Mars Deep Drill – A Mission Concept for the Next Decade

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By accessing and analyzing material from tens of meters below the surface, *in situ* science investigations may help answer some important questions about Mars, in particular about whether life ever existed there. Drilling is a proven technique for terrestrial applications that appears viable for accessing Martian subsurface samples and bringing them to the surface for analysis by a variety of instruments. An end-to-end mission concept for a Deep Drill mission has been developed and appears feasible for launch in the next decade.

Nomenclature

ARR	=	ATLO Readiness Review
ATLO	=	Assembly, Test, and Launch Operations
C_3	=	launch energy
CBE	=	Current Best Estimate
CR	=	Confirmation Review
DGB	=	Disk-Gap-Band, refers to the supersonic parachute design
DLA	=	Declination of the Launch Azimuth
DOF	=	Degree(s) Of Freedom
EDL	=	Entry, Descent, and Landing
GN&C	=	Guidance, Navigation, and Control subsystem
L_s	=	solar longitude of Mars
L/D	=	Lift-to-Drag ratio
LTST	=	Local Solar Time at Touchdown
NASA	=	National Aeronautics and Space Administration
MEPAG	=	Mars Exploration Program Advisory Group
MOLA	=	Mars Orbiter Laser Altimeter, the instrument on Mars Global Surveyor that provided accurate, global measurements of altitude on Mars (i.e., the current standard)
MMRTG	=	Multi-Mission Radioisotope Thermoelectric Generator
MSPSG	=	Mars Science Planning Synthesis Group
MTO	=	Mars Telecommunications Orbiter
PDR	=	Preliminary Design Review
PMSR	=	Preliminary Mission Systems Review
ROM	=	Rough Order of Magnitude
SPAD	=	Sample Preparation And Distribution
SS I&T	=	Sub-System Integration & Test
TPS	=	Thermal Protection System
TRL	=	Technology Readiness Level

I. Introduction

IN the not too distant future, NASA may consider sending a robotic mission to Mars to drill tens of meters below the surface to search for evidence of life. Mars science groups, including NASA's Mars Exploration Program Analysis Group (MEPAG), have repeatedly concluded that *in situ* scientific analyses of samples from significant depths below the surface are important for understanding Mars in general and for searching for evidence of past or

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present life in particular. Furthermore, there are several ongoing technology developments for relevant drills, the readiness of which seem promising for use by the second decade of this century.

In February 2001, the Mars Program Office held an international workshop in Houston to assess the feasibility of drilling on Mars. The science-side of this assessment found that, while science value increases with depth (although not linearly), there is specific justification for an early subsurface-focused mission to access at least 10 m deep **(are these reports reference-able?)**. The engineering-side of this assessment concluded that drilling technology with the capability to reach between 10 and 20 m on Mars was sufficiently advanced such that a drill system could be readied for a mission launching as early as the latter part of the current decade with acceptable risk levels. Since then, preliminary mission concepts have been developed with science objectives, first-order (Level 1) mission requirements, candidate science investigations, candidate drill systems, flight system designs, mission operations concepts, and cost estimates. These evolving mission concepts aid in defining long-lead technology requirements for such a mission, key trade studies that need to be performed, and overall mission cost estimates important for NASA program planning.

In 2003, at NASA's request, the Mars science community, with leadership from the Mars Science Planning Synthesis Group (MSPSG), developed a set of 4 Pathways[1] or Program architecture scenarios, that it felt were likely options for Mars missions in the second decade of this century. The work was based on a number of assumptions, including potential scientific discoveries in the current decade, expected technology readiness for next decade missions, and an estimated Mars Program budget. A mission called Deep Drill was included in 3 of the 4 Pathways, with a launch targeted for the end of the next decade. This paper describes a Deep Drill mission concept that has been developed during the past year in response to this MSPSG report.

Given the nature of this early, conceptual work, many of the assumptions, constraints, analyses, and choices described in this paper are very preliminary. They will continue to evolve as NASA and the scientific community become more involved, as the technology matures, and as the mission moves toward implementation.

II. Deep Drill Science

[Intro by D. Beaty:

- **Why Deep Drill?**
- **Science Value – define habitability**
- **Present vs. Past Life (or put this under discussion of objectives)]**

A. Exploration Pathways and Deep Drill

Taking into account science priorities technology roadmaps and programmatic considerations, the MSPSG developed the following four Exploration Pathways:

1) Search for Evidence of Past Life
2) Explore Hydrothermal Habitats
3) Search for Present Life
4) Explore Evolution of Mars

Each consists of a sequence of missions for pursuing an alternate line of investigation. Included in each of the first three pathways is a mission called "Deep Drill." It is described as conducting a vertical exploration at a site on Mars at which strong evidence exists (e.g., from a prior mission) for habitability. Investigations would focus on searching for evidence of past or present life. The Pathways report suggests drilling as the technique for accessing the subsurface and collecting samples for analysis by the science instruments.

B. Deep Drill Science Objectives

To aid in developing a concept for the Deep Drill mission, we created a very preliminary set of science objectives, shown in Table II-1. **[Dave, you may want to put in a caveat here about these being a placeholder and that final science objective will be more focused].**

Table II-1. Draft Science Objectives for Deep Drill

No.	Objectives
1	Characterize the geology (stratigraphy, structure, chemistry) and geophysics of the shallow Martian crust at one site, particularly as it relates to interpreting past habitability: (a) Determine as a function of depth the geologic processes that have resulted in deposition, hydrothermal alteration, diagenesis, and tectonic modification of the Martian geologic record. (b) Investigate the seismic and thermal characteristics of the Martian subsurface. (c) Obtain visual and spectroscopic images of the local landing site to establish context for the subsurface sample analysis and to determine the surface landing location.
2	Search for past and/or present life in the subsurface at one site: (a) Determine the concentration of frozen and liquid water in the Martian subsurface, and its textural relationship to the non-volatile components. (b) Evaluate the presence/absence of biosignatures.
3	Record the meteorology and seismology at one site for at least one Martian year.

Table II-2. Candidate Science Investigations for Deep Drill

[Discussion by Dave]

C. Candidate Investigations

To support the science objectives, we developed a list of candidate science investigations, which are summarized in Table II-2. They are consistent with a set of high priority investigations developed by the MEPAG. **(ref. MEPAG website for current version?)**

[Discussion by Dave]

D. Implications for Landing Site

The final selection of a landing site for Deep Drill will be made by NASA, typically close to launch. Many scientists and engineers will provide input to the process, which will take place over several years. In the meantime, it would be prudent to assume an expansion of the area of eligible sites on the Martian surface over that available to the Mars Exploration Rovers, assuming that, by the time Deep Drill begins implementation, technical capabilities to support this expansion will have reasonably increased. With this approach in mind, we have assumed the following constraints on landing sites for current analyses.

1) Latitude range: 60°S to 60°N. This range would include areas that, based on Odyssey results, may have ice near the surface.
2) Elevation: up to +2.5 km MOLA reference (or as a minimum, 0 km MOLA)
3) Area: For very localized targets, such as potential hydrothermal deposits, we estimate that the lander should touchdown within a radius of 10 – 100 m, to ensure acquisition of useful data. For other sites, landing within an ellipse of 10 km x 5 km (lengths of major and minor axes, respectively) is expected to be sufficient.

III. Preliminary Level 1 Requirements

Since Deep Drill is a mission concept in the study phase, no official Level 1 requirements have been levied. However, for planning purposes, we have developed a preliminary set shown in Table III-1. The Level 1 Requirements shown are based on the Deep Drill science objectives, consistent with NASA's policy that the robotic Mars Exploration Program is science-driven. We have also included derived requirements, with some specific metrics.

Table III-1. Deep Drill Level 1 Requirements (Preliminary)

No.	Objectives
1	Launch an *in situ* surface mission to Mars in the 2018 launch opportunity.
2	Characterize the geology (stratigraphy, structure, chemistry) and geophysics of the shallow Martian crust at one site, particularly as it relates to interpreting past and/or present habitability.
3	Search for past and/or present life in the subsurface at one site.
4	Obtain a meteorological record at one site.
5	Using a drill, bring tens of samples to the surface from various depths down to at least TBD (10-50) m.
6	Land at any location between 60 deg S and 60 deg N latitude at elevations up to TBD (0 to +2.5) km MOLA reference, where landing hazards are acceptable: (a) Land within 10 km (3 sigma) of target for Search for Evidence of Past Life Pathway, OR (b) Land within TBD (10-100) m (3 sigma) of target for Explore Hydrothermal Habitats Pathway.
7	Be consistent with planetary protection category TBD (IVc).
8	Employ at least two methods of approach navigation.
9	Provide for reliable, real-time telecommunications with an orbiting asset during entry, descent, landing, and post-landing critical events to obtain data essential for fault analysis, in the event of a failure, and for general performance characteristics.
10	For feed-forward to future missions, obtain and analyze data related to the performance of the drill, including anomalies.

Requirement 1: The Pathways show Deep Drill being launched near the end of the 2nd decade, in either the 2018 or 2020 launch opportunity. The 2018 opportunity will be used in this paper for illustrative purposes.

Requirements 2-4: These are taken directly from the high-priority science objectives.

Requirement 5: Drilling is a time-tested technique for accessing the subsurface on Earth and has successfully been used on the Moon as well **(2 Refs)**. Technology developments for drills appropriate to Mars show promise, both in terms of working in the Martian environment (e.g., no available water) and in terms of meeting mass, volume, and power constraints that would reasonably be imposed on robotic missions in the next decade. Techniques are available for bringing samples of the material accessed to the surface for analysis by scientific instruments and for providing contextual information important to the science investigations. In this paper, the larger depth, 50 m, is used as the depth requirement, and 50 is assumed to be the minimum required number of samples to be analyzed.

Requirement 6: The selection of a landing site is driven by science priorities but constrained by technical capability. Some sites may be available for one launch opportunity and not for another due to either the particular approach conditions, the mass of the entry system, or the conditions at Mars (e.g., global dust storm season) or some combination thereof. Initially, however, attempts will be made to make available all of the sites desired for science reasons between 60°S and 60°N latitude and landing site elevations up to +2.5 km MOLA. (Landing hazards at specific sites, e.g., large rock size or abundance, severe slopes, and/or high winds, may also eliminate specific sites within an otherwise acceptable zone.)

Requirement 7: NASA's Planetary Protection Officer assigns every mission to a body in the solar system a planetary protection category requirement consistent with the target body, the materials on that body that the spacecraft may and/or will come in contact with or be affected by, and the science objectives of the mission. Although we will not know what category will be assigned to Deep Drill for some time, for planning purposes we have assumed a Category IVc requirement. For the time being, we have interpreted this categorization to mean that the drill and all elements of the spacecraft that come in contact with the samples brought up from the subsurface would need to be sterilized to the highest level of cleanliness defined by NASA's Planetary Protection Officer **[Dave, is this sufficient? Do you have a different suggested wording?]**.

Requirement 8: For the purposes of this study, two methods of approach navigation are assumed to be required (e.g., radiometric and optical).

Requirement 9: Real-time coverage of critical events, particularly if anomalies or failures should occur, is considered crucial to future missions.

Requirement 10: Understanding how the drill operates is considered crucial to future missions.

IV. Mission Design and Description

A preliminary analysis of the Deep Drill mission is described in this section.

A. Interplanetary Trajectory

The 2018 opportunity to Mars is favorable in that trajectories are available with relatively low launch energy and short flight time requirements. Table IV-1 shows various relevant parameters for two reference landing sites, one at 60°S and one at 45°N latitude. (Note: the locations shown have not been selected for science reasons; rather they were chosen as stress cases for the entry, descent, and landing or EDL phase.) The data incorporate a 20-day launch period. The L_s of 320° means that the northern hemisphere is experiencing winter, and Earth coverage at arrival for high latitude landing sites is therefore, more constrained. For these cases, communication with a telecom orbiter might be considered sufficient or a different trajectory may need to be selected. The C_3 of 9.7 km^2/s^2 is the maximum across the selected launch dates for these two target sites. Somewhat higher or lower C_3 values will result for different longitudes. Arrivals in early afternoon should provide good lighting conditions for post-landing camera observations, but in the pinpoint landing case, winds, which tend to increase in the afternoons, will need to be factored in when estimating the landing accuracy.

The Delta-V for the interplanetary phase is less than 40 m/s.

Table IV-1. Parameters for Reference Interplanetary Trajectories

Launch Date (Open) yyyy/mm/dd	Arrival Date (Fixed) yyyy/mm/dd	Max. C_3 km^2/sec^2	DLA	Max Sun Range, Cruise A.U.	Max Earth Range, Cruise A.U.	Arrival V_∞ km/sec	Inertial Entry Speed km/sec
2018/05/13	2019/01/07	9.7	-20.43°	1.46	1.33	3.29	5.85
2018/05/13	2019/01/07	9.7	-20.36°	1.46	1.33	3.29	5.85
L_s	Sun Range @ Arrival A.U.	Sun-Earth-Probe Angle @ Arrival	Earth Range @ Arrival A.U.	Sun Elevation @ Landing	Earth Elevation @ Landing	LTST @ Landing hours	Target Landing Site Lat., Long.
320°	1.46	77.04°	1.33	42.7°	34.2°	13.50	60°S, 310.40°E
320°	1.46	77.04°	1.33	28.8°	5.5°	12.50	45°N, 236.75°E

B. Entry, Descent, and Landing (EDL)

The version of Deep Drill in the Search for Evidence of Past Life Pathway requires landing within an ellipse of 10 km x 5 km (herein referred to as "precision landing"). However, a version of Deep Drill consistent with the Pathway called Explore Hydrothermal Habitats requires a landing accuracy within a radius of 10-100 m (herein referred to as "pinpoint landing"). Both of these cases were investigated, incorporating design differences to the flight system where necessary.

The altitude of the landing site can significantly affect EDL. The higher the altitude, the less time the entry system has in which to decelerate the spacecraft for a safe landing. Missions requiring pinpoint landing accuracies (10-100 m) will be particularly sensitive to altitude. The reference target sites described in the previous section have landing site elevations at 0 km MOLA. Elevations up to +2.5 km MOLA have been investigated in other cases with successful results, but they have yet to be studied for the cases described in this paper.

Navigation data types of Doppler, range, and optical were found to provide sufficient accuracy at entry for both precision and pinpoint landing, with the latter requiring a knowledge update about 3 hours prior to entry. After entry into the atmosphere, a descent guidance algorithm is used, with bank-angle modulation, to keep the error from growing until parachute deployment. A single, supersonic parachute, with a diameter of just over 16 m, is used to

slow down the aeroshell containing the lander. The aeroshell, composed of a heat shield and a backshell, has a diameter of 3.65 m. The heat shield has a 70° sphere-cone angle. During the terminal descent phase, after the heat shield, parachute, and backshell are separated, the engines on the lander decelerate the spacecraft down even more, until a safe landing is achieved. Even assuming steady tail winds of 30 m/s for the pinpoint landing case, the required landing accuracies are achieved in both cases, while remaining well within the preliminary constraints on the inertial entry flight path angle (< 15°), deceleration (< 14 G), maximum heat load (< 14 W/cm^2), and maximum entry mass (< about 1640 kg for precision landing or about 1750 kg for pinpoint landing, with margin). Section V describes the flight system in more detail.

For pinpoint landing, the method outlined in Ref. III-3 **(Aron's paper)** is used. As soon as the parachute is released from the lander, new, autonomous powered descent guidance and control algorithms onboard the spacecraft use Viking-derived engines to steer the lander to the target spot. The algorithms use observed data from a camera to match and track expected features (e.g., craters and hills). An additional 170 kg of propellant are needed for this case, after taking into account the corresponding requirement for additional tank volume, plumbing, and support structure.

The Delta-V allocations for EDL are: 30 m/s for precision guidance during the hypersonic phase and 180 m/s or 600 m/s for the powered descent portion for the precision landing or pinpoint landing cases, respectively.

Communication coverage during EDL is provided by both a telecommunications orbiter and an Earth ground station. We have assumed that a telecommunications orbiter would be launched in 2018 as a replacement for the Mars Telecommunications Orbiter (MTO), that is currently in Phase A and is planning a 2009 launch. Although currently beyond its mission lifetime requirement, MTO may still be operational and available as well.

C. Operations Concept

After approximately an 8-month cruise and a safe touchdown, operations on the surface begin.

An example high-level scenario is shown in Fig. IV-1. It is based on a representative set of science instruments and drilling parameters, and satisfies the power constraints of the lander (Section V).

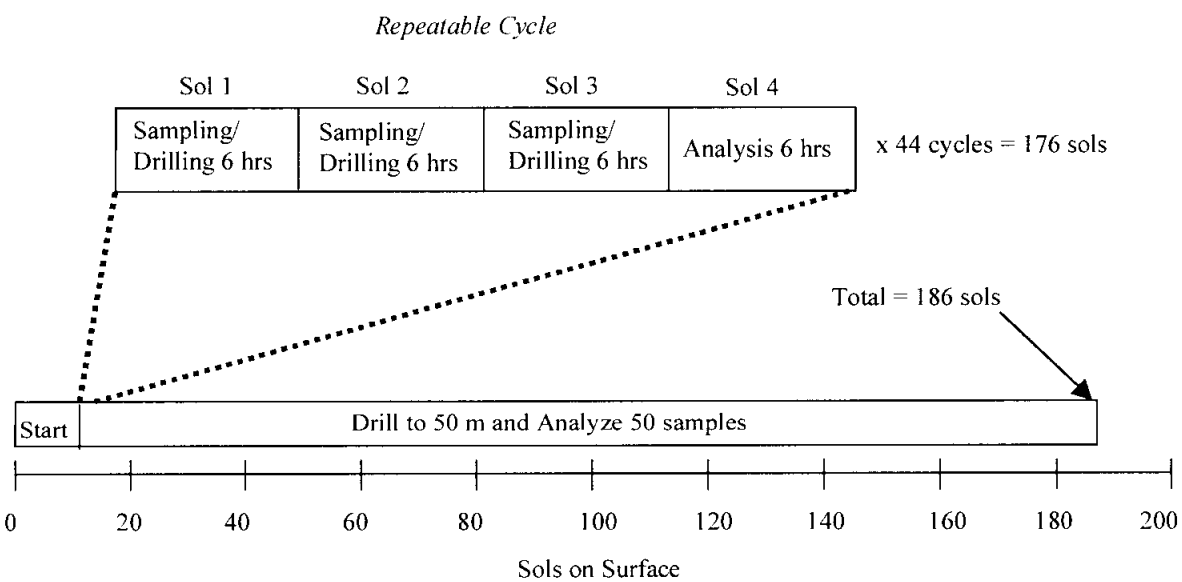

Fig. IV-1. Example Deep Drill Surface Operations Scenario

We have defined two power modes: a *drilling/sampling power mode* and an *analysis power mode*. The *drilling/sampling power mode* includes: (1) drilling a core of about 10 cm in length, (2) bringing the core and cuttings to the surface, (3) placing the core into a storage location, and (4) returning the sample collection system back down to the bottom of the hole. As the drill progresses deeper into the subsurface, additional drill segments are added autonomously as needed. We have estimated the average power need for all of these functions to be less than 60 W. Further, the entire power system has been sized to include the continuous operation of the meteorology station and the operation of the required lander functions. This drilling/sampling power mode operates for about 6 hours per sol, after which a short telecom session occurs followed by a recharging of the batteries.

The *analysis power mode* is defined to include: (1) retrieving a core from storage, (2) preparing samples as needed, such as grinding or sieving, [7] (3) delivering samples to the instruments, (4) operating all of the science instruments that require samples (both non-destructive and destructive analysis), and (5) cleaning relevant hardware to keep cross-contamination between samples within the required tolerance (to be defined). An average power requirement for these functions is estimated to be less than 50 W. The same background functions described for the drilling/samping power mode are also assumed for the sample-analysis power mode. In the example scenario, the analysis power mode operates for 6 hours per sol, after which, again, a telecom session occurs, and then, the batteries are recharged.

With preliminary assumptions for drilling parameters, we estimate that a total of 765 hours (including approximately 50% margin) is required for the drilling/sampling operations to reach the 50 m depth. We also assume a minimum of 2 (Earth) days between successive sample-analysis operations, on average, to allow for decision time on the Earth and general contingency associated with sample preparation and analysis. This constraint is easily satisfied by our scenario.

An analysis of the data transmission requirements shows that one pass per day of just a few minutes (less than 5) with a relay orbiter in a similar orbit to that planned for MTO would suffice. In fact, 3-4 passes per day are shown to be available, depending on the latitude of the landing site.

In summary, the scenario outlined in Fig. IV-1 satisfies both the power and temporal needs of the payload to achieve the Level 1 mission requirement of 50 m in depth and analysis of 50 samples.

[Discuss geophysical monitoring as a potential desirable addition]

D. Launch Vehicle

A medium-class Delta or Atlas is sufficient for this Deep Drill mission concept. Cases for which pinpoint landing is required need more thrust capability than those for which precision landing is adequate due to the larger spacecraft mass.

V. Flight System

The Flight System for the Mars Deep Drill mission is defined as the portion of the spacecraft responsible for delivering the scientific and engineering payload to the designated landing site within the requirements specified at Level I as well as providing all of the resources that allow the payload to satisfy its mission objectives. Although the final design and architecture of the flight system will be determined much later in the formulation of the mission, for our study, we have identified the primary functions and performance essential for mission success.

The flight system described herein is purely representative for planning purposes. However, it is the consensus of the team that in order to meet the delivery accuracy for precision and pinpoint landings and landed mass requirements for a mission like Mars Deep Drill, the flight system will need to consist of at least a:

1) *Cruise Stage System* – responsible for interfaces with the Launch Vehicle, for guiding the spacecraft during interplanetary cruise, and for delivering the system to a clearly defined point prior to entry into the Martian atmosphere;
2) *Entry Vehicle System* – responsible for re-orienting the spacecraft for entry after cruise stage jettison, for precision guiding and thermally protecting the rest of the system during hypersonic entry to a clearly defined parachute deployment point;
3) *Parachute System* – responsible for decelerating the spacecraft to a terminal velocity after hypersonic entry and for providing dynamic stability during heatshield separation;
4) *Powered Descent System* – responsible for delivering the spacecraft to a landing target within the error bounds for that case (either precision or pinpoint landing) as well as within velocity bounds consistent with the touchdown capability of the spacecraft (at too high of a velocity the system would either break or tip-over or both); and
5) *Lander System* – responsible for carrying the scientific and engineering payload and providing the necessary operational resources (e.g., power and intercommunications) as well as resources for delivery of the system data to the interplanetary telecommunications infrastructure.

We have studied a variety of designs and architectures that combine some of these elements into one in an effort to reduce mass and/or complexity, but it can be shown that the more mass that can be jettisoned, and the earlier in the EDL phase that it is jettisoned, the more useable payload can be delivered to the surface.

Fig. V-1 shows an exploded view of the representative flight system described in this paper. In this architecture both the Entry Vehicle and Parachute systems and the Powered Descent and Lander systems are integrated together respectively to form single systems. Tables V-1 and V-2 summarize the mass estimates for each system for the mission concepts used in this paper for precision landing and pinpoint landing respectively. Note the 3-fold increase in propellant needed for the powered descent portion of EDL from the precision to pinpoint landing case. This is due to the divert maneuver that is required in the pinpoint landing case to null out the wind drift error introduced while on the chute. In the precision landing case, no attempt to null out this error is made since this error is small in relation to the landing error ellipse (10 km x 5 km). A more detailed description of each system element follows.

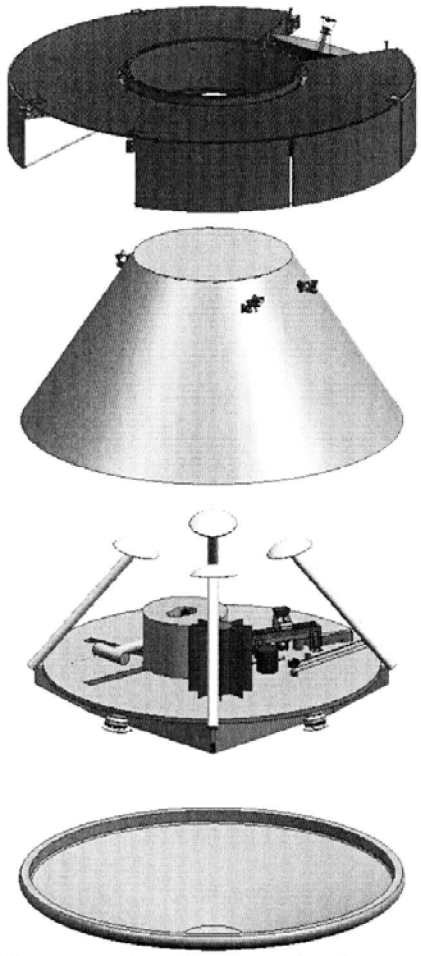

Figure V-1. Conceptual view of exploded spacecraft. From top to bottom: cruise stage, backshell, lander, and heatshield.

A. Cruise Stage System

The Cruise Stage design utilizes design heritage from several other Mars Landers (e.g., Mars Science Laboratory, Mars Exploration Rovers, and Mars Pathfinder). A large solar array generates most of the power needed during the 8-month cruise period to Mars. This array serves a dual purpose in that it also shields the rest of the system from the sun as long as the array is pointed towards the sun. Occasional off-sun excursions may be required and are permitted for trajectory correction maneuvers, but generally the array remains sun-pointed throughout cruise. Solar cell string-switching and shunt radiators are necessary to adjust power levels for the changes in solar distance during cruise. Excess power is shunted and cell strings, that are initially off during launch and early cruise, are brought online as the spacecraft moves farther from the sun.

Guidance, Navigation, and Control (GN&C) thrusters are located at positions necessary to provide 6 Degrees of Freedom (DOF) control. GN&C sensors including sun sensors and stellar reference units are also located on the Cruise Stage as is an optical navigation camera system that uses the Martian moons Phobos and Deimos for Mars approach navigation.

The propulsion system that supplies fuel to the GN&C thrusters is independent of the rest of the flight system. Separate fuel tanks, valves, and other plumbing reside on the cruise stage and are jettisoned along with the rest of the cruise stage near the atmospheric entry interface point. This greatly reduces the complexity of having to isolate propellant lines using pyrotechnic devices and allows the jettison of unused wet mass allocated for cruise since margin is necessary, but often not used.

A thermal control system independent of the other elements of the spacecraft is also needed for cruise to handle the issues associated with operating in a vacuum. Fluid loops, pumps, and radiators are carried on the cruise stage to reject waste heat generated by the lander system. Sources of waste heat might be, for example power systems for the lander, the avionics running all of the software during all mission phases, and/or heater units necessary to survive cold nights on the Martian surface.

Table V-1. Spacecraft Mass Estimates for Precision Landing case.

	Mass (kg) with Margin
Powered Descent & Lander -- Dry Mass	842.3
Lander Propellant	84.5
Powered Descent & Lander Total	926.9
Entry Vehicle & Parachute -- Dry Mass	708.3
Entry Propellant	0
Entry Vehicle & Parachute Total	708.3
Cruise Stage -- Dry Mass	297.5
Cruise Propellant	42.4
Cruise Stage Total	340.0
Total Launch Mass	**1975.1**

B. Entry Vehicle and Parachute System

The Entry Vehicle and Parachute System primarily consists of the backshell and heatshield, which are aerodynamically-shaped and covered in a layer of thermal protection system material to withstand the heat generated by the friction with the Martian atmosphere during hypersonic entry, and the supersonic parachute. For our reference system, a heatshield with a diameter of 3.65 m is used. The heatshield has a sphere-cone angle of 70° with heritage dating all the way back to the Viking Landers. The rest of the spacecraft is encased by the heatshield and backshell to protect it from the harsh entry conditions.

The supersonic parachute is a Disk-Gap-Band (DGB) chute also with heritage back to Viking. Associated hardware and pyrotechnic devices for storing and deploying the chute and for jettisoning all three elements are also part of this system.

Table V-2. Spacecraft Mass Estimates for Pinpoint Landing case.

	Mass (kg) with Margin
Powered Descent & Lander -- Dry Mass	885.9
Lander Propellant	232.4
Powered Descent & Lander Total	1118.3
Entry Vehicle & Parachute -- Dry Mass	768.7
Entry Propellant	0
Entry Vehicle & Parachute Total	768.7
Cruise Stage -- Dry Mass	299.6
Cruise Propellant	57.7
Cruise Stage Total	357.2
Total Launch Mass	**2244.3**

In both the precision landing and pinpoint landing cases, a capability known as "precision-guided entry" is employed to steer out any delivery errors from the approach navigation function. In order to be able to accomplish this, however, some control authority of the otherwise blunt entry body needs to exist. Although there are a number of ways to achieve this (e.g., control surfaces similar to flaps on aircraft or the inverse, voids in the entry body shape, or a deliberate center-of-mass offset), this study has assumed heritage from the Mars Science Laboratory baseline of a center-of-mass offset to realize a higher Lift-to-Drag ratio (L/D) of 0.18. On-board autonomous algorithms use this control authority to command changes in bank angle to control both down-range and cross-range errors using roll-control thrusters. Together with the roll thrusters, pitch- and yaw-control thrusters ensure that the system has 3-axis control while performing these bank angle maneuvers. The algorithms are derived from similar functions performed for the Apollo program.[2,3,4]

Although the precision-guided entry algorithms and entry-control thrusters are used during the hypersonic entry portion of EDL, they are actually considered part of the Powered Descent and Lander System since the algorithms execute on the lander avionics and the thrusters are the same as those used for 3-axis control during powered descent.

C. Powered Descent and Lander System

The Mars Deep Drill concept described in this paper combines the Powered Descent and Lander systems in a single system similar to that used by Viking. The Powered Descent portion of EDL for Mars Deep Drill is defined as the period of time from release of the parachute (i.e., cutting the system free from the parachute) to touchdown on the surface of Mars. The term "powered" descent is used because the descent is under 6-DOF control using throttle-able engines based on the Viking design for translation and pitch/yaw control and pulsed thrusters for roll control. Because the systems are combined for the concept described here, these engines and thrusters and all associated propulsion subsystem components (e.g., tanks, valves, plumbing, etc.) are integrated with the Lander itself.

The Lander concept is a simple, legged system with the science and engineering payload primarily mounted to the topside of a main deck while the descent engines are mounted on the bottom. The system is designed to be robust to a reasonable range of touchdown velocities in the vertical and horizontal directions and designed with sufficient underside ground clearance to tolerate landing in a specified rock field and slope combination. The specific requirements (and thus, the specific design to meet the requirements) will not be worked out until the project moves into its formulation phase, but notionally, the system would be capable of landing on slopes up to 30° and in rock fields similar to that found at Viking-1's landing site.

Since the Lander carries the brains of entire spacecraft from launch through to surface operations, the avionics subsystem is integrated with the Lander and kept in an insulated box called a warm electronics box. At a minimum the avionics consists of a primary central processor board for running all of the different algorithms and communication software used for all phases of the mission, the telecommunications interface board(s) for encoding/decoding uplink and downlink data, motor controllers for the various payload mechanisms, power conditioning systems for the main power source and battery augmentation (both thermal and rechargeable), and non-volatile and mass memory storage.

The Guidance, Navigation, and Control subsystem primarily consists of the algorithms for executing powered descent, touchdown, and engine shut-off,[5] but also includes the sensors necessary to accomplish these tasks. A multi-state extended Kalman filter[6] maintains the 6-DOF state of the system by propagating position, velocity, attitude and attitude rate using data from an inertial measurement unit and updating the state with measurements from an altimeter and velocimeter. Guidance and control algorithms then use the estimated state to drive the system to its landing target by issuing throttle changes and thruster pulse commands to maintain the proper heading and attitude. In the pinpoint landing case, a camera is added to the sensor suite for "feature-tracking" of surface features while on the chute and during powered descent so that the guidance algorithm can steer out the accumulated drift error while on the chute.

Two options for the power generation systems for surface operations have been studied: solar cells and multi-mission thermoelectric generators (MMRTG's). Solar power will strictly limit the mission duration, especially at the high latitudes that are required, where seasonal changes significantly affect the amount of available sunlight each day. MMRTG's mitigate this issue, but have the consequence of having to shunt excess heat that is generated since only a limited amount of the heat produced by the MMRTG can be turned into electricity. For the mission concept described in this paper, an MMRTG was used as the primary power generation system, however, this is also for planning purposes only.

The mechanical subsystem, in addition to providing the primary and secondary structure for the system, also provides some infrastructure to support the Scientific and Engineering Payload. This includes mechanisms for relocating the drill in the event a loose boulder is discovered immediately beneath the primary drilling location or a new drill hole needs to be started in a new position. Also, the drill prefers to be aligned with the local gravity vector in order to be the most efficient. In the event of a sloped landing or one or more legs up on a rock, the mechanical subsystem provides the mechanism to realign the drill with the g-vector. Some other components of the mechanical subsystem are included in the discussion of the scientific and engineering payload.

D. Scientific and Engineering Payload

A discussion of candidate scientific investigations can be found in Section II. A "strawperson" suite of science instruments to perform those investigations can be found in Table V-3. The mass estimates for each are included in the table. A science steering group for Mars Deep Drill may soon be commissioned to help refine these investigations and identify candidate instruments. Consequently, these are purely placeholders, used to "size" the mission and system parameters and are not intended in any way to indicate any preference as to what science should be included as part of the Mars Deep Drill mission.

Table V-3. "Strawperson" Scientific Payload for Mars Deep Drill Mission Study

Component	Mass (kg)	Contingency	CBE + Contingency (kg)
Microscope with UV source	1.300	30%	1.690
XRDF/APX	1.200	30%	1.560
GCMS	24.000	30%	31.200
Life Detection	6.200	30%	8.060
PanCam Imager /Target	0.500	30%	0.650
Drill Camera	1.200	30%	1.560
Meteorological Station	0.500	30%	0.650
EPM MORD	2.000	30%	2.600
Raman probe	2.700	30%	3.510
Ice & Water Detection	0.500	30%	0.650

The Engineering payload consists of the drill system, the sample preparation and distribution (SPAD) system, a robotic arm for surface sample collection and transfer of samples from the drill to the SPAD, and the remote sensing mast used for the panoramic camera, the meteorology station, and possibly other instruments. The primary objective of the engineering payload is to provide surface and subsurface samples to the scientific payload in such a way as to limit the cross-contamination of one sample with another. Table V-4 shows the mass estimates for the engineering payload.

The largest component of the engineering payload is the drill system. For this paper, a drill system, based on drills designed by Swales Aerospace under technology development funds from the Mars Technology Program, was used as a representative system. However, the use of this design is for planning purposes only. Swales also provided trade studies of mass/power/volume/cost versus depth to provide a menu of drill options

Table V-4. Engineering Payload for Mars Deep Drill Mission Study

Component	Mass (kg)	Contingency	CBE + Contingency (kg)
SPAD	38.462	30%	50.000
Robotic Arm	11.538	30%	15.000
Drill	80.000	30%	104.000
Remote Sensing Mast	13.100	30%	17.030

for use in the Mars Deep Drill Mission study. The estimates quoted for all resources in this paper represent one option from that menu. For redundancy and reliability purposes in this concept, the drill system carries extra drill segments up to 50% depth contingency (including a redundant drill bit segment).

The SPAD system design represented in this paper is based a study of SPAD systems by Beaty, et. al.[7] For study purposes, appropriately conservative, Rough Order of Magnitude (ROM) estimates of mass and power were used. The primary functions of the SPAD include:

1) storage of samples delivered from either the drill or the robotic arm,
2) preparation of samples (e.g., crushing of drill cores),
3) selection of individual sub-samples, aka, "precision sub-sampling",
4) distribution of samples to appropriate science instruments, and
5) cleaning the system between samples

The robotic arm used in this study is based on the arm originally built for the Mars 2001 Lander mission. Notionally, it would be long enough and dexterous enough to reach both the ground and the drill and SPAD systems with ease. A scoop on the end of the arm would facilitate digging into the surface to a depth of a few centimeters. Samples of the soil would then be brought to the SPAD for distribution to the science payload.

The remote sensing mast is a 2-DOF mechanism that facilitates ±180° and ±75° of rotation in azimuth and elevation respectively. This mast is used primarily for the stereo, context cameras enabling a 360°-panorama, but it also is used to extend the elevation of the meteorology station. Depending on the final instrument selection, the remote sensing mast may serve other instruments as well.

VI. Technology

The Mars Deep Drill mission requires the use of some technologies that have not yet been demonstrated by a flight mission. This section describes the technologies that have been identified as required to meet the representative Level 1 requirements and the process by which the Mars Program develops these needed technologies. In some cases, the development of technology has been ongoing.

NASA employs a classification system entitled the "Technology Readiness Level" (TRL) to classify the maturity of a specific technology. In order for a technology to be declared "ready for infusion" with a flight mission, the technology must have reached a classification of TRL of 6 or higher (see Figure VI-1 for a TRL summary) before the project that wishes to infuse the technology has reached its Preliminary Design Review. Although the precise definition of what represents TRL 6 to a particular technology varies, the general definition of this level is: "system/subsystem model or prototype demonstration in a relevant environment on the ground or in space." For some system-level technologies (e.g., pinpoint landing), this means that a flight demonstration may be necessary to reach TRL 6 although this flight demonstration could be accomplished in an Earth-environment. For others (e.g., the subsurface access system), a relevant ground test or series of tests is/are sufficient.

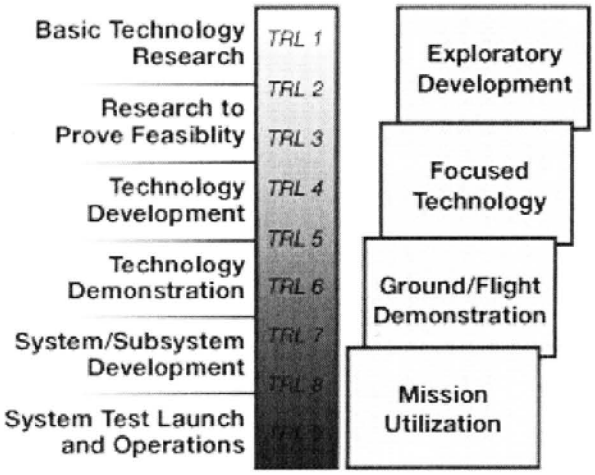

Figure VI-1. Technology Readiness Levels – Maturity level increasing from top to bottom

The new technologies that have been identified as needed for the Mars Deep Drill mission are: pinpoint landing, subsurface access (up to 50 m), forward planetary protection (Categories IVb or IVc), in situ science instruments (surface analysis and downhole), and sample preparation and distribution (including icy sample handling and storage

for up to 50 samples). Additionally, there are some technologies that we assume to be inherited from missions that are currently in development phases. These include next-generation power systems, long-term survivability on the surface of Mars, telecom network data rates, impact attenuation & landing survivability, and precision landing. Of these, all but impact attenuation and landing survivability are planned for flight demonstration with the 2009 Mars Science Laboratory at the required levels needed to support Mars Deep Drill. The levels of impact attenuation and landing survivability for the Mars Phoenix lander, to be launched in 2007, are sufficient to support the levels required for the Mars Deep Drill mission and thus, is assumed heritage from that mission.

For those technologies that have been identified as "new" for Mars Deep Drill, a plan defining these technologies including key performance parameters and cost estimates has been provided to the Mars Technology Program to help integrate the needed technologies for all of the next-decade mission concepts together into a master plan. This plan is then used to identify the resources necessary for developing these technologies. In the case of the new technologies needed for Mars Deep Drill, several concurrent developments in each of 5 areas are already underway. For example, pinpoint landing studies have been going on for some time and are continuing since this technology is applicable to a number of possible missions. Subsurface access is another area where development has been ongoing. The Swales drill design is one example of subsurface access technology development through the Mars Technology Program. The same is true for planetary protection, in situ science, and SPAD technologies.

The same plan is also used to identify those technologies currently being developed for other missions that are assumed heritage for Deep Drill and other next-decade missions. If, for some reason, these technologies are not developed by those missions to the level required, the same plan is updated to reflect that these technologies must now be allocated resources for development as a "new" technology by the Mars Technology Program.

VII. Development Schedule

The development schedule in Fig. VII-1 is representative for a Deep Drill mission launching in the 2018 Mars opportunity. The durations of specific phases (e.g., A, B, etc) are carefully chosen based on factors such as mission complexity, system heritage from other missions, launch approval processes, and required mission science return

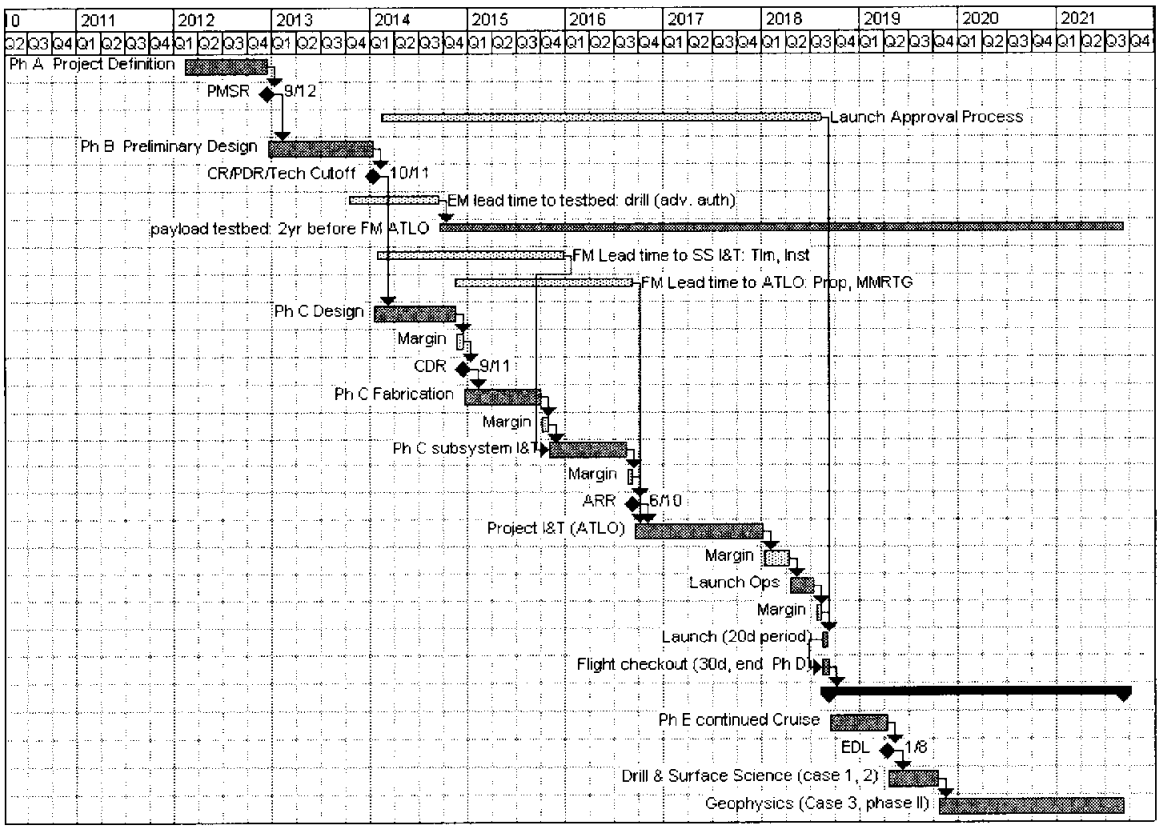

Figure VII-1. Example Deep Drill End-to-End Project Schedule

among others. Margin is required by institutional principles of design and the schedule shown is consistent with those principles. As the mission moves from the advanced studies phase into pre-project or project phases, the schedule will be refined to be more consistent with how the project is formulated. Consequently, this is merely a representation of how the schedule might look from the start of the project (Phase A) through to the end of the nominal mission (end of Phase E) using JPL and NASA practices and principles on project scheduling.

VIII. Cost Estimate

Based on the concept described in this paper, the cost for a Deep Drill mission, launching in 2018, is estimated in the range of $1.1B to $1.5B (real year dollars). Included in this estimate are: development, assembly, test, and launch operations (Phases A-D) of all flight hardware and ground systems, as well as post-launch operations and data analysis (Phase E). Excluded are costs associated with the development of required technologies to TRL 6, launch approval engineering, and public education and outreach, all of which are provided separately by the Mars Program. Similarly, costs associated with the use of the Deep Space Network and a telecommunications orbiter at Mars are not included in the Deep Drill estimate.

IX. Conclusions

A mission to drill tens of meters below the surface of Mars has the potential to answer important questions about life on the planet. A preliminary mission concept has been developed for planning purposes that satisfies a representative set of Level 1 requirements. Although there are challenges ahead, the feasibility of this mission is consistent with the current technology development plans and science objectives. Further refinements will be necessary as the science community refines its specific goals for this and other missions and as the Level 1 requirements are formally defined with the Mars Program and NASA Headquarters. In order for Mars Deep Drill to be ready for launch in the next decade, several key technologies must be developed, and the Mars Technology Program is providing funding to meet these technology needs.

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