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AN ARCHITECTURE FOR A NUCLEAR POWERED CRYOBOT TO ACCESS THE OCEANS OF ICY WORLDS

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The icy moon oceans beckon with ingredients that potentially may harbor extant life. Beginning with the Galileo and Cassini missions, measurements have revealed the presence of global oceans under the icy crust of several moons of Jupiter and Saturn. Among those moons, Europa and Enceladus have their ocean in contact with the rocky core, providing an environment similar to the conditions existing on the terrestrial sea-floor where life has developed at hydrothermal vents. A detailed trade space study was conducted to develop a technology architecture defining a system that would access an icy moon's ocean. This paper outlines the architecture with specific consideration to the power source necessary to drive the system.

I. Introduction

The Europan Ocean beckon with ingredients that potentially harbor extant life, similar to the conditions existing on the terrestrial sea-floor where life has developed at hydrothermal vents [1-3]. Accessing the Europan ocean presents considerable difficulty due to a number of issues including the depth and composition of the icy crust, the time needed to travel through the crust, the power needed to propel a probe, communication of scientific and engineering data though the ice and back to Earth, entry and mobility in the ocean and autonomous operations for the life of the mission. A detailed trade space study was conducted to develop a technology architecture defining a Cryobot that would address these challenges [4].

II. Assumptions and Mission Phases

The study's assumptions were naturally grouped into a set of notional mission phases to organize full lifecycle development of the Cryobot. To bound the landed mass for the Cryobot system, mission design parameters from the Europa Lander project were used. This includes using the SLS launcher with the same dry mass as that mission, similar trajectory design to Jupiter and then to Europa, and a similar deorbit system. The Europa Lander concept baselines a skycrane descent and lander, motivated by the requirement of not disturbing the ice surface before science operations begin. The lander system would hold and release the Cryobot and be part of the communications link. As will be described below, communication electronics will not remain on the surface due to the radiation loading, though an antenna system that can resist the radiation loading would. The antenna under development for the Lander concept or a related system would be used. Surface data from the NASA Clipper mission is also assumed and is essential to characterize the Europan ice crust including potential landing sites.

Additional assumptions involve the environment the Cryobot must operate in. Upon touching the surface, the lander vehicle and Cryobot must operate in the Europan surface environment including the radiation field, vacuum and temperature. Initial operations must include entry of the Cryobot from vacuum into the approximately 100ºK ice with a complex and chaotic surface that may have a rich salt content and uneven surface structure perhaps layered with desiccated salts. Once within the crust, a range of parameters of the ice environment are assumed. For this study we are assuming an ice crust thickness of 15 km, a specific depth-temperature profile as described in [5], and a range of salt content that can impact transfer of heat from the Cryobot. The time necessary to descend the 15 km depth is variable and highly dependent on a number of factors including the diameter and length of the Cryobot, the characteristic of the ice crust and the amount of thermal power available in the Cryobot, including the conversion of an amount of thermal energy to electrical energy to operate Cryobot systems. These factors will be used to predict the amount of time necessary to descend through the ice and be drivers for a trade analysis on Cryobot size and power to reduce the descent time to produce a system that can be engineered for flight.

To organize the Cryobot system capabilities, a set of mission phases are defined in Fig. **1**. The key functions of each phase are

- *Landing:* includes the deorbit, descent and landing
- *Surface:* includes the functions of releasing the Cryobot into the ice, maintaining communication to and from the Cryobot as well as communications direct-to-Earth or to an orbiter relay. These systems must be able to operate in the radiation and thermal environment over the life time of the mission
- *Ice Descent:* includes the functions of descending through the entire crust thickness, transmit and receive communication from the surface, and carry the science instrumentation payload.
- *Ocean Access* and Mobility: includes detection and entry into the ocean at the ice-ocean interface and exploration of the ocean.

The assumptions and mission phases were used to define a set of functional requirements for each Cryobot system. Computer-aided engineering design and analysis using a range of structural, electrical (e.g. communications, autonomy state diagrams), thermal and other tools were used to quantify the system design and allow decisions to be made. At each key decision point, maturity of the subsystems was characterized by their readiness and potential to be matured to a flight system over the ten-year time frame.

Additionally, a design principle to integrate redundant capabilities, as feasible, to mitigate unknown environmental risks was applied throughout the study. As will be outlined, this resulted in three methods for ice descent and two methods for communication

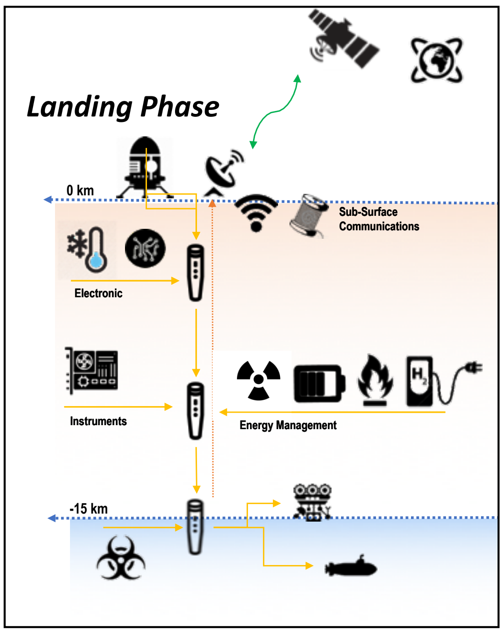

Fig. 1. Cryobot mission phases. The *Surface Phase* releases the probe into the ice and establishes DTE communication. The *Ice Descent Phase* operates the probe, communicating with the surface. The *Ocean Access and Mobility Phase* enters the ocean and deploys a science platform, working under strict planetary protection protocols.

III. Key Systems for the Cryobot

The mission phases define an architecture where the functions of the key systems can be identified and their associated technology maturity assessed. A schematic of the Cryobot is shown in Fig. **2**.

It consists of a Cryobot head where the ice descent systems are located, followed by the power system, the underwater vehicle, a stack of avionic electronics boards indicated in green and then the communication transceivers. A thermal management heat pipe system is integrated with the power system to transfer heat to other parts of the probe to prevent freeze-in.

As will be described below, during the trade study, all systems were designed to find an optimal design given the initial range of constraints. The diameter of the Cryobot became fixed, while the length of the power system can take a few values dependent on the type of packaging of the radioisotope source. After the probe diameter, the total length coupled with available power are the key parameters impacting the time for descent though the crust. Fig. **3** describes key subsystems for the mission phases and key decisions that were considered in producing an integrated system. The following is a summary of the key results.

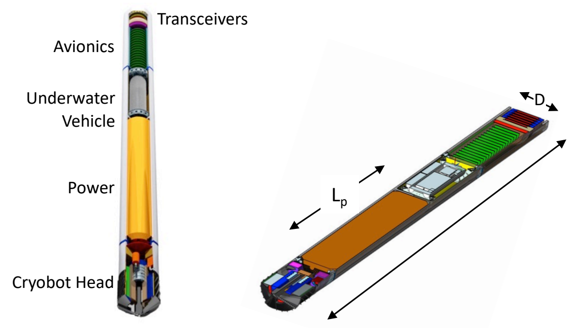

Fig. 2. Notional schematic of Cryobot systems. The probe diameter is D, the length is L and the length of the section for the power system is L_P.

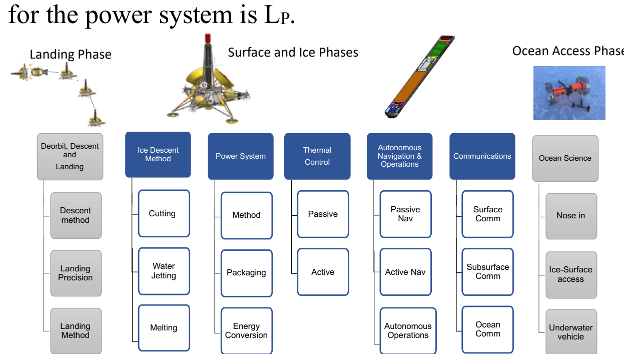

Fig. 3. Key systems of the Cryobot mission and potential options for each system.

III.A. Deorbit, Descent and Landing

The deorbit, descent and landing phase is driven by the requirement of precision landing, ruling out any ballistic hard landing or penetrator, reducing the trade space to skycrane and propulsive landing systems. To optimize mass of the overall landed system, a notional design for a propulsive lander was created that could hold a Cryobot while maintaining stability during descent, with legs that will level the Cryobot for entry into the crust was developed. The propulsion subsystem, including engines and tanks, was sized, and a set of avionics for the descent and landing phase was identified. A cap that would descend to the surface, aiding entry of the probe into the ice was also part of the lander vehicle. As described above, the key component that would be operational through the lifetime of Cryobot operation is the antenna for communications to Earth.

III.B. Ice Descent

Ice descent is driven by the requirements to descend in less than three years, maintain reliability of components for that time, operate in the ice environment that can potentially include salts, sediment layers and voids and handle potential stopping and stalling. Travel through the crust can be accomplished generally by the processes of melting or mechanical cutting. By melting the ice below the probe while maintaining a sheath of liquid around the length of the probe, the Cryobot will descend through the ice. Thermal energy raises the temperature of the ice to the melting point with the addition of the energy of latent heat to melt the ice. Through mechanical cutting, the ice can be excavated beneath the head, and if the chips are removed and a sheath of liquid is maintained along the length of the probe, the Cryobot will descend. Conduction of the heat into the ice crust will carry away a large amount of the energy, and a range of mechanical processes will impact the descent. It can be expected that sediment layers may form below the Cryobot impeding travel, or voids and obstructions can be in the path of the probe.

The energy source is intimately coupled to the ice descent approach. Given the amount of energy and length of time needed to melt the column of ice, the decision tree quickly branched to a nuclear source. The power can be generated within the Cryobot, or by a generator at the surface where the power is transferred by a tether to the probe. During the trade space development, a surface generator was assessed to be outside the mass constraint, e.g. a nuclear fission system with appropriate shielding. The tethered system also requires the tether to withstand any shear movement especially within the top brittle layer of the ice crust. This tether would be a single point of failure when using a surface power system. As a result, the trade space reduced to carrying radioisotope power within the Cryobot to supply both thermal energy for melting and conversion of the heat to electrical energy to power the probe.

An additional approach for melting is the use of waterjets with warmed water resulted from thermal melt at the Cryobot head and recirculation. The use of waterjets also brings the ability to move any sedimentation that may develop beneath the head or to melt and move material layers that may be in the ice. Under the design philosophy of integrating redundant capabilities to mitigate the unknown environmental risks, a Cryobot head integrating thermal melting, mechanical cutting and water jetting was designed. Fig. **4** shows the schematic of the head and subsystems. The mechanical blade must cut the ice and move the chips up past the head, being melted along the way. The water jet system consists of a series of pumps and valves to ingest the ice melt, warm the liquid and propel it through nozzles distributed around the head. Key considerations include maintaining optimal flow rates to melt ice ahead of the probe and eliminating any blockage from sediment build up.

A key consideration is the location of the thermal power source or sources for the thermal melting component of the descent. The energy systems and thermal management systems are key in this piece of the design

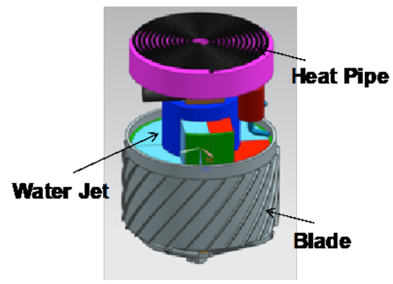

Fig. 4. Schematic of Cryobot head combining elements of melting, mechanical cutting and water jetting.

III.C. Power System and Thermal Management

Requirements for the power system are driven by the total amount of thermal energy available in the constrained volume to power the descent rates needed. The thermal management system is then required to move and manage the heat throughout the Cryobot. As described above, the Cryobot is powered by a radioisotope system based on a plutonium dioxide source. The dominate use of this thermal energy is for Cryobot descent, where the electrical energy that will be converted from the thermal source is secondary, needed for driving the motors in the water jets, cutting blade and the avionics and communication systems. This is contrary to most planetary systems where the electrical power is dominant and the thermal energy is treated mostly as waste heat. Currently available sources have a long developmental and operations history for planetary exploration [6,7]. Thermal electric materials or other converters transform the thermal energy due to the decay of PuO_2 to electrical power. For the purposes of this study, a trade space was developed, based on the $^{238}PuO_2$ material, with various form factors explored for the final packaged power source. The final form factor is dependent on a range of issues, dominated by safe use of the material. General purpose heat source blocks are one fundamental unit, with these blocks packaged into radioisotope thermoelectric generators of various types [6]. Designs of these generators are optimized for safe generation of electric power. As mentioned above, heat from the Cryobot energy source is predominantly used for descent rather than electrical power production with the understanding that the ocean worlds Cryobot application can motivate alternate packaging of the $^{238}PuO_2$ material to provide greater volume efficiency of specific power.

Accommodating the power system along with the Cryobot is central to the system trades considered. The volume and amount of thermal power available from the energy source will drive the overall design and the predicted time to descend through the crust. Designs based on individual general-purpose heat source blocks, the variants of the radioisotope thermoelectric generators and a potential new packaging approach are feasible. All systems require a fraction of the thermal power to be converted to electrical power for Cryobot operations but in the range of 10%, in-family with existing thermoelectric converters. This study examined packaging the general-purpose heat source blocks as well as a potential new packaging of the $^{238}PuO_2$ material which may reduce the volume shown in Fig. **2** for the power system [8,9]. The fundamental change is in the length and the amount of thermal energy available in the power section. Packaging existing radioisotope systems that are larger in diameter were not considered in this study but are being examined elsewhere. Based on accommodating the descent systems in the Cryobot head, the electronics packages and the science package, a diameter of 23cm was arrived at as a feasible diameter. This diameter also allowed for thermoelectric generators around the radioisotope source thermal systems for power conversion along with a fluid loop to transfer heat across the probe and the pressure vessel that holds the entire system.

Two key impacts of the volume and amount of thermal power on the Cryobot are the rate of descent through the crust and the feasibility of a thermal transfer and control system. The probe dimensions and amount of power directly impact the rate of descent and hence the overall time to reach the ocean. Depending on the volume specific power, a thermal management system that can transfer the correct portions of heat to the Cryobot head as well as across the cylindrical body needs to be engineered. Both passive thermal management systems and active heat pipe systems were considered in the study. A design which incorporates a heat pipe system into the pressure vessel walls of the Cryobot was also examined to reduce the probe diameter.

III.D. Electronics, Navigation and Science Payload

To provide requirements for the Cryobot electronics, communications, volume and mass, a strawman science payload was developed. It is expected that this payload will approximate the functionality and accommodation of a Cryobot. The payload consisted of a set of miniaturized instruments and cameras and associated structure and electronics. It included radiation hard APS imagers, a gas chromatograph mass spectrometer, and a capillary electrophoresis extraction unit. A buoyant rover for under-ice exploration (BRUIE) was used as the strawman for the ocean access vehicle.

The avionics was scoped to provide compute power to manage the autonomy systems, data collection and handling, fault protection, motor control, pump control, power conversion, and spacecraft telemetry. It was specified with block redundancy and minimum mission lifetime of ten years. A compute system and motor controller that can meet the requirements are have been studied.

Throughout the trade space, the Cryobot was constrained to operate autonomously with infrequent direction from operators. A set of autonomy functions was specifically developed for operations including lander levelling upon reaching the surface, hazard avoidance and navigation during descent, range and depth estimation, position knowledge and power usage and optimization (e.g. drill power).

III.E. Communications

Data must be communicated from the probe to the surface, through the ice, and then a link to Earth at rates that support the science instruments and housekeeping telemetry. The decision space resulted in a series of transceiver pucks to link the data, puck-to-puck from the Cryobot to the surface, and a communications package for transmission to Earth. The communications electronics package would be placed a distance of approximately one-meter beneath the surface so as to be shielded from surface radiation. A tether from the communications electronics package to the lander at the surface and the communications antenna would complete the link. An additional approach would be to use a tether that would spool from the Cryobot, attached to the transceiver pucks, and provide a redundant and greatly increased data-rate communications path. As stated earlier in the tether option for the power source, the potential breakage due to ice shear or other movement would eliminate this means to communicate and would require further study.

The transceiver pucks follow from earlier work and are a hybrid design combining RF and acoustic transmission. In the cold brittle ice, RF signal attenuation is small, increasing by an order of magnitude as the water content of the ice increases. Conversely, acoustic transmission has less attenuation in the warmer ice and penetrates ice-water interfaces such as liquid pockets in ice and slush. The pucks will be powered by radioisotope heater units with a thermoelectric converter and a set of transceiver electronics. The RF system was specified to operate at 100 MHz with a patch antenna at the top and bottom faces of the puck. The beam width for the patch at this frequency is broad, providing wide angular coverage, hence the transceivers do not need have tight alignment/tilt requirements on their deployed orientation. The transceiver acoustic element employs piezoelectric transducers integrated into the puck. The study indicated a range of 6-10 transceivers are needed, with fewer pucks needed in the cold brittle ice closer to the surface of the crust where attenuation is less and more as the Cryobot descends into the warmer ice.

IV. A Concept of operations

The study developed a notional concept of operations beginning with landing and extending until the Cryobot reaches the ocean and explores the ocean-ice interface. Upon landing, a leg levelling system allows vertical deployment of the probe. Borrowing from terrestrial drilling, a cap is lowered to the surface and allows pressure to build as the Cryobot is lowered within the cap to stop sublimation and initiate melting the ice. Initial thermal simulations indicated pressure will build with the cap as heat is transferred and the ice sublimates. The mechanical drill is also expected to be essential during surface penetration since it is more efficient in cutting brittle ice. At a distance of a few meters into the ice, an electronics package is deposited, where it is protected from the radiation. Once the electronics package is detached from the Cryobot, the probe continues to descend. A tether will be spooled from the electronics package back to the lander and the surface antenna.

During descent, the Cryobot will autonomously travel through the crust with limited ability to be controlled by a human in-the-loop. As described above, thermal transfer for melting, water jetting and mechanical cutting will drive descent. Since the radioisotope power source continually produces heat, the heat can be directed to different segments of the Cryobot as a means to slow or speed descent. The water jetting and mechanical cutting can be turned on and off, operating within a closed loop control system. Navigation data is done using a set of ground penetrating radar and acoustic sensors that will be forward looking, sensing voids or any other disturbances in the ice. Steering the Cryobot off vertical is accomplished by a combination of differential heating of the four quadrant heaters in the nose and water jetting based on the sensed data. Release of the transceiver pucks at the appropriate distance is accomplished by monitoring the signal strength between the Cryobot and each transceiver as the probe descends, and releasing one as necessary to maintain the communications channel. The Cryobot autonomously descends until the ocean-ice interface is sensed.

Once the Cryobot senses the ocean-ice interface the notional concept operations moves to a series of steps for the underwater vehicle to be deployed by tether into the water. A tether approximately 10 meters in length will allow the underwater vehicle to explore within that radius of the ice-ocean entry, and the buoyant vehicle allows the exploration at the bottom of the ice sheet. The instrument suite will sense and transit data back through the tether and through transmission by the transceivers back to the surface where is relayed to earth.

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