Urey: To Measure the Absolute Age of Mars

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Abstract - UREY, a proposed NASA Mars Scout mission will, for the first time, measure the absolute age of an identified igneous rock formation on Mars. By extension to relatively older and younger rock formations dated by remote sensing, these results will enable a new and better understanding of Martian geologic history. Thus, Mars will join the Earth and the Moon as the third body in the Solar System for which absolute dating has been accomplished.

This revolutionary science mission can be accomplished within the Mars Scout programmatic boundaries because of both extensive heritage and innovative technology. The heritage includes the interplanetary carrier stage, the Mars direct-entry system, the Mars lander, and the Mars rover that had been planned for the Mars 2001 mission before it was cancelled. Urey innovations include two ongoing technology developments that can support a revolutionary science approach. First, miniaturizing of instruments to measure K and ^{40}Ar has proceeded sufficiently to allow in situ dating. Second, the ultrasonic drill, which has been under development at Jet Propulsion Laboratory for several years, can be carried on an existing small rover with design and operational heritage from the Mars Pathfinder mission. The rover's mobility is important because it can carry the drill from the landing site to a remote bedrock location where it can acquire a pristine sample by drilling into that bedrock. The rover will return the sample to the lander for analysis. These in situ analyses will produce new data about Mars chronology, geology, petrology, and chemistry that will significantly change our understanding of the history of the red planet.

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1. INTRODUCTION AND MISSION OBJECTIVES

The Urey Mars Scout mission has been proposed (Ref. 1) to conduct some of the most sophisticated in situ analyses ever attempted on the Martian surface. (While the details of the science experiment designs and some important design features are necessarily proprietary at this time, the functional capabilities of the mission elements and architecture will be described in as much detail as prudent.) The primary goal is to determine the absolute age of a major geological unit on Mars. Using analysis of remote images, that absolute age result can then be extended forward and backward in time by comparison with younger and older

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features to calibrate the absolute chronology of the planet, including its cratering history. The instrument payload will also allow investigation of petrology and atmospheric evolution, as well as general geological exploration of this unit, including the search for organic compounds. These goals are consistent with the recommendations from the Mars sub-committee of the National Academy of Sciences Space Science Board (Ref. 2). The search for pristine samples of the Martian surface will be enabled by a mobility system (rover) carrying an ultrasonic drill (USD) that can penetrate into bedrock to capture a core sample. Once the sample has been captured, it will be delivered to the Integrated Science Payload (ISP) on the lander deck for processing and analysis.

Previously, it had been assumed that determining absolute dates required a sample return to the Earth for analysis and that mineralogy required remote sensing. Urey can accomplish dating and mineralogy analyses in situ. While terrestrial laboratories can conduct more precise analyses, the Urey analyses can improve our understanding by orders of magnitude (Ref. 1) without the prohibitive cost of returning samples to Earth. The ability to analyze many different samples at the relatively low cost of a Scout mission adds to the intrinsic value of this type of mission compared to the inherently high cost of a sample return mission. The relatively low cost of this mission depends on the return-to-flight capability of the flight systems (Refs. 3 and 4) developed during the Mars 2001 project, which was cancelled during its integration and testing phase due to the Mars 1998 Polar Lander failure. A key decision of the Urey mission architects was the selection of the USD as the lowest cost drilling device. The decision was based on the realization that any rotating drill would demand a massive and costly platform for stabilization and to supply the necessary downward force. The USD is a simple, robust linear impacting drill (i.e., "jackhammer") that needs only a very small, lightweight platform for support and that can be accommodated on the Urey (2001) rover.

The Urey mission objectives are based on evidence that Mars has had significant surface activity in the recent geological past (few x 10^8 years). There has been, however, no method to provide any absolute dates to confirm this hypothesis. For example, one era (the Amazonian) has a beginning anywhere from 1.8 to 3.55 billion ago, which illustrates the extreme uncertainty of Martian chronology. The Argon Geochronology Experiment (AGE) discussed in section 2 will provide an absolute age with a precision of 10 to 15% (Ref. 1). This result will provide a ground truth to the geological history of Mars leading to a new understanding of the volcanic and tectonic history of the planet, as well as providing constraints on the climatogical history and a context for the biological potential of Mars. An absolute age will link Mars to terrestrial time scales, allowing unprecedented comparative planetology. Because the AGE instrument can, in addition, measure atmospheric isotopes (e.g., ^{40}Ar) with high precision; the models of the history of the atmosphere on Mars can be narrowed, and there will be a new understanding of where the water is today and how much has been lost in the past.

Understanding Martian mineralogy is also an important step in determining the planet's history. Previous remote sensing and surface analyses will be improved by the analysis of pristine rock samples that are free from any weathering that could affect the interpretation. In the absence of a returned sample, x-ray diffraction (XRD) and x-ray fluorescence (XRF) are the best methods for uniquely defining Martian mineralogy (Ref. 1). The Mineralogic Identification and Composition Analyzer (MICA) will simultaneously accomplish XRD and XRF mineralogic analyses complementary to the elemental abundance data measured with the AGE experiment.

Although it is not the prime objective, the detection of organic compounds is well within the capability of the Urey instruments. The Mars Organic Imager (MOI) will use UV fluorescence and high-resolution microscopic imaging to detect organic materials in the core sample at the nanogram level (Ref. 1). A primary target will be polycyclic aromatic hydrocarbons (PAHs) which, if located in the rock fissures, would suggest the introduction of aqueous or other fluids after the rock was formed.

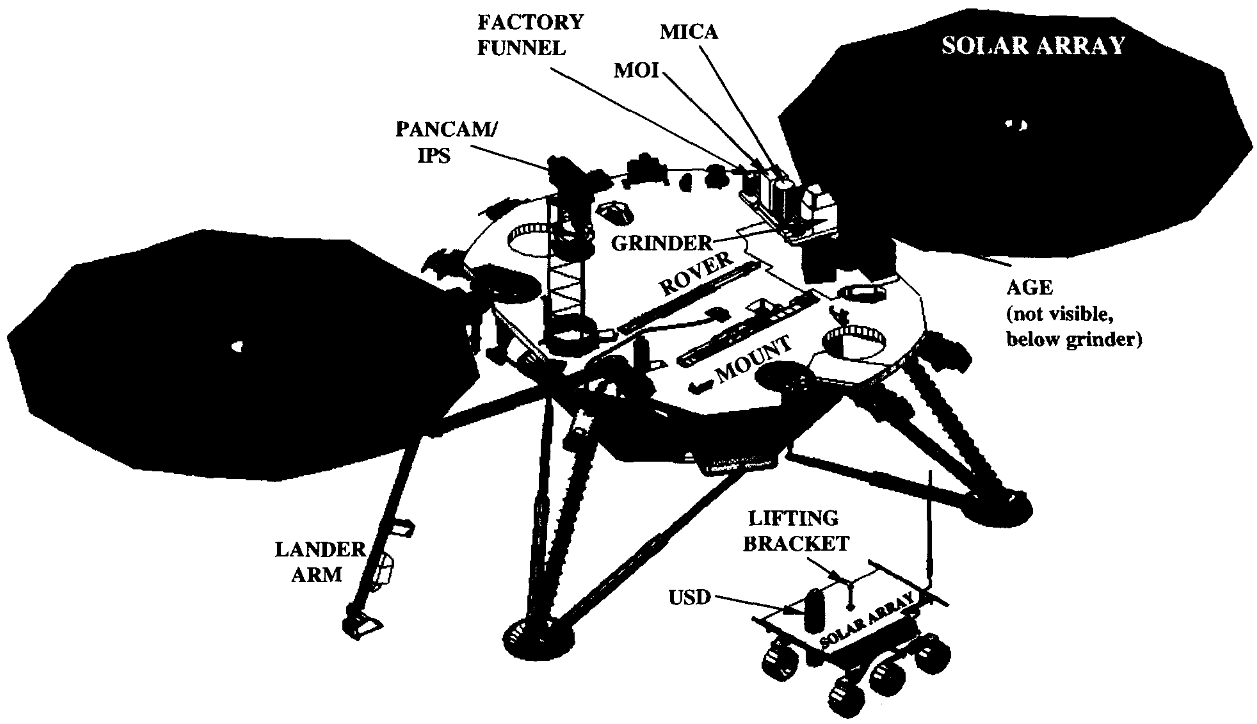

Figure 1. Urey lander configuration and deployed elements on the Martian surface

Site geologic characterization, also an objective of the Urey mission, will depend on the remote sensing payload located on a panoramic viewing platform on the lander. These observations will provide context for the in situ analyses and identify local processes on a smaller scale than can be resolved from orbital remote sensing. The volcanic surface chosen as the Urey target is expected to have a virtually pristine nature that has not been modified by more than just dust coverage and weathering. Urey's Infrared Point Spectrometer (IPS) will provide imaging spectroscopy to distinguish rock and soil types around the landing site. The panoramic imaging experiment (Pancam) will acquire multispectral stereo imaging that will provide context with orbital observations, topographic information, and site mapping for rover navigation (Ref. 1).

2. Science Payload Description

The Urey payload consists of two types of instruments:

1. In situ: for detailed analysis of the sample cores acquired by the drill on the rover
2. Remote sensing for more global observations of the landing site from the lander platform

In situ analyses of the rock sample will occur in the integrated science payload (ISP) on the lander. The ISP includes the AGE, MICA, and MOI instruments integrated on a lander platform, known as the factory, that can handle, process, and deliver the core to the instruments. One end of the factory platform contains the factory funnel (see Fig. 1) where the core sample from the rover is deposited using the lander arm. The core is deposited on a "conveyor belt" that delivers the core beneath the MOI for its optical analysis. The core is then moved beneath the MICA for its x-ray analysis. If the analyses from the MOI and MICA suggest the core is acceptable for age dating, the core continues on the conveyor; otherwise, it is rejected at this point. An acceptable core is moved to the final station in the factory, the grinder, where it is ground to a powder. The powder is transferred via a small funnel into one of the crucible receptacles inside the AGE instrument for elemental analysis and age dating.

The AGE is the key in situ instrument that will measure two types of ages on the rock samples. First, the $K/^{40}Ar$ ratio establishes the crystallization age of the core sample. Second, the cosmic ray exposure (CRE) age will provide the information about the duration of time that the rock has been within about 2 m of the surface, including its burial history. If the surface layer is not thick, then the ages should be identical. The instrument has been under development for many years, and many of its components have been developed and flown on other missions (Ref. 1). The Urey mission will be the first time that these and other new components will be integrated into a single instrument for spectral analysis and age dating. The instrument architecture includes a sample containment mechanism (crucible) that isolates one sample at a time for spectral analyses. Two different spectral analyzers will exist within the AGE instrument. The first, the laser-induced breakdown spectroscopy (LIBS) analyzer, uses laser bombardment of the material in the crucible to form a plasma above the material. The plasma emissions are spectrally resolved to detect the elements in the material, such as K, that can be measured with a precision of 10 parts per million. The other analyzer is a quadrupole mass spectrometer array (QMSA) that measures the noble gases in the sample to detect with high precision the isotopes of interest (especially ^{40}Ar). To release the gases from the material, the crucible is inserted into an oven where it is heated to about 1500°C. The released gases are then analyzed by the QMSA. The LIBS (K) results and the QMSA (^{40}Ar) results will allow K/^{40}Ar dating with a precision of 10 to 15% (Ref. 1). The results will also provide CRE dating within a precision of less than 17% (Ref. 1).

Additional in situ analyses will be performed on the core sample by the MICA and MOI instruments. The MICA instrument utilizes a radioisotope source of x-rays to bombard the rock core. The diffracted x-rays and the x-ray fluorescence are detected as an image on a charge-coupled device (CCD) that discriminates both energy and pixel positions (Ref. 1). Mineral and element identification are derived from the diffraction and fluorescence measurements, respectively. Another instrument for preliminary in situ analysis is the MOI, which will be used to detect organics at the 50-nanogram level using UV fluorescence (Ref. 1), as well as imaging the rock core with a surface resolution of 30 microns. The instrument is based on the Microscopic Imager (Ref. 1) from the Mars Exploration Rover mission augmented with UV and visible photon sources to allow UV fluorescence and color high-resolution images. When illuminated, organic molecules fluoresce and a particular PAH of interest (perylene) can be detected at the level of about 20 picograms per pixel. This would be two to four orders of magnitude more sensitive than similar experiments on the Viking lander.

Another class of instruments to be carried on the Urey lander will enable remote sensing of the landing site to characterize the mineralogy, geology, and topography of the site. These instruments will be mounted on a boom extending vertically from the lander deck (Fig. 1). The infrared point spectrometer (IPS) will observe reflectance spectral bands in the 0.4 to 2.5 micron range with a spectral resolution of 8 nm and a spatial resolution of 10 x 80 cm at a range of 10 m with a "single spatial pixel" detector. The objective of the IPS is to spectrally resolve the very near infrared characteristics of surface materials around the landing site. By rotating the mast, a panoramic infrared swath will be possible. A camera system (Pancam), is also mounted on the mast and boresighted with the IPS, can acquire multispectral stereo images in a panoramic swath around the lander. The cameras have a field of view of 18° horizontal by 9° vertical with an angular resolution of 0.31 mrad/pixel. Eleven filters on each camera are optimized to recognize the spectra of iron-bearing minerals. The Pancam will also play an important role in stereo imaging to identify topographic features that will be important during rover path planning.

Three other imagers located on the Urey rover are simple visible CCD cameras dedicated to engineering functions. Two navigation cameras (NAVCAMs) will be located on one end of the rover to assist in identifying traverse paths around any hazards. On the other end of the rover, a single wide-angle camera will be used to monitor the core drilling operations of the USD. While these cameras are designed for engineering purposes, their scientific value could be significant in identifying local features around the rover.

3. Mission Architecture and Delivery to Mars

An important characteristic of the Urey mission is the high inheritance from the Mars 2001 Lander Mission. The lander system design was in place, the flight hardware had been fabricated and integrated, and final testing was under way when the project was cancelled because of the Mars 1998 lander failure. The only changes to the 2001 design were
An important characteristic of the Urey mission is the high inheritance from the Mars 2001 Lander Mission. The lander system design was in place, the flight hardware had been fabricated and integrated, and final testing was underway when the project was cancelled because of the Mars 1998 lander failure. The only changes to the 2001 design were those identified by the failure review boards (Ref. 3), and those design changes have been made. The LMAO lander system consists of the cruise stage, the aeroshell/backshell, and lander, as shown in an exploded view in Fig. 2.

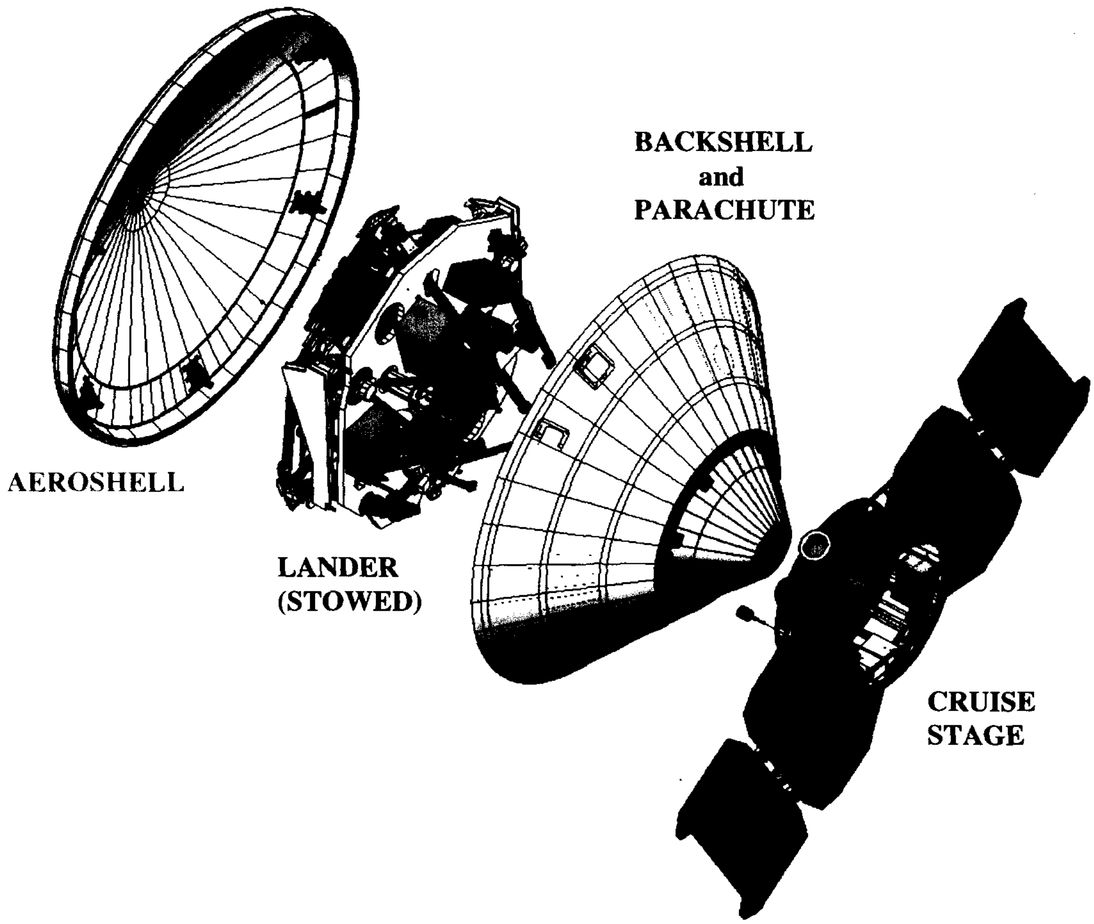

Figure 2. Exploded view of Urey system showing cruise, lander, and aeroshell / backshell

The assembled flight vehicle with a mass estimate of about 657 kg, would be launched in 2007 by a Delta 2925 vehicle with a launch energy (C3) of 14.3 km^2/s^2, as listed in Table 1. The mass estimates for each item include significant contingencies, depending on the maturity of that item. The large launch mass margin suggests a significant mass growth is possible even with the large contingencies. Attempting to choose a smaller launch vehicle (e.g., 2425) in order to reduce costs would not be viable because its launch mass performance is not adequate.

The cruise stage supports the system and acts as the communications module from launch to Mars arrival. It is then jettisoned prior to entry. The aerodynamic components (the aeroshell and the backshell containing the parachute) required for the entry are the Mars 2001 vehicles. Following the aerodynamic deceleration phase, the three lander legs will be deployed (see Fig. 1), and retro rockets will be ignited for the final soft landing. After landing, the solar arrays will be deployed, and the lander arm will lift the rover from the lander deck and deposit it on the Martian surface.

4. UREY ROVER CAPABILITIES

The deployed configuration of the rover is shown in Fig. 3 below. [See Page 6] This rover is the spare Pathfinder rover that was refurbished for the 2001 mission (Ref. 4). It has been modified for Urey by adding the ultrasonic drill (USD) to the end of the warm electronics box (WEB) as shown.

The rover operational capability is constrained by the energy capacity of the power subsystem. The rover is solar and battery powered, but both are limited by rover size and mass. Consequently, the mission controllers must consider what activities are possible with one "energy load" per sol. Fortunately, even if a large amount of energy is expended on a given day (i.e., large depletion of the battery), the Urey Lithium ion battery is rechargeable. This type of battery has a very high energy capacity for a secondary battery. A detailed analysis of various rover energy modes was completed during the proposal effort (Ref. 1). These modes are summarized in Table 2, which assumes an overhead of about 30 W-hr per sol for the rover operations (avionics, etc.). The rover has a battery capacity of 75 W-hr, and the

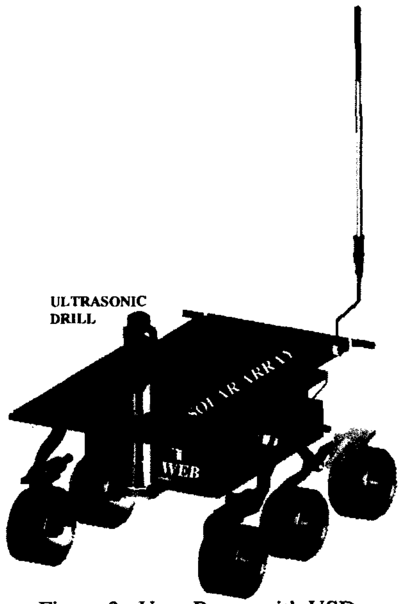

Figure 3. Urey Rover with USD accommodated at end of the WEB

Table 1. Urey Mass Summary

Item	Mass (kg)
Lander system	276
Integrated science payload	29
Lander optical payload (Pancam+IPS+mast)	8
Lander arm	10
Rover	13
USD	2
Total lander dry mass	338
Lander propellant	64
Cruise stage	84
Backshell	106
Aeroshell	65
Total wet vehicle mass	657
Delta 2925 @ C3=14.3 km^2/s^2	960
LAUNCH MASS MARGIN	303

arrays will have an equivalent energy output of more than 95 W-hr per sol. Thus, about 170 W-hr per sol of energy would be available ideally if the battery were fully charged.

Table 2 Urey Rover Power Modes

Operational Activity	Activity Energy (W-hr)	Margin per sol (W-hr)
Rover Imaging (20 stereo pairs)	54	116
Rover Mobility (move 10 m)	50	120
Drill 1 hour (with 4 stereo pairs)	75	95

The design has large energy margins that will ensure a robust capability during surface operations.

Although a detailed telecommunications analysis was completed for the proposal (Ref. 1), only a summary of the capabilities is given here. The architecture of the Urey telecommunications is based on the availability of relay communications orbiters at Mars when Urey arrives. Resources such as the Odyssey orbiter are in Mars orbit at this time, and new orbiters (such as the Mars reconnaissance orbiter) will be functioning on station by 2008 when Urey arrives. Thus, the prime communications path from the Mars surface to the Earth will be via a ~400 MHz UHF link between the surface (lander) and the orbiter, and an X-band (or Ka band) link between the orbiter and the Deep Space Network (DSN) stations on Earth. Communications on the Mars surface between the rover and the lander will be via a ~450 MHz UHF link. Analyses of these links have included a 6 dB margin for each UHF link. This margin is defined at a range of 400 km for the lander-to-orbiter link with a telemetry rate of 256 kbps, and a range of 200 m for the rover-to-lander link with a telemetry rate of 2.4 kbps. Although the analyses are very conservative, the telemetry rates are more than sufficient for the low duty cycle activities on the surface of Mars.

5. Ultrasonic Drill Design

Figure 4 illustrates the configuration details of the USD. This major new element for the Urey mission utilizes the design that has been under development at JPL for many years (Ref. 5). The major thrust of the USD development has been the piezoelectric actuator (PA) that is the basis for the linear impacting drill (i.e., jackhammer) function of the

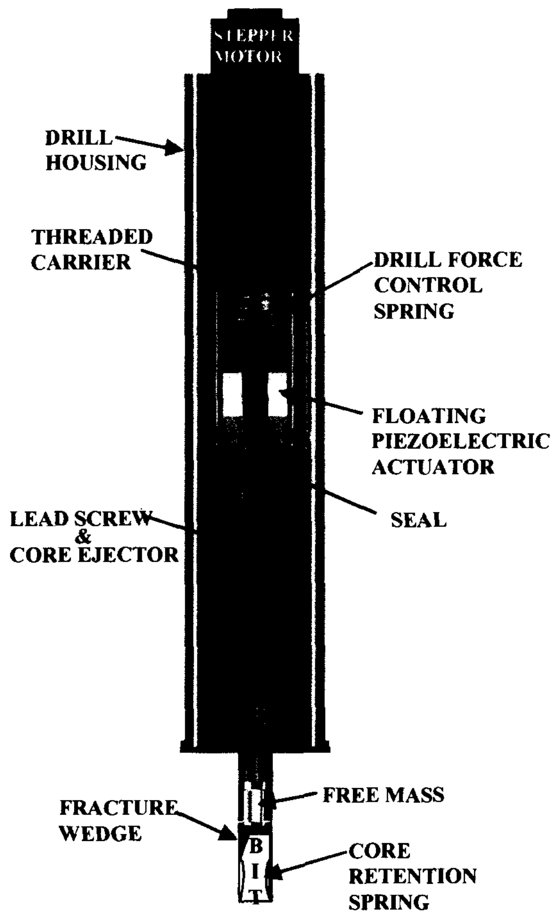

Figure 4. Urey ultrasonic drill (USD) detailed design and control concept

USD. The design of the acoustic horn and the optimization of the size of the free mass at the end of the horn (see Fig. 4) has been a key part of this JPL research, as is reported in Ref. 5.

The Urey contribution has been the simple control concept illustrated in the figure. The PA is located in a central carrier that allows it to "float" within the carrier, thereby enabling the impacting reciprocation. The spring within the carrier controls the small force (less than 0.5 N) applied to the drill to enable the core drilling. A stepper motor-lead screw actuator, acting as a precise controller for the spring, controls the vertical location of the threaded carrier. As the screw is lowered, with the drill in contact with the Mars surface, the spring is compressed to the optimum force required for core drilling. As the drilling proceeds, the actuator lowers the carrier slightly to maintain that force. When the drilling is finished and the core is captured in the bit, the lead screw is reversed causing the actuator to contact the bottom of the carrier, which lifts the bit containing the core out of the hole. The bit is then raised until it is just inside the drill housing for the trip back to the lander to deliver the core to the ISP. When the lander arm is ready to accept the core sample, the carrier is simply raised to its maximum height, which allows the end of the lead screw to eject the core from the bit tube.

All of these actions are possible because of the clever bit design. The bit is a tungsten carbide (WC) tube (see the cutaway in Fig. 4) that will last for the duration of the mission with no significant wear. Two design characteristics shown in the figure are the fracture wedge and the core retention spring. When the WC tube is penetrating the desired bedrock, a cylindrical core forms within the tube. The challenge is to break the core at its root so that it can be withdrawn within the bit as a single intact core. It has been shown repeatedly with actual testing (Ref. 6) that a simple ("fracture") wedge placed in the top of the bit applies enough horizontal impact near the end of the drilling operation to fracture the (~ 8mm diameter) cylindrical core at its root, as shown in Fig. 5. Once the base of the core is fractured, the retention spring shown in the figure will hold the core inside the bit while the rover returns to the lander. When the lander arm is in position to receive it, the core is easily ejected because the lead screw force is much larger than the retention spring force allowing the core to be pushed out of the bit into the end effector of the arm.

Figure 5. Example of USD core result using fracture wedge

6. Operations on the Martian Surface

Once the lander and rover are completely checked out and calibrated for operation, the science mission begins. The first observations are panoramic pictures around the lander to determine what local targets would be reasonable destinations for the rover.

A 4-sol cycle is necessary for the gathering and analysis of each core sample. The cycle begins with a command load being sent to the rover to direct its travel to a specific target site for the drilling operation. It is expected that an entire sol will be required to reach the site because of the slow man-in-the-loop control of the Urey rover. The rover is not totally autonomous and must rely on sending images to the Earth about its location, enabling the rover navigators on the operations team to decide what navigation command load to send next. It is expected that the rover can move from 5 to 15 m per sol using this process. The rover should reach a site about 10 m from the lander on the first sol.

The second sol will be dedicated to drilling the rock core. It is expected that detailed images of the target area from the rover will be necessary to identify the exact location to drill. From drilling experiments at JPL into hard basalt (the expected rock type), it is expected that the drilling will take about 1 hour to produce an 8 mm x 25 mm core. The drill design goal is to have a penetration rate of about 25 mm per hour at an average power of about 40 W, for a total energy of about 40 W-hr per core. The support imaging requires about 5 W-hr. The rover requires about 30 W-hr per sol for normal operations (computing, etc.). This sum of 75 W-hr is well within the available energy of about 170 W-hr per sol from the rover array and battery (see Table 2).

On the third sol, the rover will return to the lander. It will move to a specific location accessible to the lander arm, and the USD lead screw will eject the core into the effector. The arm will then move the effector (with the core) to the ISP input funnel where the core will be deposited for analysis.

The fourth sol of the cycle will be dedicated to ISP analysis of the core and returning the telemetry from that analysis. Also, the rover battery will be charged to prepare for the traverse to a new site when the cycle will be repeated.

It is expected that about 25 of these cycles can be completed in our 90-sol nominal mission. However, with no expendables designed into the mission and no failures, the lifetime of the Urey mission could be indefinite. The only limitation on the science return is the twenty receptacles in the crucibles in the AGE instrument, which means that twenty samples can be dated. The MOI and MICA experiments, however, will be available indefinitely (barring failures) for elemental and organic analyses.

7. UREY DEVELOPMENT CHALLENGES

The development challenges for the Urey mission include completing the return-to flight (RTF) modifications and qualification testing for the lander system and the rover, including the hazard avoidance development. In addition, the ISP fabrication and integration is expected to be a new but manageable development. Finally, the USD development is planned to include an extensive testing program to ensure that the drilling and handling of cores can be done for many different materials.

Following the Mars Polar Lander (MPL) failure in 1998 (Ref. 3), many design questions were revisited during the redesign effort for the Mars 2001 lander. A key recommendation from the failure review was to incorporate terminal hazard avoidance (HA) on the lander. Even though the rock abundances at the proposed site are low enough that the probability of landing success is greater than 99%, an HA system is perceived as mandatory. The current concept (Ref. 1) depends on an image controller that causes the retro engines to divert the trajectory away from hazards. A CCD imager with an ~70 degree field of view has a duty cycle of about 3 to 4 s in this control loop. The image is processed by an algorithm that optically identifies the "flattest" area in the scene. The horizontal divert distance is obviously a function of altitude. For example, at 1000 m altitude, the distance is $\leq$300 m, whereas at 100 m altitude the distance is $\leq$14 m. The key development issue for Urey is an extensive test program to demonstrate the reliability of this concept at LMAO facilities (Ref. 1).

An important factor for RTF lander development is the real time entry descent and landing (EDL) telemetry capability. This is another outcome of MPL failure review (Ref. 3). A Mars lander will be required to go through the EDL phase with, at least, continuous engineering telemetry. The 2001 lander design was modified to include a UHF link that will transmit high data rates (8 kbps) to a relay orbiter at Mars and a carrier-only UHF link directly to Earth. Again, qualification testing will be necessary to demonstrate the reliability of this design.

The RTF qualification for the rover will be more straightforward because of the extensive refurbishment and testing accomplished during the Mars 2001 project. The new addition for the Urey rover is the integration of the USD. This new small appendage is a major element of the Urey mission, and its performance on a rover is the development challenge. It is expected that a prototype USD will be integrated into an engineering model rover to evaluate the autonomous operational capabilities of the USD/rover system. This step will be followed by flight integration and testing of refinements in both hardware and software, during the flight system integration at JPL, prior to shipping the system to Lockheed/Martin for final pre-launch integration and testing.

A significant development challenge for Urey is the integrated science payload (ISP). Although the principal analytical instruments in the ISP have elements of high heritage, these elements must be integrated into a reliable operational scientific payload. The argon geochronology experiment (AGE) development will occur in multiple stages. The first stage of conceptualizing and breadboarding the instrument has been nearly completed (Ref. 1). Preliminary analysis results have been achieved in the laboratory. The second stage will be to build an engineering (prototype) model (EM) that will be operationally tested in the laboratory before shipment to a JPL testbed where it will be integrated with the ISP factory components. This procedure will enable realistic operational testing of the actual factory processing and analysis required of the ISP during the mission. At this prototype level, issues may surface that would require small changes in the AGE design; this is a realistic expectation as part of the development process. These changes would be made to the flight instrument design and fabrication. Then, the flight instrument would be delivered to the testbed again, along with the other flight instruments and factory components. Thus, the final ISP hardware and software will have been completely tested in an operational environment before sending it to the final integration and test with the lander at LMAO. Although the MICA and MOI experiments are not as complex as AGE, they will go through a similar EM and flight development process with the ISP testbed at JPL. It is expected that this process will allow refinement of the ISP system design. The functional (and environmental) testing of the ISP will result in a highly reliable payload system before integration with LMAO lander.

The final new development item on a smaller scale is the ultrasonic drill (USD). This development will capitalize on laboratory research that has been under way at JPL for many years (see Refs. 5 and 6). The piezoelectric actuator (PA) is very mature and will be virtually off-the-shelf hardware. The USD development challenge will be integrating the mechanical and electrical control system around the PA to produce an autonomous operational system. Similar to the ISP procedure, an EM of the USD will be introduced to the JPL testbed early in the development. This will allow the control software and functions to be thoroughly tested prior to the development of the flight unit. One of the special development tests for the USD includes the reliability and repeatability of the core drilling. Many possible materials could be encountered at a place like Cerberus, thus the drill must be sufficiently robust to be adaptable to this diversity. An extensive laboratory and field testing program is planned to investigate drilling techniques and bit design details that will establish a statistical database of performance variations during the USD operations.

8. Conclusions and Urey's Future

This mission can provide a profound science return at a low cost compared to a mission that would return a sample to Earth for age dating. This low cost is enabled by the high inheritance afforded by the major systems (i.e., the lander system and the rover). Once the absolute dating of Cerberus is accomplished, other missions can consider carrying this type of payload to other areas of Mars where similar dating experiments will be possible. Another unique cost-saving element of the mission is the USD. The drill, itself, will be reasonably costly to develop (on the order of \$10 M). But the fact that it can be accommodated on a small rover like the Urey rover means that significant savings (many \$10s of millions) in rover development is possible. In the future, however, larger drills that can go deeper than is required at Cerberus will be necessary and must be supported by more expensive, larger rovers that are now under development. Urey is thus in a unique position in time when the heritage and development are ready so that this exciting mission could be accomplished within the cost constraint of a Mars Scout mission.

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