RADIOISOTOPE HEAT SOURCES AND POWER SYSTEMS

FOR ENABLING OCEAN WORLDS SUBSURFACE AND OCEAN ACCESS MISSIONS

Key Takeaway: NASA, with the U.S. Department of Energy, must make investments now to repackage heat sources and create power systems over the next decade to enable the search for life in Ocean Worlds in the 2030s.

OCEAN WORLDS SCIENCE DRIVERS AND OCEAN ACCESS MISSION CONCEPTS

The search for life in the solar system is one of the preeminent goals of planetary science, with the Outer Planets Assessment Group recommending a directed life detection mission in the 2030s [1] and NASA’s Network for Ocean Worlds recommending a life detection flagship mission to a planetary ocean [2]. The most promising candidates for habitable environments are the Oceans Worlds, Europa, Enceladus, and Titan, which are likely to have hosted life or host extant life [3]. The physical and chemical measurements required to search for life are not possible through remote observations, or at the surface due to weathering, impact gardening, and, in the case of Europa, radiation bombardment. The ultimate goal for Ocean Worlds exploration is in situ exploration of any subsurface oceans and their interfaces, which necessitates traverses of up to tens of kilometers of ice [4, 5].

New robotic system capabilities need to be established in this decade to enable development of a science-driven series of mission concepts for exploration of Ocean Worlds in the 2030s. The scientific community and NASA are focusing on ice-penetrating robots, or cryobots, capable of “rapid” penetration and scientific sampling of thick ice shells down to an ice-ocean interface where it would enable ocean observations [2, 4, 6]. Cryobot concepts have been and are being studied to that end. Figure 1 depicts a few examples, including melt probes, drills, and combinations thereof. NASA’s Scientific Exploration Subsurface Access Mechanism for Europa (SESEME) development also funds candidate technologies for similar missions.

FIGURE 1. Example concepts of descent probes for ocean access.

OVERVIEW OF CRITICAL TECHNOLOGIES FOR SUBSURFACE ACCESS

A suite of new cryobot-specific technologies that are beyond the scope of NASA’s current development efforts must be matured to ensure successful deep subsurface and ocean access. This white paper discusses potential long-lead and enabling heat and power technologies.

Studies to date have determined that delivering kilowatts of electrical power via a tether from a surface power source to a descent probe at depths of tens of kilometers is impractical due to mass, volume, transmission losses, deployment risks, and potential shearing of the tether by ice movement. Also suspect is using fission power—the mass and volume of those reactors today and for the foreseeable future makes their use for cryobots problematic if not impossible, and certainly costlier and riskier than current capabilities.

It is evident, however, that only nuclear power sources are suitable options for onboard power sources when considering the total thermal and electrical energy requirements of a cryobot. When compared to fission-based options, radioisotope-based options are most amenable to minimizing landed system mass, based on the results of recent studies [4, 6], and so this paper focuses on radioisotope power systems (RPS).

RADIOISOTOPE HEAT SOURCES AND POWER SYSTEMS

RPS are frequently NASA's power system of choice to enable or enhance long-duration missions to dark, distant, or dusty locations. In addition, RPS waste heat has proven an effective way to offset or satisfy a spacecraft's thermal management needs. RPS use the natural decay of plutonium (Pu-238) as a heat source and convert that heat into electrical power. In this paper, we focus on concepts based on the use of radioisotope thermoelectric generators (RTGs) rather than dynamic RPS, given that dynamic systems can suffer from similar problems as fission systems (excessive mass and excessive constraints on probe diameter).

Heat Sources Available Today

Only two flight-qualified heat sources are available today, the General Purpose Heat Source (GPHS) and the lightweight Radioisotope Heater Unit (RHU) [7]. The GPHS starts life with a thermal inventory of ~ 250 W_t and the RHU just ~ 1 W_t. GPHS modules are used in RPS, while the RHUs are not, and so the GPHS is the only flight-qualified heat source for a cryobot's power system at this time. The GPHS is a modular heat source and is stacked vertically (see Figure 2) when integrated into RTGs.

FIGURE 2. A short stack of GPHS modules.

FIGURE 3. Cutaway view of the multi-mission RTG.

Radioisotope Power Systems

The Multi-Mission RTG (MMRTG) shown in Figure 3 is the current state-of-the-art RPS and the only RTG in production. Key relevant metrics of the MMRTG and of past (GPHS-RTG) and potential future (Next-Gen) RTGs that could be used in a cryobot are summarized in Table 1.

TABLE 1. Key relevant performance metrics of three different RTGs.

RTG Unit	MMRTG	GPHS-RTG	Next-Gen RTG
Number of GPHS	8	18	16
Beginning of life (BOL) thermal inventory, W _t	2000	4500	4000
Power, launch, W _e	110	295	400
Power, end of design life, W _e (17 years)	67	210	290
Length, m	0.69	1.14	1.04
"Finless" housing diameter, cm	29	22.0	20.5
Potential availability	"off-the-shelf"	Not in production	Qualification unit by 2028

THE NEED FOR HEAT SOURCES WITH HIGHER THERMAL DENSITY

Sensitivity of Time to Ocean

Melt probes are a leading architectural option for ocean access using RPS power and heat to melt a column down through an ice shell [2, 4, 6]. Since ice shells on Ocean Worlds could be very thick (tens of kilometers), a high descent or melt speed is essential to reach an ocean in a programmatically acceptable amount of time [8]. Ice shells are very cold and highly thermally conductive, meaning heat must be delivered at a rate high enough to melt the ice before the heat is lost to conduction.

As shown in Figure 4, heat would be dissipated from the probe in two ways: through the tip (Q_1) to make vertical progress, and through the side walls (Q_2) to keep the immediate surroundings liquid and prevent freeze-in.

International scientific modeling efforts [9] clearly show that dimensions of a melt probe have an enormous impact on the ice penetration duration per unit length of ice. Probe speed is a function of Q_1 [10] and probe diameter, while probe length dictates Q_2 to prevent the probe being frozen into the ice. Higher power density of the onboard heat source improves the situation in multiple ways. Heat sources that would fit in a smaller diameter than the presently available heat sources would improve descent performance significantly since the probe would melt a smaller volume of ice. As discussed in the following section, a compact heat source is *enabling* for a descent probe capable of penetrating an ice shell in a programmatically acceptable descent time. Further, a shorter probe would require less Q_2 and therefore a higher proportion of heat from a given RPS would be available to Q_1 , thereby improving melt speed. As discussed later in this paper, a thermal inventory of ~ 10.5 kWt at beginning of life (BOL) is a sufficient quantity for a melt probe to carry if the heat density is sufficiently high.

FIGURE 4. Heat transfer out of melt probe.

Potential Options for Increasing Heat Source Density

Current and in-development RPS use a single stack of GPHS modules as shown in Figure 2. To achieve a thermal inventory requirement of 10.5 kWt requires 42 GPHS modules. The cylindrical diameter of this stack would be 13.7 cm, around which the thermoelectric converter would be arrayed, and encased in an RTG housing. Considering the cylindrical configuration of the probe, the use of GPHS modules would be a “square peg” in a “round hole,” resulting in significant volume inefficiencies and descent time penalties.

There are potential alternative ways to stack GPHS modules that increase the thermal power output per unit length, at the cost of cylindrical diameter increase (see example shown in Figure 5). However, while the configuration in Figure 5 provides more than double the linear power density over the single-stack option, the cross-sectional cylindrical diameter has increased significantly, decreasing melt speed.

The primary issue with using a GPHS as a heat source for melt probes is the poor heat density. Both the single-stacked and the alternatively stacked GPHSs provide inferior heat densities that drive time to reach an ocean to programmatically unacceptable levels.

Two cylindrical graphite impact shells (GISs) are housed in each GPHS, and each GIS contains a pair of fuel pellets, as indicated in Figure 2. Each GIS delivers a heat output of 125 Wt. If the GISs were repackaged into a new, circular aeroshell, a significantly higher heat density could be achieved. Such a notional compact power heat source

FIGURE 5. An alternate GPHS stacking configuration viewed side on and in cross-section on the right.

(CPHS) could use up to 7 GISs, as shown in Figure 6, for a nominal heat inventory of 875 W_t/CPHS. The configuration shown here gives an optimized heat per volume based on several options analyzed.

The aeroshell thicknesses used in this design concept are based on the GPHS design. This notional CPHS aeroshell could be developed and qualified in the next 8 to 10 years.

A stack of 12 CPHSs would produce 10.5 kW_t, with just a 4 cm increase in length and a 27% decrease in cross-sectional area from the alternatively-stacked GPHS modules. That decrease in area enables reaching the ocean in an acceptable time.

Plutonium-238 microspheres would provide an even greater heat density. Studies of microspheres [11] found that heat densities greater than the CPHS were achievable. The Technology Readiness Level (TRL) for restarting production of potential microspheres is very low, and likely to be far more expensive than a repackaging of the heritage GISs into a new aeroshell. Having the potential microspheres qualified for a mid-2030s mission carries higher technical and programmatic risk. It is worth noting that the CPHS is *enabling*, while the potential microspheres would improve descent time, they are simply *enhancing*.

Another way to compare the options for heat sources is to look at the cross-sections of RPS that could be designed around the heat sources (see Figure 7). Configuration A is the traditional single stack of GPHS modules. The alternative stacking, depicted in configuration B, improves heat density but results in a significantly increased diameter. The CPHS design depicted in configuration C rearranges the GISs to increase the heat density, ρ , of the heat source and nearly recovers the diameter of the single stack of GPHSs. The metrics for the configurations are provided in Table 2.

Potential RTG Profiles

FIGURE 7. RPS profiles of potential GPHS stacks (A & B), CPHS (C), and microsphere configuration (D).

TABLE 2. Heat source metrics for comparison.

Option	A	B	C	D
Heat Source Approach	GPHS Single Stack	GPHS Alternative Stack	CPHS Stack	Microspheres
Cylindrical diam. of heat source, cm	13.7	20.8	14.6	14.6
Heat density of heat source, W/cm ³	0.29	0.32	0.57	1.06
Number of heat units	42	42	12	1
Stacked heat source length, cm	244	102	112	60
BOL thermal inventory, kW _t	10.5	10.5	10.5	10.5
RTG diameter, cm	17.1	24.2	18.0	18.0
RTG heat density, W/cm ³	0.19	0.22	0.37	0.69
Probe diameter, cm	21.7	30.1	22.8	22.8
Probe heat density, W/cm ³	0.052	0.054	0.096	0.119

FIGURE 6. Notional CPHS aeroshell using repackaged TRL 9 GISs.

Figure 8 is the product of modeling a menu of melt probe architectures and their descent times through a range of possible European ice shells. Each probe model was constrained to use one of the four heat source options in Table 2.

Each probe architecture consisted of a heat source, with associated thermal management and enclosing pressure vessel, an additional 30 L volume allocation for payload, 28 L for baseline engineering functions, and 35 L of system margin to accommodate growth in either the payload or engineering. Heat sources and associated thermal management consumed different volumes for each architecture, establishing a sizeable spread in probe masses. Additionally, architectures A and B were assigned significant additional volume for the communications subsystem due to the short-range, low-power comm relays that were assumed. Repackaging of the GIS was assumed for communications subsystem modeled in architectures C and D, which enabled a higher power comm relays, with much lower stowed volume. The modeled time a probe took to complete the journey from the surface to the European ocean depended on the structure of the European ice shell it melted. The descent time was shorter when the ice was modeled as warmer or shallower. The European ice shells considered here ranged between the 20th and 80th percentile cases identified in Ref. [5], leading to a spread of performance along the vertical axis for each architecture.

FIGURE 8. A plot of time to reach the ocean of Europa as a function of approximate mass of a melt probe. Regions A, B, C, and D correspond to the heat source configurations depicted in Figure 7 and Table 2. Those heat sources set the minimum diameter of a melt probe. Time to reach the ocean varies with mass and is estimated using an array of European ice shells. The inset adds the perspective of how fission concepts fit into the trade space.

When the GPHS stacks were replaced by the energy-dense CPHS configuration, an abrupt change took place in our modeling. The time to reach the ocean improved dramatically and the approximate probe mass dropped significantly as shown by region C. The ultimate descent time is achieved by

using the potential microspheres in a new heat source, as depicted by region D, but the gains over the CPHS-based architecture are only incremental. The microspheres improve descent time further, but are deemed *enhancing* because, by achieving programmatically acceptable descent times using a much lower risk and less expensive heat source, the CPHS allows for similar descent times and masses. The CPHS is *enabling* for these descent probe concepts.

For comparison, the purple box in the Figure 8 inset, “Fission Concepts,” shows the same metrics applied to the Tunnelbot fission reactor concept [12], which assumed a thermal inventory to 43 kWt. However, this also requires the addition of significant probe volume to account for the fission reactor, infrastructure, and shielding. The overall heat density enables a somewhat faster descent time, but at a significant additional cost, mass, radiation, complexity, and landed mass.

RECOMMENDATIONS FOR NEXT STEPS

We recommend that NASA engage the U.S. Department of Energy now to perform design studies for a heat source that could enable cryobot missions, with the goal to have a flight-qualified heat source in the 2028–2030 timeframe. Such a heat source qualified to a TRL of 6 or beyond would give NASA project managers the confidence that a potential cryobot mission should be feasible in the near future. The most immediate steps recommended are to advance the concept of a CPHS analytically to verify a proof of concept, lay out a tentative development schedule to show feasibility, and use the schedule to formulate a working cost estimate. Subsequent activities would include CPHS fabrication and qualification.

Success in these activities would equip NASA and U.S. planetary scientists to lead in Ocean Worlds exploration and the hunt for life in the solar system.

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