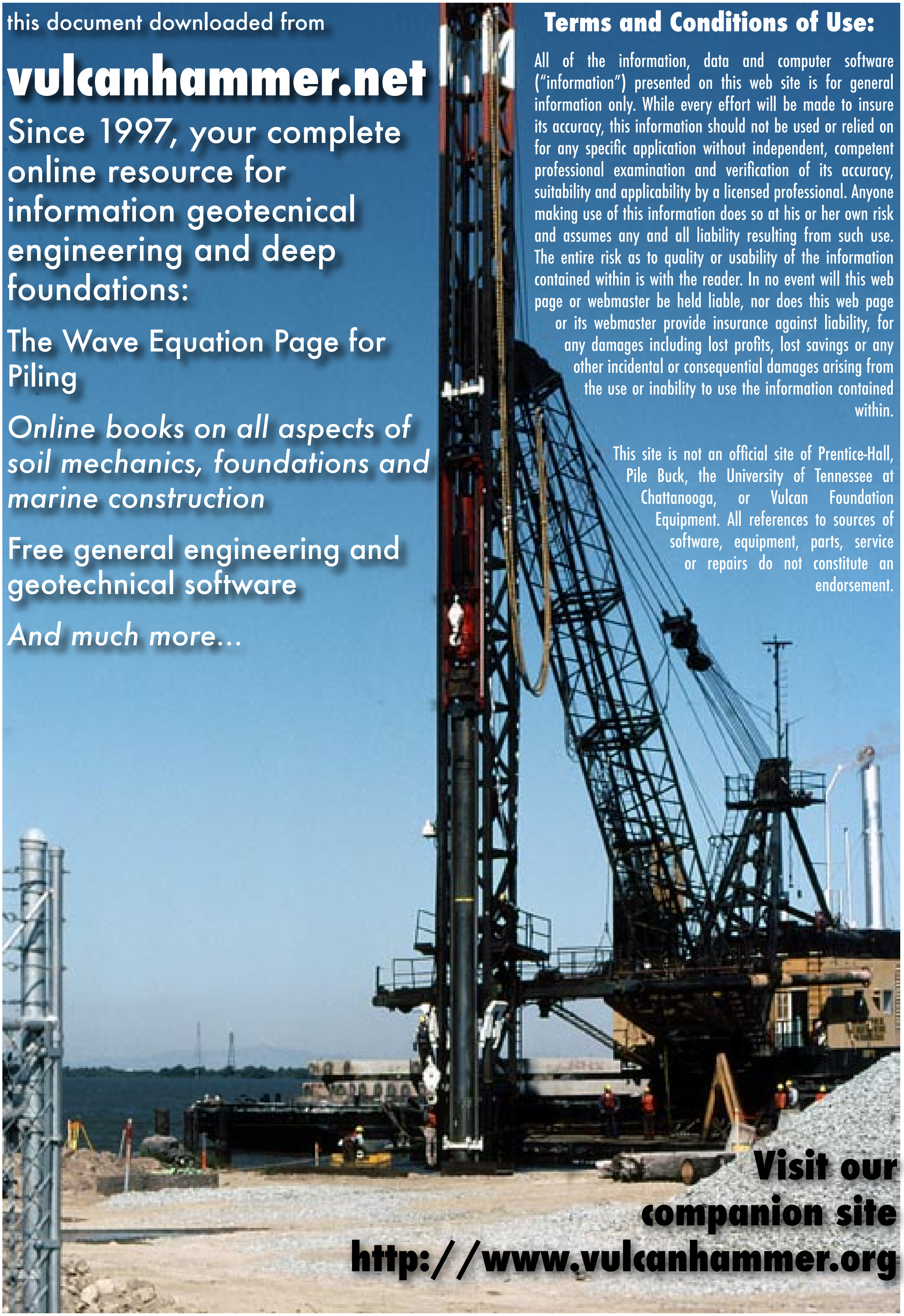

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Title: THE 3RD DIMENSION OF PLANETARY EXPLORATION - DEEP SUBSURFACE SAMPLING

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THE 3RD DIMENSION OF PLANETARY EXPLORATION - DEEP SUBSURFACE SAMPLING

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Abstract

Strategic planning for the exploration of the Martian subsurface to search for evidence of life, sources of water, and to determine the geologic makeup and history of the planet, has begun. A mission to explore and sample the Martian subsurface hydrosphere, which may be 4-km deep, will be more complex than any mission accomplished to date. In order to reduce risk, a phased approach is being planned with shallow and intermediate depth precursor missions. We researchers at Los Alamos National Laboratory are conducting a conceptual system study of a 200-m, intermediate-depth penetration and sampling mission on Mars. We constrained the study with a reasonable set of surface and subsurface environmental conditions and science requirements. Mission requirements include a 200-day duration, a soft lander which will fit within a Delta III payload fairing, a 250-kg drilling system mass limit, and a maximum available energy for drilling of 1 kW hr/sol. Existing and conceptual drilling technologies are compared, and the down-selection process results in mechanical drilling/sampling subsystems that can be mixed to produce a number of specific systems that can be studied in more detail. Promising technology areas that need further investigation are identified.

Introduction

Planetary exploration proceeds at several levels from remote sensing to in situ characterization to sample return. Up to the present, most effort has been in remote optical sensing of planetary surfaces in a range of wavelength bands, from which inferences can be made about mineralogical and compositional characteristics of surface exposures. At another level and by analogy with geologic investigations of Earth, characterization of the 3rd dimension (planetary interiors), and the 4th dimension (time history) are essential for a full understanding of planetary processes and their evolution. In the case of the 3rd dimension, planetary interiors are explored by remote geophysical techniques, direct sampling by the drill or kinetic penetrators, or indirect sampling through cratering and other processes that naturally transport subsurface materials to the surface. Direct subsurface sampling is the most fundamental technique. This is because the geophysical inverse problem is non-unique and inferences from remote geophysical measurements must eventually be validated by measurements on samples acquired from the subsurface. Samples excavated by impacts are often strongly altered from their in situ characteristics, and prior depositional depth is uncertain. Today, we only have geophysical subsurface sensing data for the Moon and these data are only validated for 1 to 2-m depth by returned Apollo and Luna samples. However in the next decade or so, we can foresee both remote and direct exploration of the Martian subsurface and perhaps other bodies such as Europa. It is timely to examine the technologies that will be needed to affect planetary exploration in the 3rd dimension with emphasis on in situ measurement and sample acquisition.

Planetary interior in situ measurement or sampling implies an access technology. For very shallow depths, scraping, scooping, digging, quasistatic or kinetic mechanical piercing, augering or even explosive excavation techniques can be considered. However, for depths below a few meters and certainly below a few tens of meters, some kind of small-bore drilling technology is needed. Based on commercial deployment and terrestrial conditions, numerous and highly varied drilling technologies have evolved. While their details differ, all drilling methods involve the application of energy to destroy the aggregation and mechanical strength of rock constituents for removal to produce a void. For terrestrial drilling, the fundamental selection factor driving technological development has been cost and secondary factors that are strongly related to cost, for example, advance rate. In extraterrestrial

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scientific drilling, cost is also the fundamental driver but the secondarily related factors are much different. Engineering R&D, fabrication cost, operating cost, safety - all cost-related factors that have strongly determined terrestrial drilling machinery designs - are relatively small in comparison to transportation costs for a drilling system on Mars or even the Moon. Hence, mass limitations will be the most important factor determining the design of extraterrestrial drilling equipment, and many secondary factors such as power are directly related to mass. However, there are some subtleties here. It does little good to land a low-mass, low-power drilling system on Mars if the drill proves incapable of penetrating the rock encountered in the subsurface, whose characteristics are almost totally unknown beforehand. Thus, high flexibility and reliability, which tend to be proportional to mass, will also be strong factors in drilling systems design.

System design is further complicated because access alone will likely be insufficient to meet many of the scientific goals of subsurface investigations. For example, the astrobiology goal of searching for fossil or extant life in putative Martian subsurface ground water will almost certainly require acquisition of samples conveyed to surface instruments for analysis, or returned to earth. Subsurface sampling in the context of planetary protection is a daunting technological challenge in itself that will have to be integrated with the drilling technology. All of this is still further complicated by the need for a high degree of automation required for robotic investigations that reduce the mission cost and reduce the risk to human explorers.

At present, others and we are considering the many factors associated with planetary drilling and sampling, and we are performing conceptual systems analyses with the goal of determining technology development paths. To acquire the desired planetary data on Mars, drilling missions approximately 4-km deep are being considered. However, an incremental approach is planned with shallow missions of 1 to 5-m and ~200-m deep as first steps. The 1 to 5-m mission might be accomplished with relatively simple existing technology; however, once the desired depth increases beyond a few meters or tens of meters, the drill system complexity increases substantially. This first study assesses drilling and sampling technologies believed to be capable of drilling a 200-m deep bore hole to retrieve rock, soil, and fluid samples maintained at close to in situ conditions.

Study Constraints

Although the requirements for such a mission have not yet been defined, previous workshops and planning exercises have discussed these issues extensively[1]. With the results of these planning exercises, we specified for this study the expected surface and subsurface environment in which the drilling/sampling system would operate on Mars, and a reasonable set of mission constraints for mass, power, and duration.

The expected Mars atmosphere and surface environment is listed in **Table 1**. This environment has several important implications for any drilling system that must operate under these conditions. First, the extremely cold temperature of the near surface will be below the triple point of CO_2 (216 K) and will require that (1) all fluids used are maintained above their freezing point, and (2) the viscosity of these fluids remains low enough to pump through the system. Also, some common structural materials will be prone to brittle fracture at these temperatures. Rock at these temperatures will likely be more brittle and higher strength than those found in terrestrial environments. The low moisture content will increase the coefficients of friction. It is likely that predicting Mars drilling-system performance will be difficult when using terrestrial drilling data. The low atmospheric pressure ($1/127^{th}$ of an Earth atmosphere) will require very low vapor-pressure fluids or pressurized, near-leak-free systems. Thermal management will also be a challenge at these low pressures. Shielding from the high radiation environment at the surface and the possibly corrosive dust will be required.

Table 1: Atmosphere and Surface Environment Assumptions

- Atmosphere 95 % CO_2
- Dust storms with particles up to 100 μm
- Atmospheric pressure 600 +/-200 Pa
- Surface temperature 150–290, average 200 K
- Wind velocities 5 m/s average to 50 m/s max. for a maximum wind loading of 90 Pa
- Maximum slope of 30 degrees to the horizontal
- Surface material strength varies from unconsolidated sand to solid basalt or igneous rock
- Dust assumed to be highly oxidized, possibly corrosive particulate
- High coefficients of friction due to extremely low moisture content
- Ultraviolet and ionizing radiation at surface renders organic materials unusable

Table 2 lists the subsurface environmental assumptions, and likely science measurements. Although the full range of possible rock formations that might be encountered in the Martian subsurface is not known, best estimates from the survey by Clifford and workshop discussions result in the minimal list of rock materials shown[1]. Any drilling system must be robust enough to deal with this wide range of possibilities. Highly permeable formations will likely be penetrated, and this will preclude the use of cooling or cuttings transport systems that would allow significant flow into the formation. Frozen soils are to be drilled if encountered; therefore, melting-induced wellbore collapse and melting samples while coring must be avoided.

Table2: Subsurface Environment

- Likely rock types:
  - -Solid, fractured and vesicular Basalt
  - -Cemented and unconsolidated sediments
  - -Frozen soils and ground ice
  - -Crater debris analogous to lunar samples
- Drilling system not designed for pressurized zones - monitor and sample flow
- Conduct geophysical logging

  Measure While Drilling:

  -Bottom hole temperature, pressure, borehole caliper, natural gamma or other chemical log

  -Drilling process – weight on bit, torque, rotation speed, BHA & core temperatures

  Science during operations

  -Volatile gas sampler, reduced carbon detection, acoustic monitoring using surface sensors

  Science post-operations

  -Post-drilling (recovered) temperature, rock composition, resistivity, acoustic velocity, televiewer, borehole seismic array

To simplify the analysis at this early stage, it is assumed that the system will not be designed to continue drilling if pressurized formations are encountered; however, the sensing system should monitor and sample flow from the pressurized zone. Geophysical logging will also be required, and a minimal list of measurements is also shown in Table 2.

A reasonable set of mission requirements is listed in **Table 3**. Particularly the mass, but also the power limitations, will severely constrain the system size. Very small hole diameters will be required. Also required will be low bit thrust, or some type of anchoring system that will perform on landing sites that may vary from hard rock to unstable sand. Very thin-wall, low-density, high-strength tubing will be needed for drill stem and bore stabilizing casings. Transport of common well-construction materials such as drilling fluids and cements will likely be unfeasible. The transport volume will limit threaded and coupled pipe lengths to about 1 m, and continuous tubing will be transported in a coil limited to around 1.5-m in diameter.

Table 3: Mission Requirements

- Maximum system mass of 250 kg for the penetration and sampling system
- Maximum system energy requirement of 1.0 kW hour per sol
- Lander compatible with 4-m diameter Delta III payload fairing
- Drill a near vertical 200-m deep sampling and monitoring hole
- Drilling and sampling must be completed within 200 days (~1 m/sol)
- Autonomous command and control
- Legacy requirement – favorably weighted subsystems will scale to 4-km deep system
- Biological contamination avoided by sterilization to Viking standards before launch
- Chemical contamination limited to elements found in typical drill bits, candidate thin-metal containers and cutting fluids
- Core sample minimum dimensions: 1500-mm^3 volume, 10-mm diameter., 20-mm length
- One sample per meter of hole depth
- Maintain sample near in situ conditions: < 10 K ΔT, < 10 times atmospheric pressure variation

No drilling operation has ever approached the level of autonomous control that will be required for this robotic mission. Terrestrial drilling in previously undrilled terrain is often a trial and error process until an economic drilling method is identified and successfully adapted to meet unique local conditions. Commercial drilling systems tend to be composed of modular subsystems that are readily customized to adapt to unexpected conditions. Equipment (including spares) to deal with all anticipated problems must be transported, and sophisticated expert systems must be developed which can analyze and correct problem situations as they occur. This will require drilling process monitoring and expert system performance that far exceeds the capability available on today's drill rigs.

Taking a core sample every meter will require efficient and reliable insertion and removal of the drill stem and coring subsystem. Continuous coring while drilling, separate bottom-hole coring, or side-wall coring could be employed. Sidewall coring requires a larger bore, and initial calculations indicate that it will be eliminated due to mass constraints. If attempted, it should be done from the bottom up after drilling and surveying is completed to prevent premature loss of access to the hole. In order to avoid biological contamination, acceptable organic materials or inorganic substitutes need to be identified to serve as low vapor-pressure lubricants, wire insulation, and seals. Maintaining the core samples at near in situ conditions will make down-hole thermal management a major challenge. In addition to a very slow and efficient rock comminution process, active cooling will likely be required.

Potential Drilling Technologies

A comprehensive survey of existing, prototype and conceptual drilling methods has been completed, and **Table 4** contains a condensed list. We have tried to include all technologies that may be applicable to deep planetary drilling missions. Some of these technologies include today's commercial deep-drilling methods. These are mechanical systems that include top-drive rotary and bottom-hole-powered rotary or percussion systems. Overburden drilling is an effective commercial technique for dealing with near surface, unstable boreholes. The jack hammer drifter and flame jet spallation drills are used in the mining industry. A number of the techniques, such as the jet, electric arc, and laser drills, are used in rapid machining of hard materials. Also included are methods that are research prototypes or concepts that have not been fully developed or commercialized. It is likely that none of the methods listed can be used as a standalone drilling system. However, the successful system will be a combination of several methods that can be combined to drill through all rock types, acquire samples, and stay within the mass and power budgets.

Down-selection of Drilling Technologies

Starting with this list of potential drilling technologies, we did a first-order screening using a pass-fail criterion by comparing each drilling method to the mission requirements using simple calculations and engineering judgement. We tried to be generous in passing systems for more detailed analysis, but had to reduce the list to a manageable number given the limited resources of the study. Searches were made on oil and gas, mining, ceramic machining, trenchless utility industry, civil engineering, and defense literature to develop detailed descriptions of systems and to obtain operational data. Proprietary or classified sources were not used. Considerable engineering judgement was needed at this point to visualize adaptations of terrestrial drilling systems to Martian conditions. There is a general lack of quantitative and operational data on systems or prototypes. We did not attempt to analyze several theoretical concepts for this reason, but instead favored systems for which we could find adequate data. This inevitably led to a biased screening, but was in line with our objective of favoring demonstrated capabilities over unproven concepts.

We had planned on using a weighting scheme to rank the best systems. However, this was not feasible for two basic reasons. First, we did not find adequate data sets to support reasonable comparisons. Second, we did not find theoretical, "first principles" models of the physics of rock penetration processes that would allow an objective comparison. So called "specific energy" has been used by some researchers to compare drilling systems, but this is not a satisfactory measure. Specific energy is not a material property but is really a process energy that has been defined in the literature in different ways. Specific energy depends on a myriad of factors including rock physical properties, comminution mechanisms, specific process variables such as cutter design, rotation rate, weight on bit, effectiveness of cuttings removal and a host of others. Change any variable and the specific energy changes. Therefore, this parameter cannot be used as the basis of a quantitative weighting algorithm but only as a general guide; for example, systems characterized by lower process energy consumption are generally preferable to those that use more energy, all else being equal. We used specific energy or process energy in our analyses when that was all that was available, but only in a general, non-selective way.

Subsystem Technologies

Our detailed analysis focused on subsystems and generic approaches rather than specific drilling systems. Based on our experience with terrestrial drilling we assume that rock comminution will consume the most power from the total energy of 1kW hr/sol available for the drilling system. Solid basalt is assumed as a worst case from a process energy point of view. The preliminary power budget assumed is shown in **Table 5**.

After the initial and detailed screening described above, of the possible comminution mechanisms (mechanical, thermal, jet), the lightest and most efficient mechanical methods are all that remain. Systems that require the use of liquid or supercritical fluid circulation were removed because (1) excessive fluid losses would occur to any permeable rock, (2) severe contamination of permeable core samples would occur, (3) circulation will tend to melt and destabilize frozen formations, and (4) fluid jets in the low-pressure

Drilling Method	Rock and Soil Comminution	Drill Conveyance	Description
Surface percussion drills [2,6,15,16,17]	Mech. rotary/ percussion	T&C †† drill steel	Rotary percussion drills with surface power units that reciprocate and rotate the drill stem to power a down hole bit or core head.
Cable deployed drills [2,6,16]	Mechanical percussion	Umbilical sandline	Drilling assemblies deployed on a mechanical wireline (sandline) or electric wireline (mechanical, telemetry, and/or electric power)
Rotary drills [2,3,4,5,16]	Mechanical rotary	T&C drill Pipe	Drilling assemblies deployed on segmented drill stem and rotated from the surface with a rotary table on the rig floor or a top drive power swivel.
Downhole motor and rotary hammer drills [4,5,6,7,8,9,15]	Mechanical rotary/ percussion	Continuous tubing	Drilling assemblies deployed on coiled tubing and rotated and/or reciprocated using downhole rotary motors and/or hammers. These systems can be deployed on segmented drill stem (and rotated from the surface to eliminate the need for a downhole rotary or indexing motor) but telemetry is more difficult.
Piercing soil drills [18]	Local formation compaction	T&C push rods	Soil piercing and ramming assemblies deployed on segmented push rods design to transmit high compressive impact loads.
Overburden drilling systems [16,18]	Coring, local compaction, erosion	Special piercing casing	Drilling systems based on advancing a casing for borehole stabilization in unstable surface formations while or before drilling a smaller diameter hole to penetrate harder formation where these systems will not drill.
Subterranean moles [18,JPL+RDS]	Local formation compaction	Self propelled mole / umbilical	Systems based on a self propelled drilling machine that closes the hole behind itself or fills a large fraction of the hole behind itself leaving a small diameter hole for an umbilical connection to the surface which serves a conduit for power, cooling fluid circulation and cuttings disposal.
Jet and cavitation Drills [6,10,11]	Hydraulic Impact/erosion	Continuous tubing with utilities	Drills that produce holes with a high velocity fluid jet impacting the rock to cause brittle failure or eroding the rock. These systems are assumed to be deployed on coiled tubing and rely on downhole motors or angled jets if rotation of the jet(s) is required.
Thermal Spallation drills [6,10,12,19]	Thermal stress spallation	Continuous tubing with utilities	Drilling using rapid downhole heating or cooling of rock to induce thermal spallation - rapid temperature change to produce near surface stress failure of the exposed rock. These systems are assumed to be deployed on coiled tubing and rely on downhole motors if rotation of the jet(s) is required.
Rock melting drills [6,10,13]	Thermal fusion	Continuous tubing with utilities	These are a family of systems based on partial or complete fusion of rock to produce a densified cast bore lining and excess melt removed by extrusion & solidification of small particles.

†† Threaded and coupled

Table 4. Condensed List of Potential Deep Planetary Drilling Technologies

bore will be unstable and inefficient. The mission mass limitations eliminated the jackhammer drifter drill that relies on massive, thick-wall drill steels to transmit power, the abrasive jet drill that requires mass and power-intensive separation equipment for abrasive reuse, and thermal spallation drills that require propellant transport or an in situ propellant plant. The rock melting method was eliminated because the resulting hole size did not support the acquisition of a core sample which met the size requirements, and there was concern about thermal destabilization of water-saturated frozen ground.

Table 5: Process Power Breakdown

Process	Power budget fraction
Rock comminution	1/3
Bore stabilization	1/6
Drill assembly conveyance and cuttings transport	1/6
Thermal management	1/6
Automation, control, & sensor support	1/6

The resulting drilling/sampling subsystems are shown in **Table 6**. These subsystems can be mixed and matched in matrix fashion to produce a number of specific systems that cannot easily be compared at this point, due to a lack of relevant data on the their performance under Mars-like conditions.

Example Systems

To further illustrate what an optimum system might look like, we have put together three EXAMPLE SYSTEMS that embody most of the range of possibilities. These example systems, listed in **Table 7**, are currently being analyzed to determine the total mass and power of their components to illustrate how tradeoffs might be made.

The first system, shown in **Figure 1**, is a coiled-tubing-deployed rotary diamond core drill and a polycrystalline diamond (PDC) reamer. The system employs a down-hole hydraulic motor for coring and reaming and uses a refrigeration cycle for down-hole cooling. This allows power and coolant to be transported in liquid form through small-diameter tubing. The continuous reeled tubing sequentially conveys the coring drill, reamer, and bucket auger. Borehole stabilization is accomplished with an expanded metal liner fabricated down hole. A metal strip moves down with the bucket auger, and is spirally wrapped and welded or zippered down hole to form the casing. Rock is removed as a continuous core, with the remaining cuttings transported to a junk basket by pulsed airflow with acoustic agitation. A bucket auger is deployed following reaming.

Figure 2 shows a schematic of example system 2. This is an umbilical wireline-deployed percussion (cable tool) sonic core drill. It is surface-reciprocation powered, with heat dissipated by conduction to the surrounding formation. Rock is removed as a continuous core, with the remaining cuttings cleaned from core bit by air blast and acoustic agitation. A wireline-deployed bucket auger is deployed between core runs. A liquid or slurry made from fine cuttings is injected into the formation porosity and fractures that then freezes or dries to form a formation binder. This binder will require development effort, since none exist for basalt or clastics to form a counterpart to calcium carbonate cements.

Example system 3, shown in **Figure 3**, is a micro-PDC rotary core bit deployed on segmented drill stem. The core bit is powered by a down hole electric motor. The hole is stabilized with an overburden casing advance system with a rotary reamer shoe on the bottom of the casing. An umbilical contains tubes for telemetry, gas flow, and closed-loop refrigeration cooling. The umbilical is run down after the drill stem is deployed, and is connected to the assembly with a dry version of "wet connect" technology. Rock is removed as continuous core. Finer cuttings are moved up auger flutes in the core drill with pulsed airflow and acoustic reciprocation to a junk basket.

Conclusions

Given the presently agreed upon mission mass and power limits, only high efficiency mechanical, overburden-type drilling approaches are feasible. If these constraints are relaxed some drilling approaches, such as fluid jet and thermal drilling, can be reconsidered. Research is needed on all of the subsystems we have identified; however, the most critical areas are rock comminution, cuttings transport and disposal, drilling automation and robotics, hole support, and materials applicability.

Rock comminution mechanisms need to be investigated since a wide range of rock types will be encountered with almost no data on key properties of strength, cohesion, and coefficient of friction under low temperature, near-vacuum conditions.

Cuttings must be removed and transported from the penetration face. If cuttings are not efficiently removed, they are reground unnecessarily, expending energy, and cause excessive frictional heating. Terrestrial methods, which use drilling muds, foam, or compressed air, are not feasible under the constraints of

ROCK COMMINUTION	*DRILL STEM*	*POWER*	*THERMAL MANAGEMENT*	*CUTTINGS TRANSPORT*	*BIT DRIVE*		*BORE STABILIZATION*
					Rotary	*Thrust*	
Rotary diamond kerf (sonic)	Coiled tubing	Hydraulic	Closed loop liquid circulation	Continuous core	Surface motor	Surface thrust	Overburden drilling casing - Segmented tube - Fabricated tube
Percussion-OBD (sonic)	Segmented drill casing	Electric	Conduction	Bucket bailer	Bottom motor	Surface recip.	Bottom fabricated casing
Rotary PDC eccentric reamer (sonic)	Umbilical - Structural cable - Telemetry cable - Flexible tube	Mechanical - Recip. - Rotary	Closed loop refrigeration cycle	Air puff to cuttings basket		Bottom thrust	
Sonic (rotary)	Segmented drill stem		Heat pipes	Continuous gas circulation		Bottom hammer	
				Sonic agitation		Bottom recip.	

Table 6. Subsystem Technology List

SYSTEM	*COMMINUTION*	*DRILL STEM*	*POWER*	*THERMAL MANAGEMENT*	*CUTTINGS TRANSPORT*	*BIT DRIVE*	*BORE STABILIZATION*
1	Rotary diamond core drill and PDC reamer	Coiled tubing	Hydraulic motor - closed loop	Closed loop refrigeration	Continuous core, pulsed airflow, & acoustic agitation Transport of core kerf cuttings to junk basket Bucket auger run following reaming	Bottom drive	Overburden drilling casing
2	Cable tool percussion sonic core drill	Umbilical wireline	Main drill: mechanical Reciprocation Electrical for acoustic source & bucket auger	Conduction cooling	Bucket bailer	Surface recip.	Wireline-deployed injection tool. Inject compound that dries or freezes
3	Micro rotary PDC kerf drill	Dual-string segmented drill stem and casing Umbilical for telemetry, gas flow for cuttings & coolant	Electric motor for core bit Mechanical rotary for overburden casing	Closed loop refrigeration	Pulsed airflow, acoustic reciprocation, & rotary auger to cuttings basket Bucket auger rotary drill stem between core runs	Top drive drill stem rotation	Overburden casing, rotary reamer on casing bottom

Table 7. Example Systems

this study. The transport of cuttings short distances using (ultra)sonic vibration, auger ramping, and dynamic gas flow (puff) appear feasible, and need to be investigated under Martian conditions.

Drilling is a complex unpredictable process, making automation difficult. Installing and operating rugged process sensors is also a challenge. However, drilling on Mars will require automation that has never been achieved in terrestrial practice, which relies on a few parameters sensed at the surface. Real-time down-hole measurement of the drilling process telemetered to the surface is required. Comprehensive control software will have to be developed.

Current knowledge of the Martian subsurface suggests that unconsolidated or otherwise unstable zones will make up at least part of the stratigraphic column in even relatively shallow holes. Destabilizing pore or ground ice while drilling is also possible. Hole stabilization is required for any credible, reliable drilling system. Temporary hole support is achieved using drilling muds in terrestrial practice, but these methods are not feasible on Mars. Overburden drilling using a concentric casing and drill string is feasible; however, modified drilling methods may be required using thin-walled, lower strength tubing. Down-hole casing fabrication methods also have potential.

Materials applicability in all subsystems will have to be researched. Current diamond-impregnated bits and aluminum and titanium alloys may not be suitable for percussive loads at 200 K, and currently used polymeric materials may contaminate core samples.

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System I

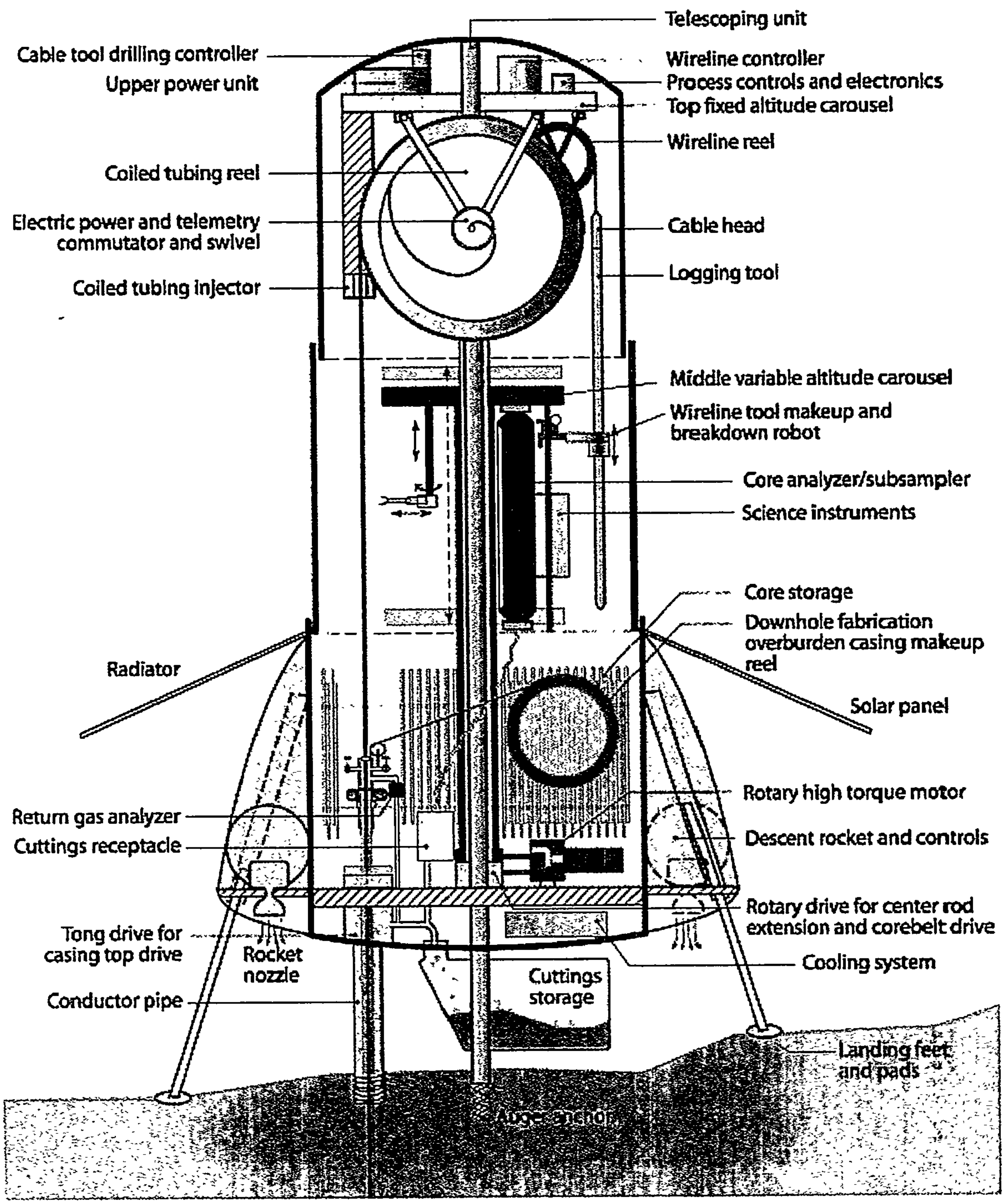

Figure 1. Example system 1, coiled tubing deployed diamond core drill.

System II

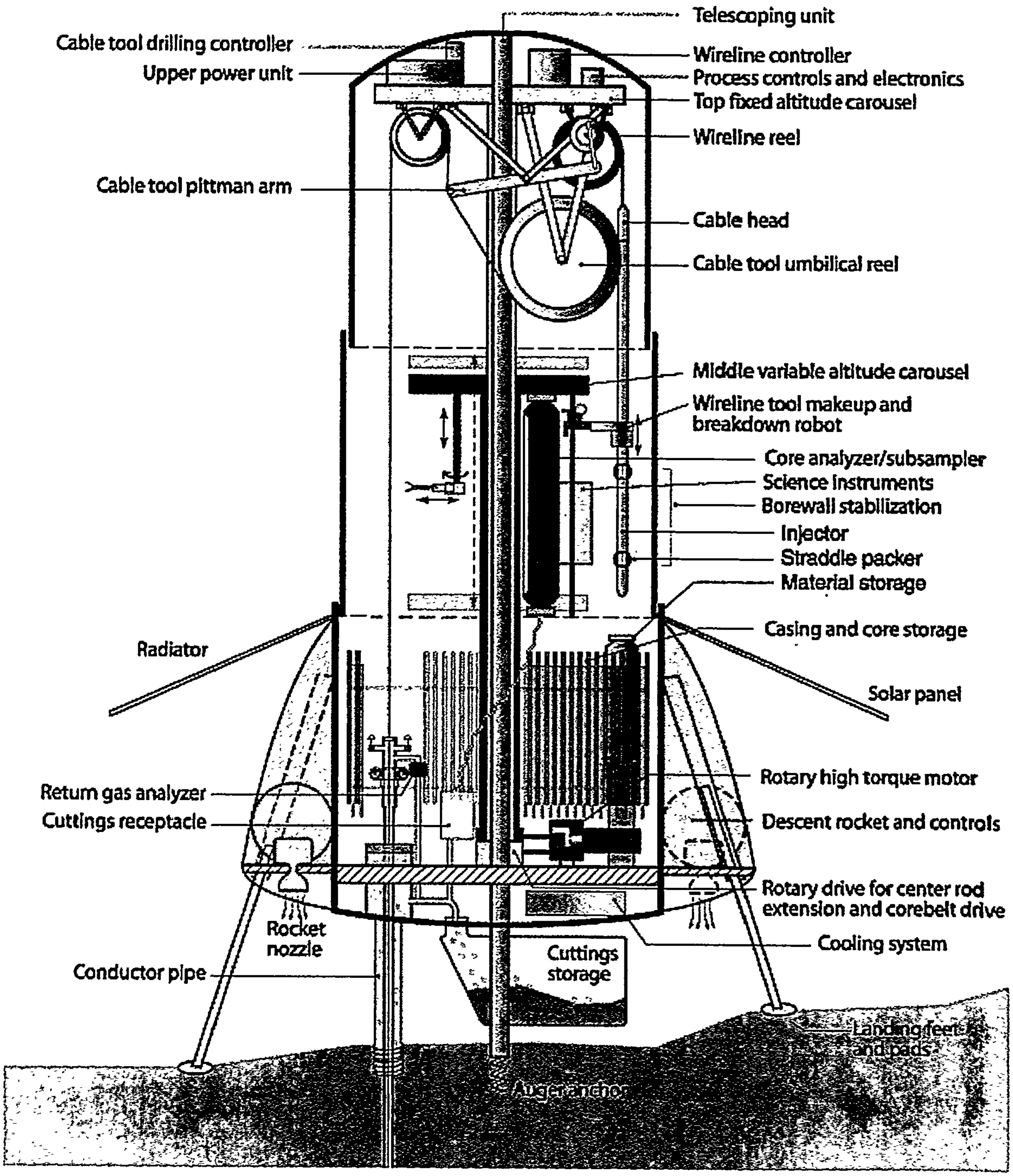

Figure 2. Example system 2, umbilical percussion cable tool.

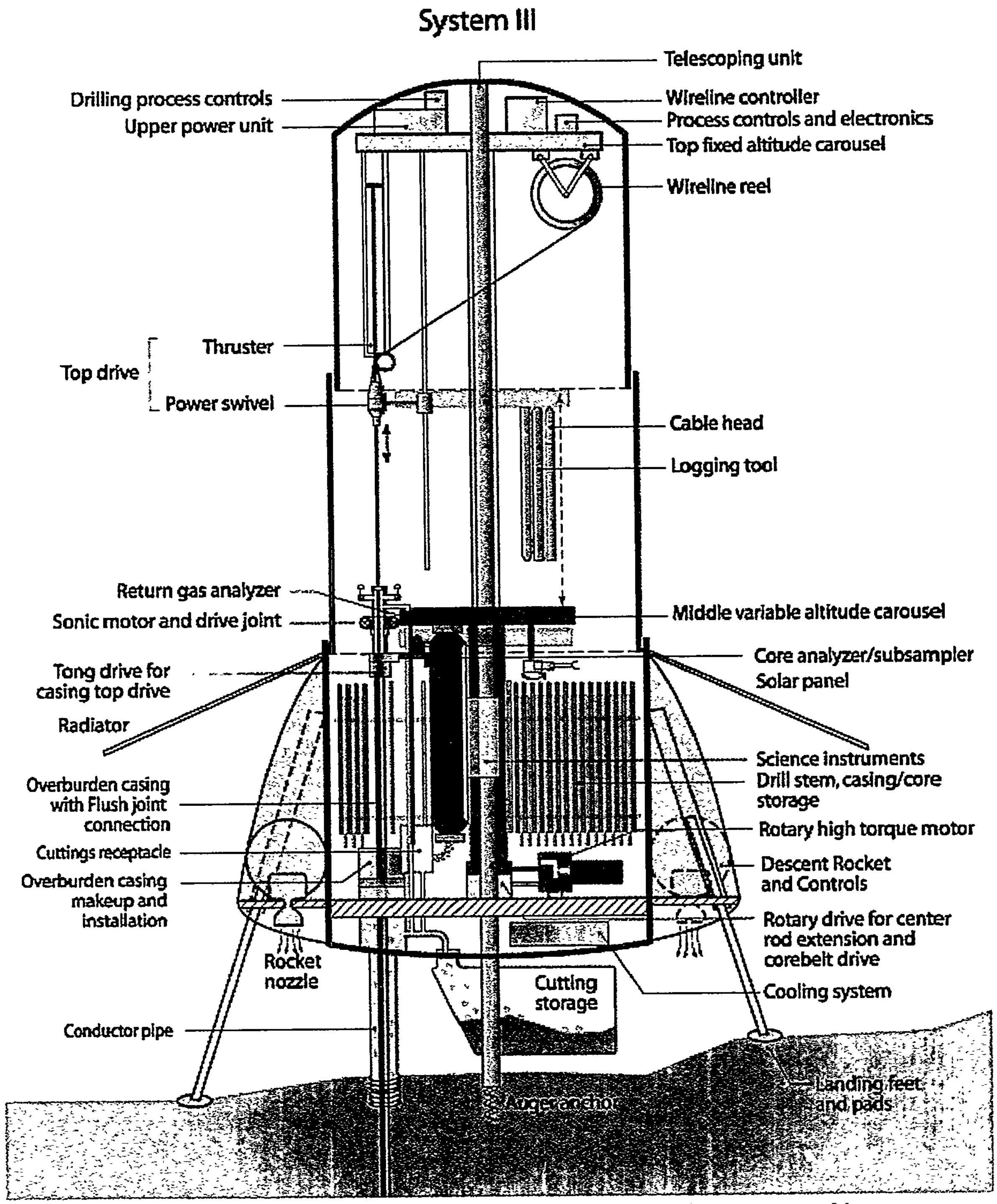

Figure 3. Example system 3, segmented drill stem with rotary core bit.