Mission Concepts for Deep Subsurface Exploration of Planetary Ice Enabled by Nuclear Power[1,2]

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Abstract— The exploration of subsurface ice environments on the Mars polar caps, as well as the icy moons of the outer solar system, has gained increasing attention in recent years. A number of mission concepts have been developed to varying degrees to explore these subsurface regions. In prior studies the ability to access these environments to significant depths has been limited primarily by the power systems available for application to such missions. The current state of development of compact nuclear fission power sources, however, brings new opportunities for deep, long term exploration in planetary ice, enabling missions to explore the full depth of the Martian ice caps, and potentially explore the icy shells of the Jovian moons.

In this paper a complete mission design is presented for one such mission to the north pole of Mars. The mission concept includes a design for a potential lander configuration, based on adaptation of current technology as developed in early studies for the Mars Science Laboratory (MSL) project. The mission design also makes use of the basic entry, descent, and landing (EDL) proposed for MSL, with modifications to accommodate the configuration and mass of the ice probe and other landed elements.

Two alternative methods of ice exploration are discussed, both enabled by a small 15 kW (thermal) surface fission power system. The first of these designs considers a lander-mounted reactor configuration with the reactor supplying 3 kW of electrical power to an electrically heated ice probe, based on designs currently in development and tested in terrestrial applications. The second concept considers a design in which the nuclear reactor is incorporated directly into the body of the ice probe, allowing the full thermal output of the reactor to be used in melting the ice. Each of these concepts brings distinct system design advantages, which are discussed in the paper, as well as the potential application of these concepts to the exploration of other solar system bodies.

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1. INTRODUCTION

The planning of Mars surface missions has progressed in recent years in the direction of increasing complexity and science return within the capabilities of existing or planned technologies. This has meant, until recently, a focus primarily on solar energy, which places inherent limitations on both mission power and longevity. The longevity issue can be addressed in a very efficient manner by the use of Radioisotope Power Systems (RPS), as are currently being considered for the Mars Science Laboratory (MSL) mission in 2009. RPSs have demonstrated their capability in the Martian environment with the Viking 1 and 2 missions, which lasted six and four years, respectively, on the surface of Mars. The Viking generators provided about 70 We to each lander, and new designs currently under development would provide RPSs with a power level of about 120 We per unit.

Beyond power levels of about 1 kWe, however, the application of RPSs begins to be significantly massive and expensive, especially for a landed system. At levels above about 3 kWe, the use of a fission power system for surface applications becomes an attractive alternative. A design concept for just such a surface fission power system has been developed recently by the DOE in the form of the Heatpipe-Operated Mars Exploration Reactor (HOMER) 15

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kWt heat-pipe reactor coupled with a 3 kWe Stirling converter [1]. This surface fission power system would combine low mass and a simple design supportive of near-term technical feasibility in a package that lends itself well to application in current-technology Mars lander design. A team from JPL, working together with the DOE was tasked with exploring mission options that could make use of this power system to enable innovative Mars science in missions that could be launched within the next decade.

The team evaluated a number of concepts for stationary high-powered science missions, but a clear favorite soon emerged in the form of a mission to send a lander to the Mars north polar ice cap equipped with an electrically heated thermal probe for investigation of the historical climate record contained in the polar ice. This mission concept promised to return unprecedented science leading to a better understanding of Mars' past and possible evidence of extant life. The fission power system's output would be enabling to support the electrically heated cryobot's high power needs (1-3 kWe), and the landing location on the north polar ice cap presented system design benefits as a result of the neutron reflection and shielding properties of the water ice landing surface.

In the year since the initial study was performed, members of the team have had a chance to reevaluate the implementation of the cryobot design and refine the science objectives of the mission. This has resulted in the preliminary design of an alternative concept for the mission that is thought to have additional implementation advantages. In this new concept, the full thermal power of the reactor is put to use to effect the melting of the ice by incorporating the HOMER reactor directly into the body of a larger thermal probe. This implementation appears to provide numerous benefits, allowing a broader mission that includes elements of surface environmental characterization as well as enhanced subsurface investigations.

2. Mission Science

The polar caps of Mars consist of broadly dome-shaped accumulations of ice and dust, up to about 3 km thick, and extending hundreds of kilometers away from the geographic poles (Fig. 1). Orbiter images reveal a series of troughs spiraling away from the center, and exposed in the trough walls are many hundreds of horizontal, meters-thick layers. These layers are thought to represent the geological record of climate change in the recent history of Mars [2]. The polar deposits consist of two geologic units of Amazonian (most recent) age, a thin residual polar ice deposit (Api), and a thick sequence of underlying layered terrain (Apl).

Figure 1. MOLA-derived image of north polar cap and Erg of Mars, with general area of mission interest shown in red.

These polar deposits are very young geologically [3], raising the question of the nature of polar deposits earlier in Mars history [4]. Variations in orbital parameters, such as obliquity and eccentricity, may cause the cap to be larger or smaller than its present volume, or even to disappear completely. The bed of the north polar cap is significantly warmer than the upper layers as a result of geothermal heat, but the present cap is not thick enough to cause basal melting [5], unless composed of a mixture with greatly reduced thermal conductivity [6]. An increase in thickness, or a variety of other factors, could cause basal melting and the storage of liquid water below the cap. Indeed, evidence has been presented that the major topographic re-entrant into the cap, Chasma Boreale, is due to basal melting and catastrophic outflow [4].

Underlying the north polar layered deposit (Apl) is a lower platy unit (LPU) in excess of several hundreds of meters thick, and apparently different from the overlying Apl and the underlying Vastitas Borealis Formation (VBF). This unit, initially documented by Byrne and Murray [7], may be the geological record of the residue formed when the polar cap melts or ablates, releasing its accumulated debris [8].

Underlying the LPU and covering the extensive northern lowlands is the Vastitas Borealis Formation of Hesperian age. This unit is closely correlated in time and space with the vast water outflow channels and may be the sublimation residue of the outflow channel effluent [9]. The outflow channels represent catastrophic release of groundwater from the subsurface aquifer, an environment that is a candidate habitat for life.

In summary, the basal domain of the north polar cap represents a compelling environment for the search for extant (and fossil) life. The polar layered terrain holds the climate record of the Late Amazonian, a time when climate change produced periods of liquid water flow on the surface, and thus might harbor life in more clement periods. This deposit also provides access to the nature and evolution of the climate; deconvolving this record will provide an understanding of the past climates of the planet as a whole, which will provide predictions about when and where clement conditions might have prevailed.

3. MISSION IMPLEMENTATION

A cryobot is a robotic vehicle that achieves mobility in an ice environment by thermally changing the phase of the icy solid to a liquid or gas through which the vehicle can pass [10]. In both concepts presented in this paper the nose of the device heats the icy medium by means of a hot water jet and effects the phase change. Cryobots are similar to remotely operated vehicles in the ocean; they carry electronics to power and control the system, and also carry an on-board instrument payload. In the icy cavity, the cryobot's instrumentation suite can perform imaging, sampling, and a variety of scientific investigations. For the Mars polar cryobot application the cryobot would be tethered to the lander vehicle. The tether enables power and signals to move to and from the lander and the submerged vehicle. Two fundamentally different conceptual implementations of cryobot design are considered in this paper.

Electrically Heated Cryobot

The first of these concepts is based on developments carried out at JPL and proven in a variety of field-test applications.

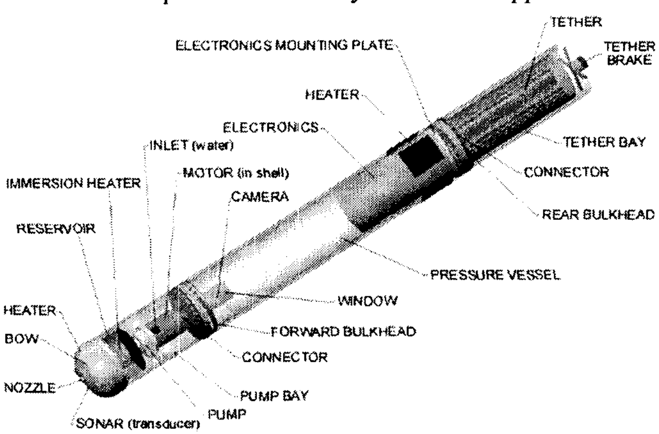

FIGURE 2. Illustration of Cryobot Subsystems.

The basic structure of the cryobot vehicle is cylindrical and divided into Bays: Nose, Pump, Instrument, Electronics, and Tether (See Figure 2). The nose bay contains the passive melt system and jetting nozzle; the pump bay holds the water jetting subsystem. The instrument and electronics bays use a pressure housing very common to oceanographic probes. The tether is used to supply power and serve as a data and command communication cable. The cryobot vehicle would be controlled to maintain vertical orientation during passive melting, but is also capable of directional change via differential heating of the four quadrants of the nose bay heater plates. This directional control may be used in the mission to allow the cryobot to maneuver around submerged obstacles, as well as to perform melts at vertical angles around the landing site (after successful completion of the initial vertical bore) to obtain information on regional variations in the ice sheet.

The cryobot instrument suite for the initial study included a visible/ultraviolet macro-imager for obtaining high-resolution images of the borehole walls. Visible imaging can allow characterization of the dust layers deposited on the ice over geological time scales, while the UV images facilitate a search for evidence of fluorescent organic markers trapped in the ice. The instrument bay also accommodates a high-resolution electrospray ionization/ion mobility spectrometer (ESI/IMS). This instrument would be used as a tool to analyze the effluent during cryobot operations and determine the composition and abundance of possible biomolecular species to aid in the search for traces of life (past or present) on Mars.

Nuclear Heated Cryobot

An additional study effort is now underway to evaluate an alternative design of the cryobot for this mission. In this concept, the full thermal power output of the reactor is exploited by incorporating the reactor directly into the hull of the cryobot. In addition to efficiency of power utilization, this concept has significant advantages over a surface-mounted nuclear system powering an electrically heated cryobot, since the polar ice would very effectively shield all surface assets from the operating reactor once it has begun its mission. An additional important advantage of this implementation is the minimization of the reactor's thermal impact to the environment around the lander, allowing more accurate assessment of surface conditions over the duration of the mission. The reactor would use a thermal-to-electric power conversion system to provide electricity to the surface elements to support science, telecommunications, and survival heating. A preliminary configuration of this alternative cryobot design, incorporating the HOMER 15 reactor, is shown in Fig. 3. This preliminary design concept will be refined and optimized in the ongoing study.

The cryobot, which is about 3 m in length and 0.5 m in diameter, is designed to use heatpipes to transfer the thermal output from the reactor to heat water jets expelling through the nose. These jets are the primary method to melt the ice ahead of the cryobot, with gravity acting to drive its descent through the ice. A heated sample probe is included in the nose of the cryobot to obtain pristine meltwater samples slightly ahead of the main cryobot hull. Water samples would be transferred either to instrumentation within the cryobot itself, or pumped via a tubing system up to analysis equipment on the lander. The instrument bay on the cryobot provides a generous volume for accommodation of a variety of instrument payloads. In addition to sample analysis, the instrument bay incorporates imaging instruments, able to make detailed observations of the ice through windows, lenses, and illuminators.

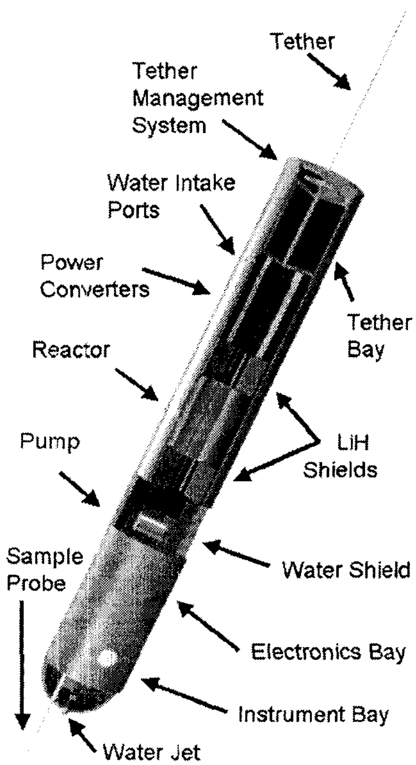

Figure 3. Nuclear Heated Cryobot Configuration

Electrical power is produced for both the onboard cryobot systems and surface lander elements by power conversion equipment (e.g. thermoelectric or Stirling generator) located in the power conversion bay shown in the figure. Heatpipes brought from the reactor provide the thermal energy needed for these converters. Electrical power for surface elements is supplied by a tether system that deploys from the aft end of the cryobot as it descends into the ice. Minimal LiH shielding is provided to protect the cryobot electronics from radiation during its initial deployment. A Water-filled compartment forward of the reactor provide the bulk of the shielding for onboard elements during the mission. This compartment will be filled with meltwater as soon as the cryobot is immersed in the ice, thus allowing a significant reduction in landed mass.

The configuration shown in Figure 3 represents an initial conceptual design. Several trades remain to be performed to arrive at the optimum power system configuration in terms of performance and technical risk.

Mission Design

The landing site selected for the study is on the north polar ice cap at 84° N and 32° E (see Fig. 1). At this location, the ice cap is believed to be approximately 2-3 km thick.

In the initial study the team targeted the mission for a November 2011 launch resulting in an August 2012 arrival. The 2011 launch date was chosen as the first opportunity following launch of the MSL mission in 2009, which will serve to test several of the systems used in the design of the cryobot lander. The spacecraft will launch aboard a Delta IV heavy launch vehicle (Delta 4050H).

The natural transfer geometry to Mars in 2011 favors landings at low or southern latitudes. The northern polar cap only becomes accessible by using transfers which are close to 180° heliocentric and require high launch and arrival energies. A 20-day launch period has been found which minimizes launch energy given a constraint of a 20° declination of the arrival asymptote at Mars. This launch period is described in the following table:

TABLE I. Mission Transfer Parameters.

Parameter	Opening Day	Closing Day
Launch date	2011-11-27	2011-12-17
Arrival date	2012-08-16	2012-09-15
Launch energy, C_3 (km^2/s^2)	24.8	30.6
Delta 4050H capability (kg)	5830	5160

This mission would use a direct Type I transfer with relatively high energy from Earth to Mars, leading to a direct entry into Mars' atmosphere. An MSL-derived aeroshell and heatshield would protect the lander during entry until the spacecraft has decelerated enough for a Viking-style parachute to open and slow the velocity further. Within a few kilometers of the surface, the on-board radar altimeter would begin operating and at the appropriate altitude will signal parachute release and initiate powered descent to a soft landing on the polar icecap. Surface operations including communications, deployment and power system startup would be battery-powered until the nuclear reactor achieves full-power operation. Science operations would commence within a week or two of landing and continue for a nominal mission of 5 yr (2.6 Mars years). It should be noted that planetary protection considerations, which may be significant given the nature of the mission, were not addressed in this initial study.

Lander Design – Initial Study

Configuration – The Cryobot Lander configuration for either of the cryobot designs results from adaptation of a baseline design for the 2009 MSL mission pallet lander. For the electrically heated cryobot concept the fission power system is mounted to the base of the pallet lander deck

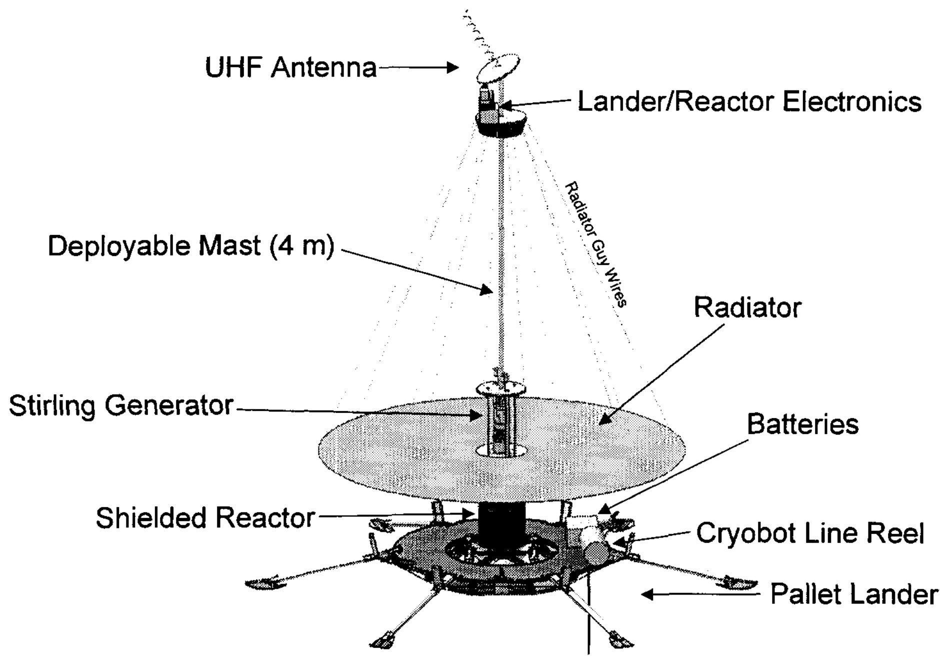

FIGURE 4. Lander Configuration

(Figure 4). The lander batteries and the cryobot mechanical systems also are mounted on the deck, with the cryobot itself being lowered from the side of the lander into the ice. The deck area would experience very high radiation doses during the course of the mission, allowing only the most radiation-tolerant equipment to be located there. Electronics for the reactor, lander subsystems, and science instruments are all located on a shielded platform extending four meters above the top of the power system.

The power system radiator takes the form of a 20 m^2 disk extending around the plane of the Stirling cold collar. The radiator rejects heat from its upper surface only; the lower surface is insulated to minimize heat input to the ice. Guy wires shown in the figure serve to stabilize the mast and radiator, and are also used to deploy the stowed radiator following landing

Mass Summary – The Delta IV launch vehicle provides a worst-case launch mass capability of 5160 kg for the high C_3 needed for this mission. The lander payload mass, including the fission power system, electronics, and science payloads totals to 1404.7 kg, as summarized in Table II. Using an MSL-derived pallet lander (which itself is estimated to weigh 1000 kg) brings the total landed mass to approximately 2405 kg. The MSL-derived entry system for this mission is estimated to weigh about 1142 kg resulting in a total entry mass of about 3547 kg. A mass of about 400 kg is estimated for a basic cruise stage, patterned on those under consideration for MSL, bringing the total launch mass to 3947 kg. The MSL design that we have adopted uses the lander propulsion system for cruise attitude and trajectory correction maneuvers. Propellant mass is included in the mass estimate for the entry system.

The wet launch mass of 3947 kg leaves a mass margin of 1213 kg over the Delta 4050H worst-case capability. This gives a spacecraft mass margin of better than 30% for this mission.

The Cryobot Lander was designed to fit within the envelope of an MSL-derived 4.57 m-diameter with an extended backshell to accommodate the height of the power system (Figure 5). This is the largest aeroshell that can be launched by currently available launch vehicles and it gives fairly good performance in terms of landed mass capability.

TABLE II. Lander Payload Mass Summary.

Element	Mass (kg)
Reactor Power System	458
Structure	35
Telecom	32.7
Thermal	2
Avionics box	17.3
Primary battery (for EDL and deployment)	37
Secondary battery	53.4
Power electronics	34.8
Radiator	72
Shielding (incl. Electronics platform)	578
Mast-mounted science payload	2
Cryobot & Tether	80
Astrobiology science package	2.5
Total Payload Mass	**1404.7**

Using the current Mach 2.2 qualification envelope of the Viking-style supersonic parachute this aeroshell is estimated to allow a landed mass of about 2048 kg to be delivered to the surface. The cryobot lander estimated landed mass exceeds this by some 350 kg, which will probably require an expansion of the qualification envelope of the supersonic 'chute. It is estimated that the same Viking-style parachute, if qualified to a Mach 3 envelope could increase landed mass capability for the same aeroshell to as much as 3600 kg. The availability of this Mach 3 parachute has been assumed for this mission study. It should be noted that the use of a Mach 3 'chute requires no new technology development, but is rather a question of increase in the qualification envelope of an existing, proven design.

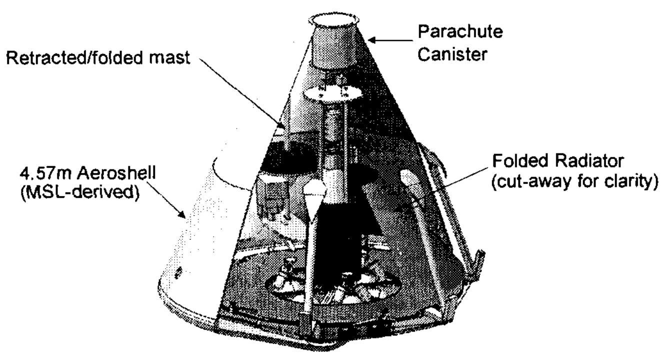

FIGURE 5. Lander in Aeroshell.

Surface Fission Power System – The HOMER-15 surface fission power system (Figure 6) uses a heatpipe-cooled, UN-fueled, stainless steel-clad, pin-type reactor with a Stirling power conversion system [1]. Heat would be rejected to the cold Martian surroundings via a set of capillary pumped loops embedded in a deployable disk-shaped thermal radiator.

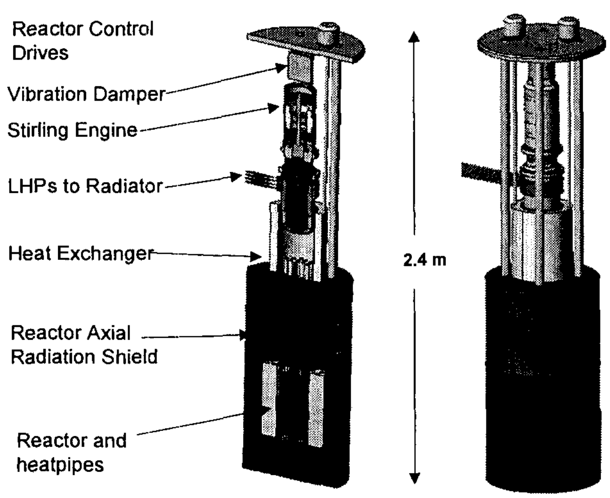

FIGURE 6. Surface Fission Power System.

Shield Design – By far the dominant factor influencing the design of this mission is the shielding necessary to provide a safe haven for the lander and instrument electronics. A baseline requirement was that total mission dose to electronics should be kept below 200 krad to allow the use of currently available technology. The need to minimize shielding mass has led to a unique solution to this problem. It became clear that shielding the full area of the lander deck to acceptable levels would be a prohibitively massive proposition, and scattering from the Martian surface precluded the adoption of a simple shadow shield, such as might be effectively applied in a space environment. The solution takes the form of a combination shield consisting of two major parts: a preferential 4π shield around the reactor and a shadow shield under an elevated electronics platform as can be seen in Figure 3. The platform is placed atop a 4-m boom that extends from the top of the power conversion system. A 4-m length was chosen as a balance between shielding and structural/deployment concerns; this height allows approximately 100 kg of shielding to be placed at the base of the platform. The 4π shield contains most of the mass and does most of the shielding, largely by preventing neutrons from scattering off of the surface and spacecraft components. A certain minimum amount of 4π shielding, ~200 kg, is required to keep doses acceptable to power system components (control drives, Stirling engine parts, etc.). In the lander design the 4π shield is considerably augmented, weighing 465 kg. This allows the platform shield mass to be kept within the requirement of ~100 kg, and the extra 4π shielding keeps doses lower to the cryobot, feed cables, and other lander components. The platform shield consists of additional neutron shielding (20 cm of additional LiH) and a 0.5 cm thick depleted uranium gamma shield. This gives the platform shield a total mass of 113 kg. The total mission dose at the electronics platform resulting from this shielding design is shown in Table III for gamma and neutron dose.

TABLE III. Radiation Dose Results (5 years at 15 kWt).

Location	Neutron (krad)	Gamma (krad)	Total (krad)*
Platform Average	139	205	180
Platform Center	129	142	157
Platform Edge	160	188	197

*note that total for platform locations includes assumed 5x reduction in gamma dose provided by electronics boxes

The shielding would result in radiation dose levels that meet the requirements and should ensure the life of electronic components exceed the duration of the mission.

Lander Design – New Configuration

The Lander configuration for the nuclear heated cryobot design, although also based on early designs for the MSL pallet lander, has a number of differences from that conceived for the original study (Figure 7). Chief among these, visually, is the absence of the large heat rejection radiator and electronics mast that are necessary with the lander-mounted reactor concept. The incorporation of the reactor into the body of the cryobot eliminates the need for an external radiator, and, since the ice itself would provide shielding from reactor radiation soon after the cryobot begins its descent, the need for remote mounting of lander electronics is also eliminated.

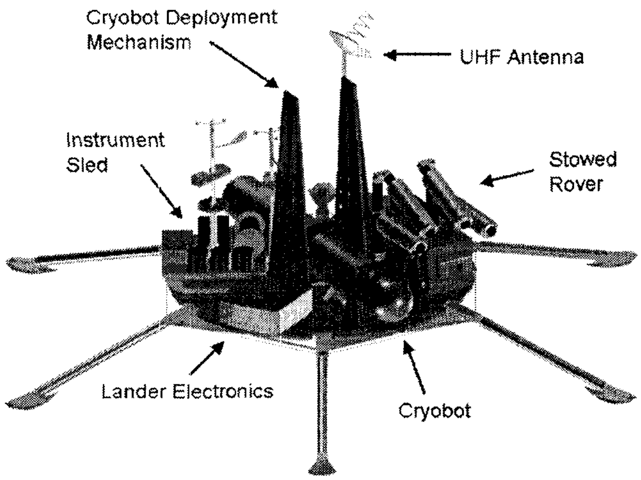

Figure 7. Nuclear Heated Lander Configuration

In this configuration the lander deck is dominated by the large deployment mechanism used to erect and launch the lander through an opening in the middle of the lander deck (Figure 8). In addition the configuration shown includes packaging of additional mission elements that have been incorporated in the updated mission architecture. These consist of an instrumentation sled, which carries local environmental and meteorological instrumentation, and a small rover, which would be operated either tethered or using rechargeable batteries, to be used for placing the instrument sled as well as performing local investigations around the landing site.

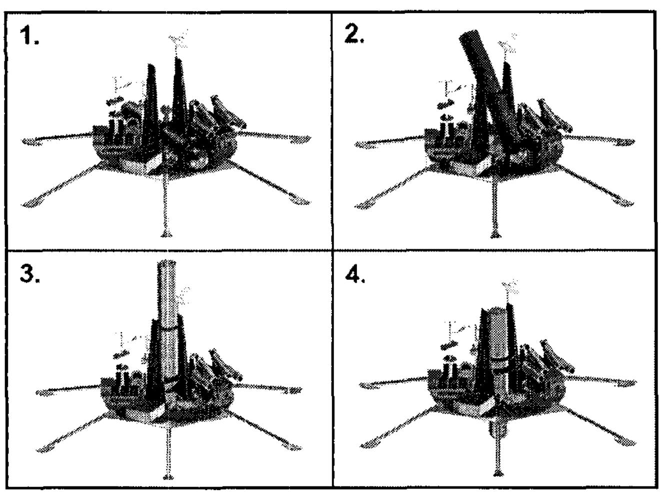

Figure 8. Cryobot Deployment Sequence

Power produced by the reactor in the cryobot would be delivered to surface assets through the tether, which is payed out from the cryobot as it descends. Surface assets in this case include lander electronics and communications systems, surface science platforms, and possibly additional sample analysis equipment supplied with meltwater pumped up from the submerged cryobot.

Mass Summary – While detailed design work remains to be performed on this cryobot mission concept, a preliminary estimate has been made for the mass of the nuclear heated lander configuration. The lander payload mass is summarized in Table IV.

TABLE IV. Nuclear Heated Payload Mass Summary

Element	Mass (kg)
Cryobot	
Reactor/Controls	244
Cryobot Structure	589
Power Conversion	80
Tether	60
Pumps	20
On-board Instrumentation/Sample Handling	80
LiH Shielding	100
Balance of Payload	
Telecom	32.7
Thermal	2
Avionics	17.3
Primary battery (for EDL and deployment)	37
Secondary battery	53.4
Power electronics	34.8
Cryobot Deployment Structure	30
Rover	100
Instrument Sled	40
Total Payload Mass	**1520.2**

The reduced need for reactor shielding in this concept and the elimination of the radiator has been offset by the mass needed to construct a large cryobot pressure vessel able to withstand the pressures at the bottom of the ice cap. When combined with the mass allocations for the rover and instrument sled, the total payload mass comes to about 1520 kg. Still assuming a 1000 kg pallet lander mass, the total landed mass comes to 2520 kg. The MSL-derived entry system mass of 1142 kg results in a total entry mass of 3662 kg. The addition of a 400 kg cruise stage then brings the total wet launch mass to 4062 kg.

For this heavier option, assuming the same mission design and C3 requirement as that of the original study, the wet launch mass of 4062 kg leaves a mass margin of 1098 kg over the Delta 4050H worst-case capability. This results in a spacecraft mass margin of about 27% for this mission option.

The conceptual nuclear heated cryobot mission is designed to fit in the same MSL-derived aeroshell as that developed in the initial study. Given the landed mass required by this design, it is expected that this mission concept would be even more likely to require the qualification envelope of the Viking parachute to be extended to the Mach 3 range.

Nuclear Reactor System – The baseline nuclear power system incorporates the HOMER-15 surface fission power system design, modified for use in the cryobot (Fig. 9).

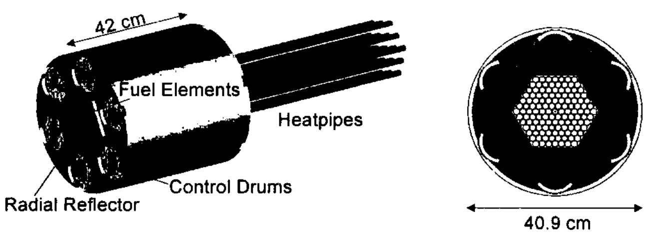

Figure 9. HOMER-15 reactor with control drums

Absent its radial LiH shield, the present design of the HOMER reactor core is less than 41 cm in diameter, including reflectors and control drums. It is possible in this unique application to dispense completely with the radial shield, since the water and ice surrounding the cryobot in its operating environment would serve this function.

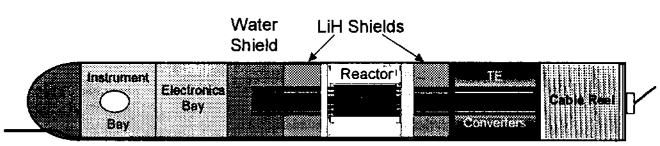

Figure 10. Shielding Layout

Shielding for the onboard electronics and instrumentation must still be provided in this design, but once again the unique operating environment of the cryobot provides an opportunity for an innovative solution. In this design it is proposed to provide empty compartments forward of the reactor, which will be filled with meltwater immediately upon submerging into the ice cap. The precise thickness of the water shields needed for the overall design remain to be calculated, but it is expected to be on the order of less than 50 cm. Initial design concepts also include minimal LiH shielding to be carried for limited shielding of onboard electronics during the initial operation of the reactor prior to submergence in the ice (Figure 10).

The conceptual layout of the cryobot systems places the reactor amidships in the hull. This location was chosen to provide adequate separation and shielding distance from the sample area to limit the effects of reactor-produced radiation on the samples. Likewise, onboard sample analysis instrumentation is designed to be placed as far forward as possible, both to protect sensitive equipment as well as to minimize radiation during sample analysis.

4. Application To Other Bodies

The value of deep subsurface investigation is not limited to application on Mars. An obvious alternative destination for a cryobot is the icy crust of Europa. Previous studies have evaluated the application of cryobots in the Europa environment [10], [11] proposing a cryobot design similar to that evaluated for the initial study described in this paper.

Operation of a cryobot mission on Europa brings unique challenges relative to the polar caps of Mars. The first of these involves soft landing on the surface of what is essentially an airless body. This would require the development of new landing technologies that can deliver a significant mass to the Europan surface without the aid of aeroshells or parachutes. Much more challenging, however, would be the Europan surface environment itself, which is bathed in levels of environmental radiation that would be lethal to even the most hardened electronics within one to two months.

The first of these challenges is assumed to present no insurmountable obstacle, given the successful history of airless body landings proven in lunar exploration missions. The second challenge is much more serious. The thickness of the Europan ice is predicted to be several kilometers and boring through this, while sending back significant data will take time. A cryobot descending into the ice would be protected from this environment fairly soon after submerging, but any surface assets would be quite limited in operational life. In this situation, it appears that a meaningful mission will need to incorporate its entire active complement of mission-critical subsystems into the body of the cryobot, leaving only passive, radiation insensitive elements on the surface.

The nuclear-heated cryobot described in this paper offers an excellent vehicle for just such an application. The size and power of this cryobot design should allow a complete autonomous mission to be packaged within the cryobot hull. Communication could be through a tetherless system involving the placement of miniature radio relay devices at intervals as the cryobot descends through the ice. Surface systems in this way could be limited to a passive radio antenna for transmission of data back to Earth.

5. Conclusions

The design studies for the Mars Cryobot Lander have produced a viable and scientifically exciting concept for a Mars surface mission enabled by nuclear power. The cryobot science mission is particularly well suited to the early use of fission power in a Mars surface environment. The mission as conceived uses existing technology for science and is able to provide a level of power and a mission duration that will enable a full characterization of the north polar ice cap in the region around the landing site. The cryobot mission offers an ideal packaging of science instrumentation for a nuclear powered mission. Following initial deployment the cryobot and its sensitive electronics are effectively shielded from the reactor as it descends into the ice. Finally, the landing site itself aids in the shielding design, since the water ice upon which the lander rests would help to mitigate the scattered neutron dose to the lander.

The lander design with deck-mounted reactor developed in the initial study represents a versatile configuration that can also be adapted to a host of other surface missions with little modification. The study team considered a number of different options for science-driven missions including deep drilling for geological exploration, high-powered laser induced breakdown spectroscopy to investigate regional mineralogy, and in-situ resource utilization. The concepts explored in these studies can also be extrapolated to higher-powered surface missions, likely to become increasingly important to the development of robotic bases or precursors to human exploration.

The nuclear heated cryobot design under development as an evolution of the initial study has particular benefits to the science goals of Mars polar cap exploration, improving on the initial study by enabling a mission that can characterize not only the subsurface environment, but the polar surface as well, without the environmental anomalies that a surface mounted power system would entail. Although further work is planned to develop this option into a full mission design, the major technical challenges appear manageable.

An additional benefit of the nuclear heated cryobot design is its completely self-sufficient design and lack of need for active surface elements. This makes it an excellent choice for operation beneath the surface of Europa, where all active components can be effectively shielded from the harsh surface radiation environment.

These studies have served to open the door to the possibilities enabled by fission-power applied to surface and sub-surface missions. The results imply that such missions are feasible today, with the technologies already available or in late stages of development. Further work should be aimed at optimizing designs and expanding the envelope of potential applications that will revolutionize the potential for science return from Mars and beyond.

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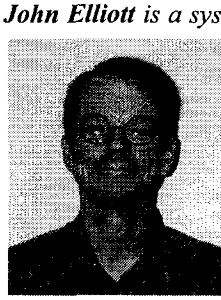
BIOGRAPHY



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