necessary for a precise calculation has not yet been collected, and models are fairly ideal, most calculations have shown that near the equator the cryosphere starts about 100 to 200 meters below the surface, while more than 30 degrees latitude away from the equator the cryosphere is stable all the way to the surface.[6] Likewise, we do not have data required for the calculation of the bottom of the cryosphere, but ideal models have shown that it is expected to be on order of 2.3 km at the equator and up to 6.5 km deep near the poles.[7] Underlying the cryosphere is the expected region of liquid water, the hydrosphere.

The cryosphere will certainly contain plenty of water, and it is fair to ask the question: Since the cryosphere is relatively close to the surface, why can’t this be used for a water source, instead of drilling all the way to the hydrosphere? In fact, it is likely that early bases, particularly those located more than 30 degrees from the equator, where the cryosphere approaches within a couple meters of the surface, will collect water by mining and melting permafrost. However, there are two basic drawbacks to this approach. First, it is difficult to get the permafrost from the ground. An operation equivalent to a terrestrial strip mine would be required. Since permafrost at Martian temperatures is as hard as basalt and as sharp as glass, the mining equipment would have to be very rugged, and the entire operation would be labor intensive and dangerous for the personnel involved. Second, the permafrost would not replenish itself. Once an area had been mined, the facility would have to be packed up and moved off to a new site. Both of these requirements mean that for any large scale water recovery effort, a permafrost mine will involve continuous, hard labor for many people.

TO THE MARTIAN HYDROSPHERE

So, again we are confronted with the question: What is the most economical way to access the Martian hydrosphere? First, we need to determine how deep we must go to reach the hydrosphere. Based on the preliminary calculations referred to above, the cryosphere in equatorial regions starts at 200 meters and extends to 2.3 km beneath the surface. To access the hydrosphere here, we would have a drilling profile consisting of 200 meters of dry rock (probably layered impact ejecta, volcanic flows, and sedimentary deposits), 2.1 kilometers of permafrost bound rock, followed by water saturated rock to the desired final well depth. However, this is the expected average profile of the megaregolith in these regions, and does not account for local variations. Mars has a long history of volcanic, impact, and possibly tectonic activity, all of which may cause extreme local variations in the thickness of the cryosphere. There are many processes that can cause thin local regions in the cryosphere. For example, there may be local regions where there are higher concentrations of salts that depress the freezing point of water, or low thermal conductivity rock, which increases the temperature at depth. Either of these processes would decrease the depth of the cryosphere. Two of the most likely processes that would decrease the depth of the cryosphere would be seismic pumping and hydrothermal circulation.

Seismic pumping occurs when a geologic event or an impact sends shock waves through the surface material, which can fracture the cryosphere or cap rocks and/or compress deep water reservoirs. For example, the Alaska earthquake of 1964 caused dozens of shallow aquifers to break through the (admittedly thin, relative to Mars) permafrost and discharge to the surface. Mars has likely had thousands, if not millions, of events as large or larger than the Alaska earthquake. It is certainly possible, even likely, that some of these events have forced water from the hydrosphere into reservoirs above the nominal depth of the cryosphere.

Hydrothermal activity is a semi-stable circulation pattern that develops whenever a thermal anomaly occurs in an area where groundwater is present. Hot water and steam rise from depth to the top of the hydrothermal anomaly and cool and condense. The cool water moves away from the hot anomaly in a radial pattern, and sinks back to the bottom of the plume. On Mars, this circulation is likely to have been frequently induced by volcanic activity.[8] The proximity of the hydrothermal circulation to the surface of Mars is a function of the time since the last active episode of volcanism. It has been suggested that more than 10 percent of the total surface area of Mars has been volcanically active within the last 500 million years, and as much as 1 percent within the last 50 million years.[9] Land that has been active within the past 500 million years will have temperatures above 253 Kelvin (the expected freezing point of the briny Martian subsurface water) at a depth of about 1.5 kilometers, while land that has been active within the past 50 million years will have 253 K temperatures below about 500 meters. It is even expected that a small percentage of the land area, that active within the last half million years or so, will reach liquid water temperatures within 250 meters of the surface. Hydrothermal sites are expected to be the most important and likely places to search for near surface water.

Thus, we see that there is almost certainly liquid water within reach of current technologies. A properly sited drilling rig capable of reaching one kilometer depths will not only be able to penetrate the cryosphere, but will be able to reach depths at which generation of geothermal energy is viable. Thus, once the effort is made to complete the bore, not only will liquid water be available to the base without net power input, but it will provide a generous power supply. In addition, the suspected hydrothermal activity is of particular biological interest as potential sites for possible Martian life. So the total benefits of drilling into a Martian hydrothermal vent will be threefold: an effectively infinite liquid water supply, plentiful power, and outstanding scientific value for both exobiologists and planetary scientists.

WHERE TO DRILL

To reap the benefits of a drilling operation, the rig will have to be sited properly. The costs of a dry hole on Mars will be exorbitant relative to that on Earth, so it will be imperative to characterize the subsurface fully before beginning the actual drilling operation. Fortunately, it is an easy process to tap terrestrial technologies, with little modification, for this purpose. In fact, terrestrial technologies will have a much easier time on Mars, as there are not expected to be any large deposits of oil, natural gas, or other fluids with densities significantly different from water. The primary technologies that will be used to pinpoint potential drilling sites will be visual imaging, spectroscopy, ground penetrating radar, and seismic mapping.

Orbital spectroscopy and visual imaging will be used to determine the mineralogy and contours of the surface.[10] Hydrothermal alteration zones will show tell-tale signs of unique mineralogy, topographical irregularities, and possibly ground warmth (detected by thermal emission sensors). Visible and near-IR reflectance spectroscopy will be useful tools for determining the mineralogical composition of the surface. The mid-IR band, from 2.08 to 2.35 μm, will reveal areas rich in clay type minerals that have resulted from hydrothermal alteration. Gamma ray spectroscopy will be able to map chemical variations across the surface. Intensive spectroscopic measurements will be concentrated on areas that seem likely candidates for hydrothermal activity based on high resolution visible and IR photo imagery, such as that currently being gathered by Mars Global Surveyor. The photo imagery will be particularly useful for detection of geological lineaments indicating underlying fracture zones.

Spectroscopy is the tool of geoscientists, and experiments will be placed on various orbiters whether or not there is ever any interest in searching for hydrothermal sites for use by a base. Regardless of the initial goal of the spectroscopy experiments, once the data has been collected and analyzed, sites of hydrothermal activity should be apparent. At this point, satellites specially made for detection of subsurface water with ground penetrating radar (GPR) will need to be launched. If we can expect to find water at about 1 km, and radar can penetrate about 10 wavelengths into the dry Martian soil, then long wavelength radar, on the order of 3 MHz, will need to be used. With two receiving antennas in orbit, a multiple kilowatt transmitter should be able to generate a decent two dimensional map of desired areas (squares approximately 50 km per side) within a few months.

If the GPR is able to verify liquid water within about a kilometer of the surface, the next step would be several landers equipped with extremely sensitive seismometers. These instruments should be emplaced as deeply as possible (a minimum of two meters) in the regolith in an array around the desired area. A minimum of four landers will be required to get a reasonable three dimensional picture of the subsurface. Once the instruments are in place, a number of seismic events will have to be induced. Terrestrially, this is accomplished with small chemical explosives emplaced up to several hundred meters underground. On Mars, this is not likely to be cost effective. Larger charges can be fired from remote locations on the Martian surface by a mortar type apparatus, or missiles can be fired from orbit. In addition, the landers can have auxiliary geophysical equipment, including thermal conductivity and electrical resistance sensors. The data transmission rate or storage capacity of the landers will have to be quite high relative to the spectroscopic or radar satellites, so these missions will be considerably more expensive.

For the exploration program outlined above, a total of four launches will be required, not including the high quality orbital imaging that will be completed long before missions to search specifically for subsurface liquid water are launched. The spectroscopy experiments at all required wavelengths will be the equivalent of one complete discovery class mission with a Delta II launcher. The GPR satellites (one transmitter and two receivers) can be made with one Titan equivalent launch vehicle. The seismology experiments will likely require about two launches - a Delta class for a high data rate orbital relay, and a Titan class for the four soft landers. The total costs of these missions, figuring $250 million for the Delta class payloads and about $1 billion for the Titan class payloads, will be on order of $2.5 billion. Compared with the cost of the drilling mission outlined below, the exploration phase is roughly an order of magnitude cheaper. Thus, a thorough mapping of the drilling site will be warranted.

DRILLING MISSION DESIGN AND EQUIPMENT

Once liquid water is located with precision, a drilling mission may be considered. For the purposes of this paper, the authors have baselined a drilling rig capable of reaching 1000 meters depth, yet one that can be launched with the available capacity of a single landing based on the NASA design reference mission (DRM) architecture. Proven off the shelf terrestrial drilling equipment and technologies are used to the greatest possible extent.

Transportation Vehicles

The drilling mission outlined in this paper is designed with the express purpose of being able to launch and land on Mars using no more than the vehicles proposed for the NASA DRM architecture. The benefits of scaling a drilling mission to fit on vehicles that will be required anyway for the baseline human Mars missions are obvious.

The NASA DRM currently proposes using two launches of the Shuttle derived Magnum launch vehicle per vehicle launched to Mars. Each Magnum launch can put about 70 tonnes of payload into LEO. One of the launches will contain the TMI stage, which will have three 15,000 lbf thrust NTR engines and about 50 tonnes of hydrogen fuel. The other launch will contain the Mars payload module, which will mate with the TMI stage and perform the burn to Mars. The Mars DRM payload module for crew transfer has two 14 meter tall decks. The bottom deck is about 40 tonnes of fully fueled landing stage to perform the Mars terminal descent. The top deck is about 30 tonnes of habitat payload.

The Mars payload module will consist of a braking and landing stage similar to that proposed by the DRM for crew transfer, with internal modifications. The same aeroshell module can be used as in the DRM module, but the position of the landing rockets will have to be modified. The drill rig module will have a large and massive wellhead, 18" in diameter, sitting precisely in the middle of the landing module floor. The wellhead must be on the bottom of the lander so that it can be placed firmly into the ground. This required placement causes havoc with the baseline DRM landing stage. The four RL-10 class engines will have to be placed in a rectangle around the wellhead and the plumbing will have to be modified appropriately. It is proposed to place the propellant tanks on the top deck. Although this is comparatively far away from the engines, it allows the drilling rig equipment to be placed in the open space around the wellhead on the lower deck, which will expedite construction and start up of the drilling rig after arrival on Mars.

The total landed payload is approximately 30 tonnes. The drill rig landing stage will double as the support structure for the drill rig and pressure enclosure for the work crew. Current NASA plans are to provide landing modules with wheels for mobility. This may be a significant advantage but is probably not necessary, strictly speaking, since a drilling module will only land after there is enough human presence on the planet to provide terminal landing guidance.

Drilling Fluid

The primary difficulty in drilling on Mars is the lack of readily available drilling fluid. On earth, water based muds are commonly used for cleaning and cooling the bit, breaking up rock under the bit, removing cuttings from the bore, and internal support of the bore. Terrestrial mud settles in a pond, allowing removal of most of the cuttings. Obviously, settling ponds are impossible on Mars, and water based drilling fluids are impractical at best, at least until a large source of water is available. Water could be imported, but this approach is extremely mass intensive (a 4 inch diameter, 1 kilometer bore is about 8 cubic meters volume; about 3 times this much mud would be required for the drill rig) and any significant lost circulation in the bore would bring operations to a screeching halt until more water could be shipped in.

Table 1

THERMODYNAMIC PROPERTIES OF LIQUID CARBON DIOXIDE[11]

Figure 1 Assumed drilling profile for near-equatorial region with hydrothermal anomaly.

To solve the drilling fluid problem, the authors suggest using liquid carbon dioxide gathered *in situ* in place of a water based mud. As the Martian atmosphere is 95% CO_2, using liquid carbon dioxide means that no drilling fluids need to be transported, and any lost circulation can be replenished *in situ*. The energy cost of acquiring carbon dioxide on Mars impose the requirement of a closed circulation system, but this will be necessary no matter what drilling fluid is used, and the benefits of making up the initial inventory of the system with readily available fluid are enormous. Thermodynamic properties of carbon dioxide are shown in Table 1.

The properties of liquid CO_2 turn out to be precisely what is required for slimhole drilling on Mars, although borehole pressure must be maintained at a fairly high level. A complete drilling rig has been designed using terrestrial slimhole techniques with a non-rotating string, hydraulic motor, and carbon dioxide drilling fluid. Similar mechanical systems have been thoroughly tested in terrestrial laboratories, and have been used for terrestrial drilling for years. The modifications of the systems to work with carbon dioxide are relatively minor, with the higher operating pressure being the most troubling. An overview of the entire drilling rig and baseline drilling profile, assuming a near-equatorial drilling location, is shown in Figure 1. A preliminary equipment list is shown in Table 2.

Table 2

MASS ESTIMATES FOR PROPOSED DRILLING SYSTEM

Borehole Design and Drilling

Numerous parameters come into play in determining the desired borehole dimensions. However, the primary constraint is the mass of the drill string, which is the heaviest single component of the entire drilling system. For the Mars drilling mission, the string material must be strong yet lightweight, able to support the entire weight of the string in tension without excessive stretching, or to transmit compression without buckling. The string must also possess adequate corrosion resistance, particularly with CO_2 drilling fluid, as any water encountered during the drilling will cause immediate and severe acid corrosion to non-resistant materials. Faced with these constraints, Ti / 6 Al / 4 V alloy (density = 4450 kg/m^3) was selected as the drill string material. A 3" outer diameter string with 1/4" wall thickness is the practical minimum to allow sufficient downhole fluid flow. For 15 cm at the end of each tube length, the wall thickness is 3/4" to allow a tapered threading for flush fit connections between string segments; flush fit connections are required for the linear feedthrough on the wellhead. Four meters was determined to be about the optimum for each string segment. This means that each tube masses about 27.5 kg and weighs a little more than 100 Newtons on Mars. Thus, these tubes can be maneuvered relatively easily inside the 14 meter tall drilling module, and can be manhandled, if necessary, by a single worker. A total of 260 drill string tube segments were included in the baseline design.

For a 3" OD, 2.5" ID drill string, a 4" borehole will provide annular flow area approximately equal to the string internal flow area. Thus, a 4" diameter borehole was selected for the base design. This leaves only 1/2" around the string, so bits must be chosen with care to ensure fine cuttings traveling uphole. A high carat fine tooth diamond bit, such as the American Coldset Super Trigg double concentration diamond bit, would be appropriate for this duty. A bit of this nature can be expected to last approximately 500 meters when cutting basalt, so four bits were included on the equipment list.

Casing was also included for the first 100 meters of the hole. The lower part of the hole, in the cryosphere and in solid rock layers, is expected to be nearly immune from severe wear and lost circulation, and casing was eliminated for this portion of the hole to reduce launch mass and labor requirements. However, the first portion of the bore, which penetrates compacted unconsolidated materials, may be prone to caving. Casing the first 100 meters was baselined as a reasonable estimate of the amount of casing required. Welded aluminum casing, 5" OD, 1/4" wall thickness, 25 four meter lengths, was selected to case this portion of the bore, and a single 5.5" diameter roller cone bit was included for drilling the cased region. The casing will be free hanging, welded to a neck in the wellhead.

Using a non-rotating string lightens the drill rig considerably by eliminating the rotary table, kelly, and supporting equipment, and by reducing the wall thickness of the string. However, power to the bit must be supplied by a downhole motor. A hydraulic motor has significant advantages over an electric motor, and has been used extensively in terrestrial applications. The baseline system is a 3" OD motor (with counter torque stabilizers to the bore diameter, of course) with 1" shaft. If the carbon dioxide provides a 62 bar pressure drop and has a density of 1000 kg/m^3, then the motor should provide about 20 - 25 kW to the bit. For a 4" bit, this translates to 55 - 70 kgf-m (400 - 500 ft-lbs) torque at 300 rpm. Two motors were provided in the equipment list. Figure 2 shows a terrestrial hydraulic motor with flush fit connections and diamond bit.

Mud System Design, Energy Balance

Once borehole dimensions have been established, the mud system can be designed for the necessary duty. The complete design of the mud system is shown in Figure 3. The two parameters of greatest interest are the uphole mud velocity and the mud temperature profile. Since liquid CO_2 at temperatures of interest has a relatively low viscosity (1.14 x 10^{-4} Pa s at 260 K), a high velocity was used to ensure adequate cuttings entrainment and removal. With the given annular flow area of 31.7 cm^2, a flow of 3.4 liters/sec of CO_2 with a 960 kg/m^3 density (temperature = 268 K) gives a velocity of 0.97 m/s (about 190 ft/min). This flow rate is considered excellent by terrestrial standards. The corresponding mass flow rate is 3.3 kg/s. Assuming the downhole mud flow is at 260 K, the downhole flow rate is 1.04 m/s, or 3.3 liters per second at a 1000 kg/m^3 density. This provides a downhole Reynolds number of 580,000 and an uphole Reynolds number of 414,000, so flow in both directions is nicely turbulent. From the Reynolds number and flow path geometry, assuming bore surface roughness of 1 mm (fanning friction factor = 0.025), we calculate the total frictional pressure drop for a 1000 meter borehole of about 16.5 bar.

Figure 2 Hydraulic downhole motor with diamond bit.

The drill bit will have bottom cleaning jets, which clean the bit as well as assist in breaking up rock. The assumed pressure drop across these jets is 27.5 bar. The total pressure drop for the CO_2 liquid in the circulation loop, including the 62 bar in the downhole motor, is thus 106 bar.

Therefore, the mud pump has to move 3.3 kg/s of 1000 kg/m^3 density fluid through a 106 bar pressure rise. Assuming the fluid is essentially incompressible and the pump achieves 70% efficiency, this means that 53 kW (71 hp) of pumping power is required. Maintaining the pump inlet at substantially below the bubble point reduces the required NPSH for the pump, and eliminates the possibility of impeller damage from cavitation. A 55 bar suction pressure maintains 31 degrees of subcooling at the pump inlet and was chosen as the baseline for the system. The minimum system pressure is maintained with a high pressure inert (Ar, N_2) atmosphere in the CO_2 storage tank. The pump discharge is 161 bar.

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Figure 3 Rough diagram of mud system schematic.

The drill rig module, based on the NASA DRM, uses four RL-10 engines to soft land on the Martian surface. Each RL-10 engine has a common shaft with the liquid hydrogen (or methane) pump, the liquid oxygen pump, and the gas expander. The liquid oxygen pump performs approximately 90 kW pumping duty on a high density cryogenic liquid while the engine is in use. Unfortunately, the discharge pressure is only about 110 bar. However, if the pump casing thickness can be increased to take the maximum pressure of the mud system, the pump internals should be adequate to handle the CO_2 flow. For the baseline mass estimate shown in

Table 2, two of the four RL-10 LOX pumps (primary and spare) were modified to handle the CO_2 flow. The drive shaft was modified to be able to disconnect from the gas generator and connect to a commercial 100 hp (75 kW) electric motor during use on the drill rig.

The temperature profile of the mud flow is a function of total power input and mud flow rate. Power input will come from the mud pump (53 kW) and heat leak. Since the inlet temperature of CO_2 into the system is 260 K, the drilling fluid should always be above the temperature of the bore, based upon the estimate that liquid water will occur at temperatures above 253 K (i.e., we should hit water before the bore reaches a temperature of 260 K). Thus, in reality, we would expect heat to be leaking *from* the drilling fluid into the bore, resulting in cooling for the mud as it flows downhole. However, to be conservative, the authors assumed no net heat leak from the bore into the fluid, and thus the total heat input into the drilling fluid is the 53 kW from the mud pump, most of which will show up as frictional heating of the bit on the rock. This power input into 3.3 kg/s of 260 K liquid CO_2 will result in a temperature rise of 7.5 degrees K (heat capacity = 2.12 kJ/kg,K). Thus, the CO_2 will flow through the pump and downhole at 260 K, will heat up to 268 K while cooling the bit, will return to the surface, and be cooled back to 260 K in the external air cooled heat exchanger.

Since the carbon dioxide flows in a closed loop, solid separation from the uphole flow must take place in an in-line separator. A diagram of the proposed solid separation apparatus is shown in Figure 4. In this apparatus, the mud first flows first into a chamber with an overflow baffle. The residence time for the fluid behind the overflow baffle will be about two minutes (400 liters). Assuming the fluid behind the baffle is more or less quiescent, and the average solid particle density is 3500 kg/m^3, then this time is sufficient to settle any particle larger than about 0.1 cm, based on an ideal Stokes' Law calculation. Particles that settle to the bottom of the overflow chamber will accumulate in collection canisters. These canisters can be sealed from the solid separation chamber with a gate valve, which will allow them to be emptied without shutting down and depressurizing the drill rig.

Figure 4   Rough diagram of in-line solids separator.

The fluid that pours over the baffle will go through a series of fine screens, starting with about a 20 mesh, and going to close to a 100 mesh. The screens will be near vertical with a slight bias. Particles collected from the screens will fall into collection canisters similar to those used in the overflow chamber.

Immediately below the primary separator there is a small magnetic separator. It is unknown exactly how magnetic Martian material will be; the sample return mission should help settle these questions. If there is significant magnetism, then a magnetic separator may be very useful in removing the finest material from the liquid. A cleanout port is provided at one end of the magnetic separator to allow an operator to reach in with a raking tool and scrape out any collected material. Before the magnetic separator is cleaned out, the separator system must be isolated and depressurized.

After the separation system, a heat exchanger is required to remove the enthalpy gained during the drilling fluid circulation (53 kW total). Figure 3 indicates a plate fin heat exchanger, but this may not be the optimal design for the thin Martian air. It is possible that a finned air cooler may be more appropriate for the required duty. Design work is required to optimize this heat exchanger.

Following the heat exchanger, the cool liquid CO_2 flows back to the storage cylinder, ready for another circuit through the bore. The carbon dioxide storage cylinder has a total of 24 cubic meters volume, which is three times the total volume of a 1000 meter deep bore. This volume will provide margin for the system in case of lost circulation. Liquid CO_2 is collected for the system by a large sorption pump with 1000 kg of sorbent material. This should allow collection of about 160 kg of high pressure carbon dioxide per night. During the day, the sorbent bed is heated and the relatively high pressure carbon dioxide is pumped into the mud system with a small, electrically powered positive displacement compressor. During the sorption phase, this same compressor operates as an induced draft fan to prevent the buildup of a diffusive barrier by the inert gases (primarily Ar and N_2) in the Martian atmosphere. These gases, pumped to the high pressure side of the compressor, can be collected for use as pressurant for the mud system and welding shield gas.

Wellhead, Feedthrough, CO_2 Feed

The wellhead is the most critical piece of equipment on the drill rig. A wellhead detail is shown in Figure 5. For the proposed drill rig, the wellhead will have four primary functions. The first function is to handle the return flow of cuttings-laden drill fluid. The second is to provide a feedthrough for the string as the bit penetrates the rock. The third is to seal the bore from the working environment, yet allow access to the drill string. The final function is to prevent overpressure accidents in the event of a kick.

As designed, the wellhead is 3 meters tall, 12" ID, with 3" thick walls made out of Ti/ 6 Al/ 4 V alloy. The wellhead is significantly overdesigned for any expected service conditions, but the authors felt it would be prudent on a first of a kind mission to include this margin. The top of the wellhead is a removable flanged piece that can be lifted to allow access to the drill string. In the center of the top is a 3" diameter linear feedthrough with labyrinth seals. The drill string can push through the feedthrough, but only a minimal amount of CO_2 will leak through the seals into the working environment. Support chocks will hold the string in place while tubing is added.

Approximately 1.5 meters below the wellhead top is the 6" bore isolation ball valve. The string can be pulled up through the linear feedthrough with the bit and downhole motor still in the wellhead but above the ball valve. Then the bore isolation ball valve can be closed, allowing pressure to be retained in the bore while the top portion of the wellhead is depressurized (depressurization valve not shown in Figure 5) and the flanged top is removed. Immediately below the ball valve is the drilling fluid outlet to the separator with a 6" butterfly isolation valve. Below the fluid outlet is a crush type blowout preventer for emergency use in the event of a kick. At the very bottom of the wellhead are supports for the flared end of the top casing segment.

Figure 5 Proposed wellhead detail.

The base of the wellhead is fixed to the ground with anchors. In addition, the wellhead is an integral part of the spacecraft, which is fixed to the ground with anchors in the landing legs. Any force in the wellhead will be transmitted both to the anchors at the base of the wellhead, as well as through the spacecraft frame to the anchors in the landing legs.

The CO_2 feed is located at the top of the drill string, as shown in Figure 3. It has a swivel connection between the 4" flex line feed from the drilling fluid pump and the flush fit connection to the drill string. Although not shown in Figure 3, it also has a vapor feed connection at the top to allow a feed of high pressure vapor to force liquid carbon dioxide fluid out of the drill string pipe.

Support Structure for Drill Rig

The landing module will provide the basic support required for the drilling apparatus, but this has been supplemented by some additional supporting beams. The beams are made of titanium, which provides excellent strength for very low mass. The maximum tensile mass on the center of the drill rig structure is estimated to be about ten tonnes, which is a load of about 37 kN. Four vertical titanium I-beams, type S4 x 9.5, are used to support this load in addition to the landing module structure. Similar beams are used for horizontal support of the crown block and other items of tackle. A total of 305 linear feet of the beams have been provided. Catwalks and ladders made of normal steel grating have been provided to allow crew members access to all levels of the drill rig structure.

Typical equipment used for drilling has been provided for working the rig. This includes the crown and traveling blocks, and a small drawworks. A small selection of drilling tools has been provided, including a 4" reamer, fishing tools including an overshot, packers for bore completion, and a selection of useful charges. A wide selection of hand tools and power tools, including two complete pairs of power tongs has been provided for the crew. Mass considerations make it impossible to include all the tools typically provided for terrestrial drilling rigs, so the selection of the tools attempts to provide the most useful all around items.

Numerous subsystems are required for various miscellaneous tasks on the rig. The valves in the mud system require an actuation method. Electric motors are likely to be too heavy for actuation of the valves, so the mud system was provided with an inert gas distribution and actuation system. High pressure normal Mars air can be used for this system, or a small amount of the vapor in the mud system can be tapped for this purpose.

A small (50 amp, 240 V) welding machine capable of stick and TIG welding has been provided for repair jobs. The residual gas pumped from the sorption pump during the nighttime carbon dioxide sorption phase is about 60% nitrogen and 40% argon, which is not good enough for welding shield gas. However, this gas can be sent through a single pass membrane separator, which will produce about 80% argon in the retentate. This gas will be accumulated and used for TIG welding shielding.

Total power requirements of the drill rig are expected to be a maximum of about 500 kW. It will be utterly impractical to power this drilling operation using solar power, particularly if work proceeds on a 24 hour schedule. A 500 kW nuclear reactor is the baseline power system for the drill rig.

DRILLING MISSION OPERATIONS

The design and equipment of the drill rig mission outlined in the previous section are all well and good, but how will the equipment be operated once it reaches Mars? This section briefly describes the working environment, operations, and procedures enabled by the lander previously described.

Working Environment

The drill rig is located in an enclosed module similar to the habitat modules in NASA’s design reference mission. This is a pressure enclosure and will allow the module to be shipped out pressurized, and to operate in a positive pressure relative to Mars ambient. This has numerous advantages.

During the ten month interplanetary shipping phase, about 1 psi absolute of nitrogen will be sufficient to prevent the loss of lubricants to vacuum. This will also prevent a thin layer of lubricant grease from forming on every exposed surface in the module, and will allow relatively easy maintenance of the equipment by the crew after arriving on Mars.

During operation on Mars, the internal pressure can be boosted to 2 - 5 psi absolute, and will be a mixture of carbon dioxide, nitrogen, and argon made up from the Martian atmosphere. Again, this prevents loss of lubricants, and also allows better thermal convection and sound conduction from working equipment. In addition, it will help alleviate the crew fatigue caused by an overly stiff pressure suit (assuming about 4 psi pure oxygen in the pressure suits). The drill rig module will be protected by a pair of relief devices, including a relief valve set to slightly above desired cabin ambient, and a large volumetric flow burst disk set to 20% below the module bursting pressure.

Note that the crew will have to wear life support suits. As desirable as a shirt sleeve working environment may be, it is impossible to provide one cost effectively. Leakage from the bore, wellhead, and mud system will be high enough to raise the concentration of carbon dioxide in the small module volume above toxic levels in an extremely short time (order of minutes). There is no practical way to maintain a breathable atmosphere in the drilling module. In addition, the pressure suits are an important safety consideration. In the event of an accident (a sudden kick, a blowout, stuck bit, etc.), numerous things can happen which would make it advisable for the crew to leave the rig rapidly. Pressure suits allow the crew to evacuate quickly without immediately dying on Mars. The major disadvantages of the pressure suits are the unwieldiness for the working crew and the requirement for a pressure lock and external rover/ living quarters.

The temperature of the drill rig module during operations will be determined by the temperature of the carbon dioxide in the storage cylinder. It will be desirable to maintain rig temperature at or below this temperature to avoid any heat leak into the fluid or the need for refrigeration units. A temperature of 255 - 260 K will be cold for the crew, but not too cold to work in. Insulation in the pressure suits and/or parkas will be required.

Set Up Operations

After the drilling module has arrived on Mars, the crew will travel out to the rig in the mobile living quarters. If the lander is designed to be mobile, it will be precisely maneuvered to the desired location; if the rig is not designed with surface mobility, considerable care will have to be provided for a precision landing.

After rendezvous and positioning of the drilling module, the crew will remove equipment that will be external to the module. This equipment includes the CO_2 collection system (sorption pump and other equipment), the heat exchanger, the mud system particulate separators, and associated piping and valving. The engine bells will be removed from the underside of the lander. The ground under the lander will be leveled and the lander will be lowered until it rests firmly on the ground. Both the wellhead and the landing legs will be anchored to the ground. Design and setting of these anchors is critical, as a 10,000 psi kick, for example, will transmit 63 tons of upward force to the wellhead through a 4" bore. The wellhead must be able to safely distribute this potential load to the anchors.

When the lander is settled and anchored, the CO_2 acquisition system, and drilling fluid system will be constructed and piped. The acquisition system will be started as soon as it and the CO_2 storage vessel are completed, which will allow accumulation of drilling fluid while other set up work is proceeding. Since the acquisition system is designed to accumulate about 160 kg of carbon dioxide per day, 25 days of production will be about four cubic meters of liquid CO_2, which should be enough to start drilling. While the acquisition system is accumulating carbon dioxide for the specified period, the remaining parts of the drilling fluid system and the auxiliary systems (electrical, hydraulic) can be completed and checked out. The estimated time from arrival of the crew at the rendezvous to ready for start up (RFSU) is 60 days.

Drilling Operations

At RFSU, a quad fishtail spudding bit will be attached to the motor and first segment of drill string. The wellhead isolation ball valve will be opened and the well spudded using a very low fluid circulation. After spudding, the bit will be changed over to the 5.5" roller cone casing bit, which will drill until it is consumed. The bore will be completely depressurized while the 5" casing is set, with each section welded to the next. After casing is set, the 4" diamond bit will be attached and drilling will proceed, changing bits as required, until final depth is reached.

During normal drilling operations, adding string will use the following procedure:

1. Trip mud pump and close pump outlet valve. This will stop drilling fluid circulation.

2. Use the high pressure inert gas feed at the top of the CO_2 feed to force liquid CO_2 through the check valves in the drill motor into the bore.

3. When the entire string, from pump outlet valve to motor check valves, is emptied of liquid

CO_2, depressurize the string by venting to atmosphere.

4.

Pull up and chock string in linear feedthrough. Detach CO_2 feed from top string segment and lift to the level of the crown block.

5.

Attach a new string segment and pull up to specified torque with power tongs. Reattach the CO_2 feed.

6.

Repressurize the string with high pressure inert gas. Open mud pump outlet valve, restart pump, and ramp to desired flow.

7.

Bleed excess pressure, if any, caused by inert gas repressurization to maintain desired bore pressure.

When the bit or motor needs to be changed during normal drilling operations, the following procedure will be used:

1.

Follow the procedure above to empty and depressurize the string, and remove the CO_2 feed.

2.

Pull the string up, detaching each section as the joint passes the feedthrough.

3.

When only one drill string segment is attached to the drill motor, the motor will be pulled up to the feedthrough and the bore isolation valve will be closed.

4.

High pressure inert gas will force liquid CO_2 from the wellhead above the isolation valve into the line to the separator. After the liquid is gone, the top portion of the wellhead will be depressurized.

5.

The top of the wellhead will be removed and lifted and the bit or motor changed.

6.

When desired changes are complete, the process will be reversed to repressurize the bore and start drilling again.

Normal operations should be quite straightforward, with few technical problems. A crew of two will be sufficient to run the rig, although it may be desirable to have a crew of three on duty for safety reasons. However, drilling is a very complex operation and problems and non-standard operation are inevitable. The mass constraints on the system prevent sending a large number of specialized tools to solve whatever problems may arise, so a selection of good all-around tools has been included in the rig equipment list. These tools should be sufficient for the vast majority of common problems that may be encountered.

Stuck bits and stuck pipe are commonly encountered in drilling operations. To some extent, this problem should be partially alleviated by using 3" titanium string with 1/4" walls, a non-rotating string, and a straight bore. The strength of the string relative to the desired drilling depth (string length) and drilling forces should eliminate buckling. Nevertheless, it would not be wise not to include equipment and procedures for dealing with these eventualities. The first step, as in any terrestrial rig, would be to try to work the obstruction free using the tackle and drill fluid. Vary the pump pressure and flow, reverse the motor, pulse pressure, and apply different axial forces with the crown block. However, if the unit is well and truly stuck, numerous charges have been included in the cargo for eliminating the problem. For a stuck bit, cutting charges would sever the string above the motor, and the good string would be withdrawn. The motor and bit would then be fished with hook and/or overshot as in terrestrial applications. As a last resort, a series of toroidal charges can be dropped to destroy both motor and bit so that the pieces can be fished. For stuck pipe, the string can be cut above and below the obstruction. The good string can be withdrawn, the obstruction destroyed with toroidal charges, and the bottom segment (with motor and bit) fished. The hole will be reamed out and drilling can restart.

Lost circulation (loss of drilling fluid to the surrounding formation) is another problem that may arise. In one respect, this factor alone is what drove the authors to consider liquid CO_2 for drilling fluid, since lost circulation with any Earth imported fluid is a potential show stopper. If lost circulation remains within a manageable range, it can simply be replaced with daily make up from the acquisition unit. However, if losses exceed the capacity of the acquisition unit, bore pressure will have to be reduced. Reducing bore pressure means that the system has to be run at a lower temperature to maintain the subcooled margin of the fluid (alternatively, margin can be trimmed, with the potential consequence of damaging the mud pump), but this can be managed without undue difficulty. The lower temperature may reduce the maximum duty of the heat exchanger, which may slow circulation and reduce drill penetration rate. The exact operating pressure and temperature will be that to achieve the maximum penetration rate, and will have to be determined daily by the crews on site.

Potentially the most serious problem to be encountered by the operating crew will be kick, which is when the pressure of the bore exceeds the mud system pressure plus the static head of the liquid at the bottom of the bore. Kick has numerous adverse effects, the severity of which is mainly dependent on the rate (and, to a lesser extent, the type) of fluid inflow from the formation to the bore. A severe kick threatens a blowout, which can damage or destroy the bore and equipment, and endanger the lives of the crew. The lower gravity on Mars reduces the overburden on fluid reservoirs, which should lessen the severity of any kick.

The first line of defense against kick will have to be in the training of the crew. Consequences of kick are lowered by recognizing the phenomenon quickly and, conversely, heightened by not recognizing it in time. The crew of the Mars drilling mission will have to be one of the best trained and most experienced groups of roughnecks ever to work a rig. Once a kick is recognized, excess pressure can be bled from the system by removing bore fluid. Then the mud pump pressure and/or density (via particulate injection or a lower working temperature) will have to be increased at the pump discharge. If none of the countermeasures work, or if the kick is too rapid and threatens a blowout, the wellhead has been provided with a crush type blowout preventer as a last resort. Mass constraints preclude sending equipment that will allow the well to be restarted after the BOP crushes the string, so, in this event, operations will have to be suspended until additional recovery equipment can be flown in.

Completion and Production Operations

The drill rig has been designed as a one-shot piece of equipment. After drilling operations, the drill string can also be used as production tubing, which eliminates a considerable mass from the mission requirements. After reaching the final depth, the string can be depressurized and withdrawn to remove the motor and bit assembly. Alternatively, a cutting charge can be sent down to blow loose the motor and bit. In any event, the string desired for production tubing will have to be withdrawn to set the packers, two of which have been included on the equipment list. Once the packers are set, the well can be produced, if freeflowing, through the drill string. If stimulation is required, two perf guns and numerous charges have been included. In addition, the mud pump can be used with a heater for hot water/steam or supercritical CO_2 injection. If pressure is not sufficient for a freeflowing well, a 3" production pump can be attached to the bottom string section. Water will tend to freeze at Mars ambient temperature, so heaters may also be required along the length of the bore to prevent ice formation. Alternatively, the well can be continuously produced, venting water when it is not required for other purposes.

Failure Modes and Countermeasures

There are too many possible failure modes of drilling rig equipment and operations for a complete analysis in this paper. However, some of the more common and expected failures are briefly described along with steps to prevent them or mitigate the consequences.

Pump impeller wear, as well as erosion in piping systems, can be caused by erosive solids in the drilling fluid. Eliminating this problem may require finer mesh screens in the solids separator or, perhaps, different separation techniques. In case of a pump failure, a spare pump has been included in the mass estimates.

A similar problem will be corrosion. Water and carbon dioxide make carbonic acid, which can very quickly corrode even high grade alloys. It is likely that during drilling through the cryosphere, some ice will get into the drilling fluid. This ice must be maintained as a solid by careful monitoring of the temperature. If problems still arise, the temperature of the drilling fluid may have to be reduced further, or the piping system may have to be glass lined. Extensive experiments to determine the effect of a carbon dioxide drilling fluid on various alloys will need to be performed during the development phase of the drill rig.

Thread galling of the flush fit connections between piping sections can be caused by overtightening or by downhole stresses. The drilling module is actually tall enough that two drill string sections can be removed from the bore, which may solve the problem. However, if this method fails, the string will have to be cut and the bad connection removed.

Operator error is probably the most likely cause of system failure. So many things can go wrong, from overtightening connections to overspeeding the pump, that it seems inevitable that there will be errors along the way. This will have to be solved with training, not only in how to operate the system, but in all imaginable failure modes, and in the design tolerances and capability of each tool and piece of equipment in the system. This will allow the operators to assess a failure accurately, and quickly develop solutions using available resources. The required exceptional level of training cannot be overstressed.

CONCLUSIONS

Water is an essential commodity on Mars, particularly if we wish a large and expanding human presence on the Red Planet. The majority of potential sources of water on Mars either require a significant amount of power or a large crewed effort to collect appreciable quantities. The one exception to this is the hydrosphere, which requires a relatively large up front effort, but provides nearly unlimited water after a bore is completed.

It seems likely that water will be found within a kilometer or so of the Martian surface. Terrestrial drilling techniques can be adapted to find and reach water at this depth using very lightweight drilling rigs, capable of being launched with no more than the vehicles proposed for the NASA design reference mission. The key to making a lightweight Martian drilling rig, as with many Mars efforts, is to use the materials available *in situ* to reduce the material that must be brought from Earth. Since the most massive portion of a drilling system is the drilling fluid, using liquid carbon dioxide from the Martian atmosphere will reduce the imported mass considerably. In addition, strong lightweight alloys can reduce the mass of components, and eliminating unnecessary tools and equipment will reduce the total mass of the proposed drill rig to 10 - 33% of an equivalent terrestrial rig, not including the mass savings from the drilling fluid. In summary, the mass of a Martian water drilling mission can be reduced to a level that can be launched with near future systems and relatively soon in a series of crewed Mars missions.

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