National Aeronautics and Space Administration

# Feasibility Study of a Pulsed-Power Peristaltic Melt Probe for Highly Efficient Cryo-Ice Penetration

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## Program: FY21 R&TD Innovative Spontaneous Concepts

## Objectives

This study aimed at investigating the feasibility of a novel **"pulsed-power" cryobot** concept for penetrating the cryogenic icy crusts of ocean worlds, which may allow for a ***significantly smaller RTG*** than previous cryobot concepts (Fig. 1). Instead of descending within a steady-state "melt pore," which requires traditional melt probes to waste a significant portion of their thermal inventory preventing the side walls from refreezing, this pulsed-power concept allows the probe to freeze into the borehole but for brief periodic thermal pulses. These high-power bursts allow the probe to "flash melt" a thin annular melt film around the side walls with minimal conductive losses into the surrounding ice. The probe then "falls" into the melt pore that has grown beneath it (e.g. through a water-jetting tip) and refreezes into the borehole. This repeating cycle produces a peristaltic ("inch-worming") motion that requires a much lower average power to the side walls than it takes to maintain a steady-state melt jacket.

## Background

RTG-powered melt probes or "cryobots" have emerged as a leading mission concept for penetrating the icy crusts of Ocean Worlds to access their subsurface liquid oceans. However, due to the enhanced thermal diffusivity of ice at cryogenic temperatures, a descending cryobot within a closed liquid melt pore requires a significant amount of heat power on its side walls in order to prevent the annular melt film from refreezing and stalling the probe. In the ~100K ice near the surface of Europa, these radial conduction "losses" can amount to 80-90% of the total thermal inventory, leading to slow penetration rates and requiring a large probe and RTG. Thus, perhaps the two greatest programmatic hurdles for a future cryobot mission are (1) the sheer size and cost of a flight-like cryobot architecture (mass of 300 – 500 kg and an estimated mission cost of $3-5B as per the JPL-Next PRIME study) and (2) the significant amount of heat source plutonium oxide required for the onboard RTG—roughly 10 kWt (equivalent of 5 MMRTG's) or over 12 years of dedicated production at the DOE's current fixed-rate target of 1.5 kg/yr.

## Approach and Results

Our study consisted of three primary tasks: (1) thermal modeling of the pulsed-power operation; (2) an identification of engineering requirements, challenges, and trades to achieve the desired performance; and (3) a notional design of a pulsed-power cryobot for Europa.

In order to understand the power and energy required to "flash melt" the ice frozen to the side walls, we cast the thermal problem as a transient 1D radial conduction from r=R (probe wall) to infinity, in which the ice domain starts at ambient temperature (100K) and whose thermal properties are a nonlinear function of temperature (Fig. 2). The key result we found was that ***higher power pulses required less energy*** to raise the ice to 0C at r = R. Thus, if we can generate thermal pulses on the order of 1 MW/m2 (for 10s of milliseconds) and descend several centimeters per stroke (one pulse every ~10 minutes), only a small fraction of the RTG power is required for the side walls, reserving most of the power for forward melting.

The modelling work confirmed the feasibility of this concept and allowed us to identify six key engineering requirements to realize it (see Fig. 3): (R1) a high-power side wall thermal pulse (>1 MW/m2 for <50 ms), (R2) a means to deliver this power to the probe skin from (R3) an onboard storage system with sufficient power/energy density, (R4) a very low skin thermal mass (<200 J/m2K), (R5) a means to continuously melt ice beneath the probe while stalled, and (R6) a high flow-rate melt-water feedthrough system that allows the probe to fall at (>10 cm/s).

Based on these results, we conceived of a (low-fidelity) Europa cryobot design based on a 16-GPHS (4-kWt) RTG (Fig. 4), which is about 20cm in diameter and 3m long, with an average speed of about 7 km/year—a performance that would require a ~4x larger RTG for a traditional steady-state probe (Fig. 5). The design builds upon that of a traditional probe (and thus can operate in steady state when needed), but includes an additional thin electrically resistive skin (~30µm Inconel-718), that is rapidly heated from an onboard capacitor bank. It is also equipped with a circulating water jet in the nose for forward melting and the entire body is slightly tapered to reduce the melt film freeze rate after pulsing. Finally, the probe has an internal meltwater reservoir with a spring-loaded hydraulic piston to induce a substantial backpressure behind the probe, forcing it to fall faster.

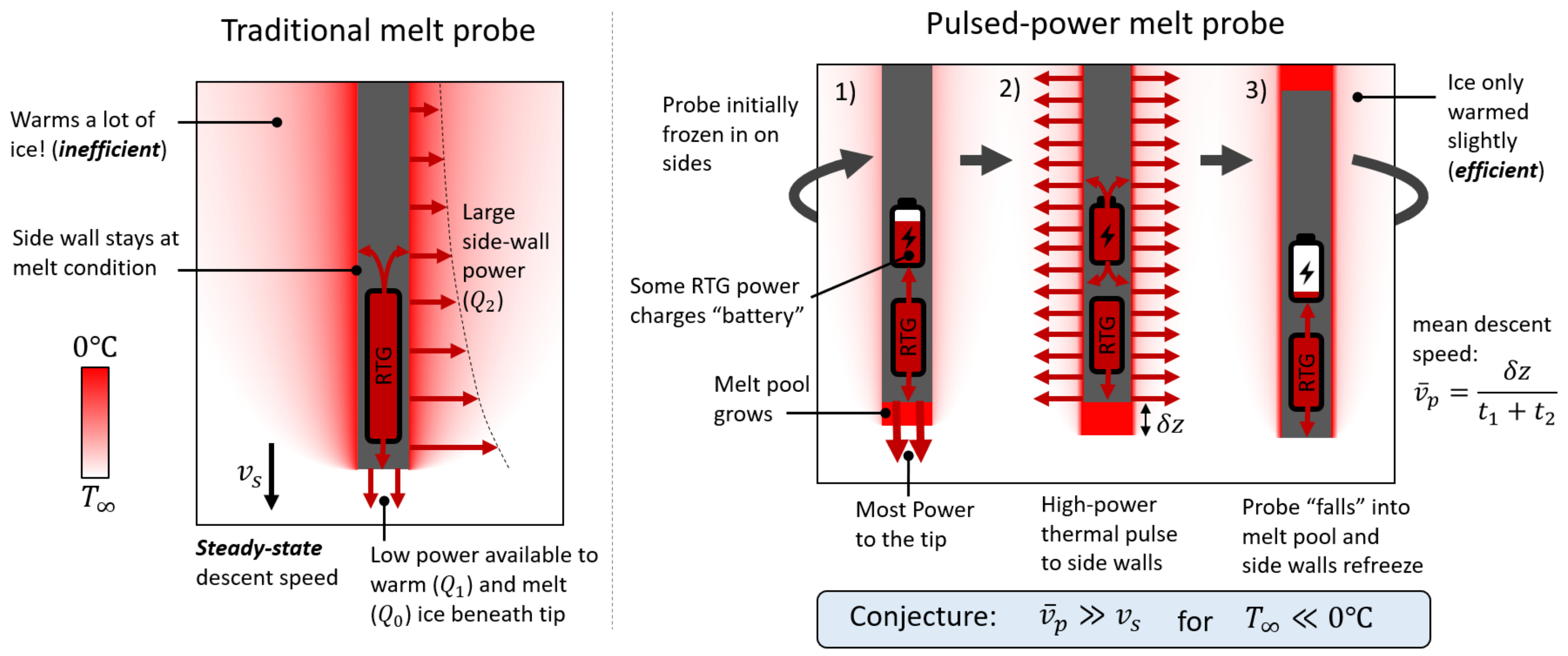


**Figure 1.** Concept sketch of pulsed-power melt probe investigated in this study compared to a traditional steady state melt probe. The steady state melt probe operates within a contiguous melt pore**,** which requires large continuous side-wall power to prevent refreezing, whereas the pulsed-power probe spends most of its time frozen within the borehole, except for brief periodic side wall thermal pulses that allow it to "fall" into the leading melt pool. The conjecture explored in this study is that this allows the pulsed probe to descent much faster than traditional melt probes.

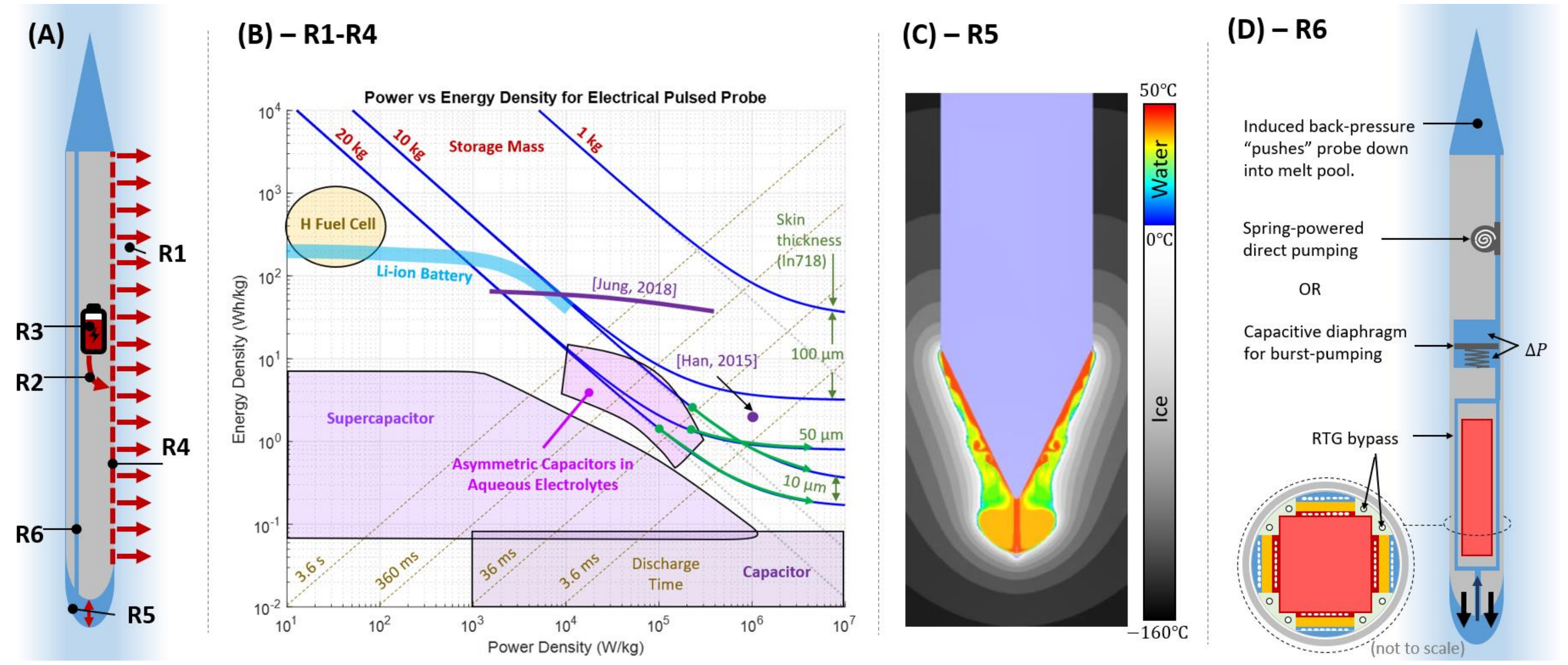


**Figure 3.** Sketch of some of the engineering feasibility analyses performed in this study. **(A)** Sketch of key engineering requirements identified for a pulsed-power probe: R1 – High power flux, R2 – High power delivery to skin, R3 – Sufficient energy/power density storage, R4 – Low skin thermal mass, R5 – Continuous forward melting, and R6 – High flow-rate meltwater feedthrough during "fall" stage. **(B)** Electrical energy/power density requirements for thermal pulses compared with available storage technologies. **(C)** two-phase CFD modelling of forward melting with a water jet. **(D)** Notional sketch of meltwater feedthrough system with burst pumping.

## Significance/Benefits to JPL and NASA

In our search for life in the solar system, a mission to the liquid water of an Ocean World seems an inevitability, and cryobots have shown the greatest promise in doing so. However, the cryogenic icy environment of Europa is challenging and all prior designs to date have called for RTGs (or reactors) with a very large thermal inventory, which poses a serious programmatic risk for sustained technology development programs (e.g. SESAME). This work attempted to take a fresh look at the ice-melting problem by rejecting the traditional notion that a cryobot must operate within a steady-state melt pore—a very inefficient mode in cryo-ice. Instead, we showed that a pulsed-power probe can avoid radial conduction losses almost entirely by remaining frozen in the borehole but for periodic thermal pulses, which dramatically improves the descent rate. Engineering challenges notwithstanding, this effort has opened a door to a potential class of smaller, lower-cost thermal probes for Europa that can be fueled with a modest 16-GPHS RTG (or smaller with some performance compromise), and has positioned JPL to be a key player in ongoing and future efforts in Cryobot technology development.

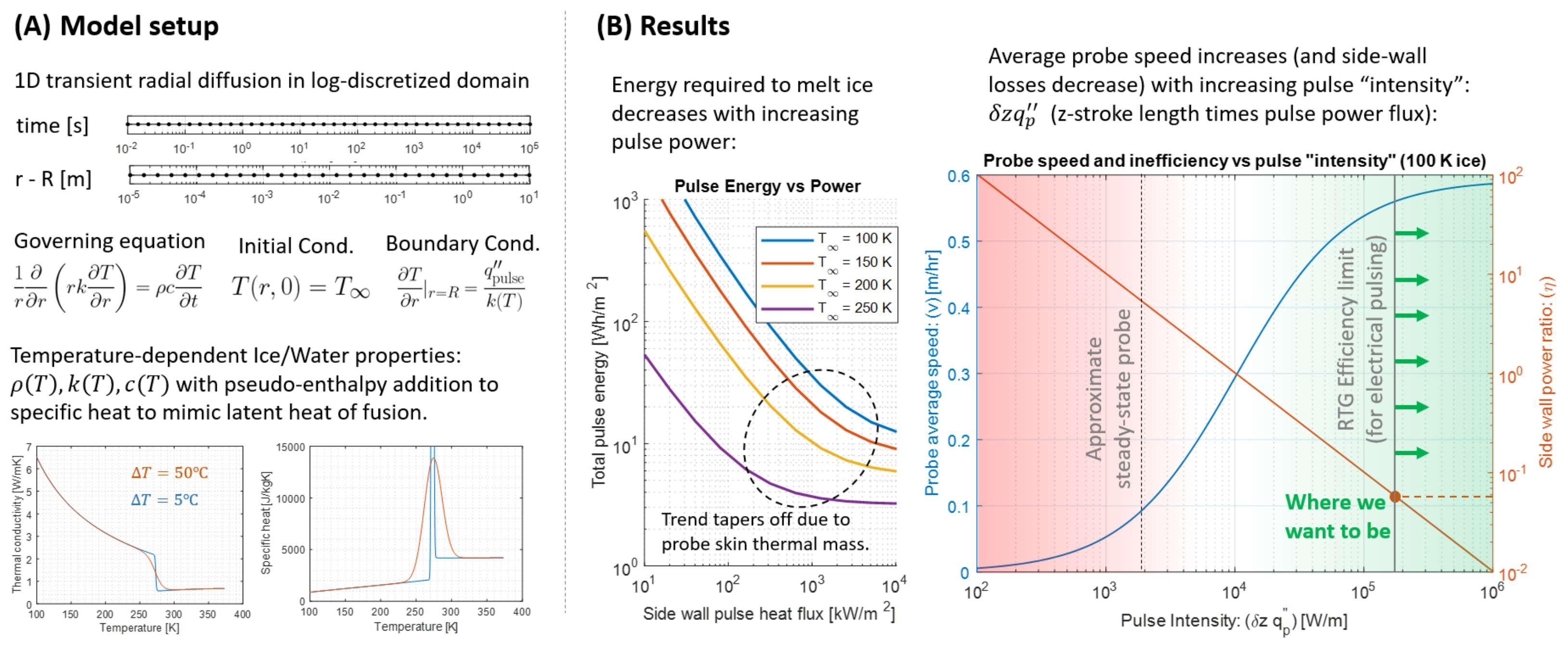
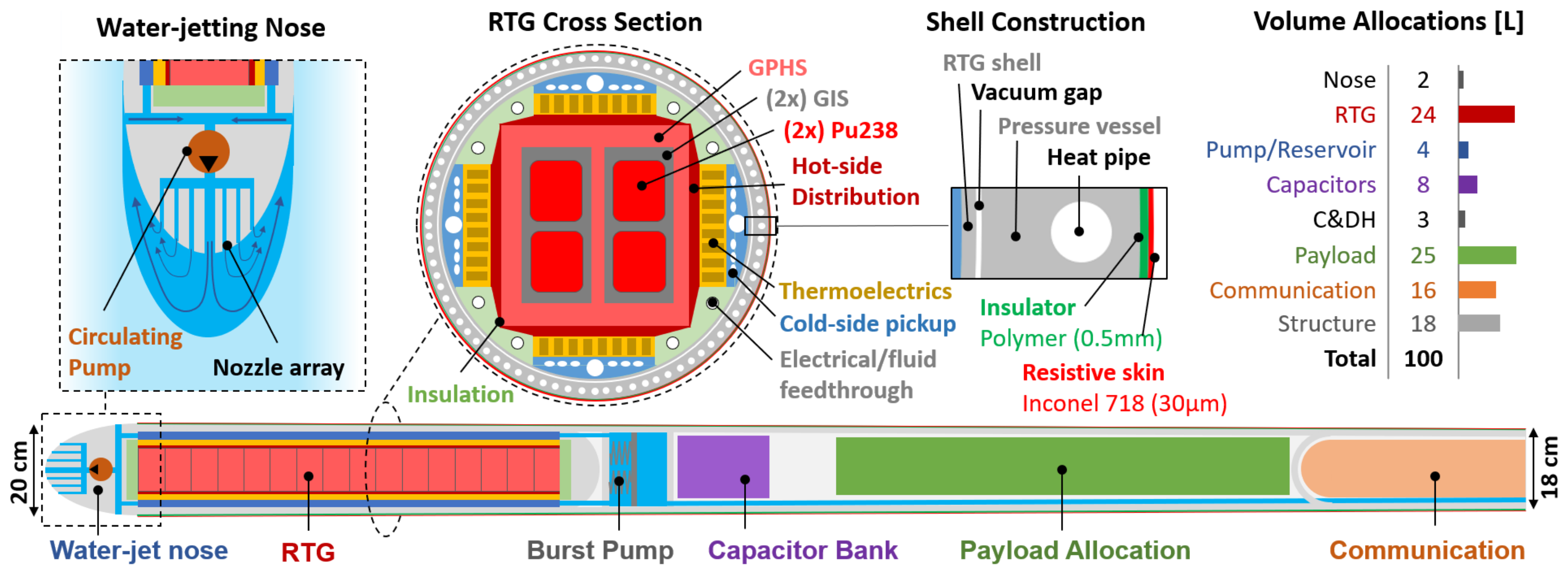


**Figure 2.** Thermal modelling summary. **Left**: Side-wall thermal pulses are modeled as transient 1-dimensional diffusion, since probe is axisymmetric and z-diffusion is minimal. **Right**: Illustration of **key result**: side-wall *pulse energy decreases* and average probe *speed increases* with increasing pulse power**.** Thus, our design target is a stroke length ($\delta z$) of ~10cm and a pulse power flux >2 MW/m$^2$, corresponding to a pulse duration of only 10s of milliseconds.



| Volume Allocations [L] | |
|---|---|
| Nose | 2 |
| RTG | 24 |
| Pump/Reservoir | 4 |
| Capacitors | 8 |
| C&DH | 3 |
| Payload | 25 |
| Communication | 16 |
| Structure | 18 |
| **Total** | **100** |

**Figure 4.** Design sketch of a notional pulsed-power cryobot architecture. Bottom profile illustrates internal subsystem layout (not quite to scale), including, from tip to tail, the nose water jet, RTG, Pump/Reservoir, Capacitor bank, C&DH, Payload, and Communication. Additional detail on the nose water jet system, RTG cross section, shell construction are shown above, as well as a volume allocation summary table.

| | | | | | | This work | |
|---|---|---|---|---|---|---|---|
| | | **A** | **B** | **C** | **PR*** | **D** | **E** |
| | Probe type | Steady state | | | | Pulsed | |
| RTG | RTG Power [kWt] (BOL) | 4 | 8 | 12 | 10.5 | 2 | 4 |
| | **# GPHS bricks** | **16** | **32** | **48** | **---** | **8** | **16** |
| Size | Probe Diameter [cm] | 20 | 20 | 20 | 23 | 20 | 20 |
| | Probe Length [m] | 3.2 | 4.1 | 5.1 | 4 | 3.1 | 3.6 |
| | Probe Mass Est. [kg] | 210 | 270 | 336 | 350 | 204 | 238 |
| Performance | Speed (100 K) [m/hr] | .003 | .057 | .15 | .21 | .25 | .49 |
| | Speed (250 K) [m/hr] | .73 | 1.6 | 2.6 | 1.7 | .52 | 1.0 |
| | **T2O (15 km) [yrs]** | **63** | **6.6** | **3.0** | **2.8** | **4.6** | **2.3** |
| | T2O (30 km) [yrs] | 120 | 13 | 6.0 | 5.6 | 9.2 | 4.6 |

*PRIME cryobot design using CPHS heat source and 23 cm diameter

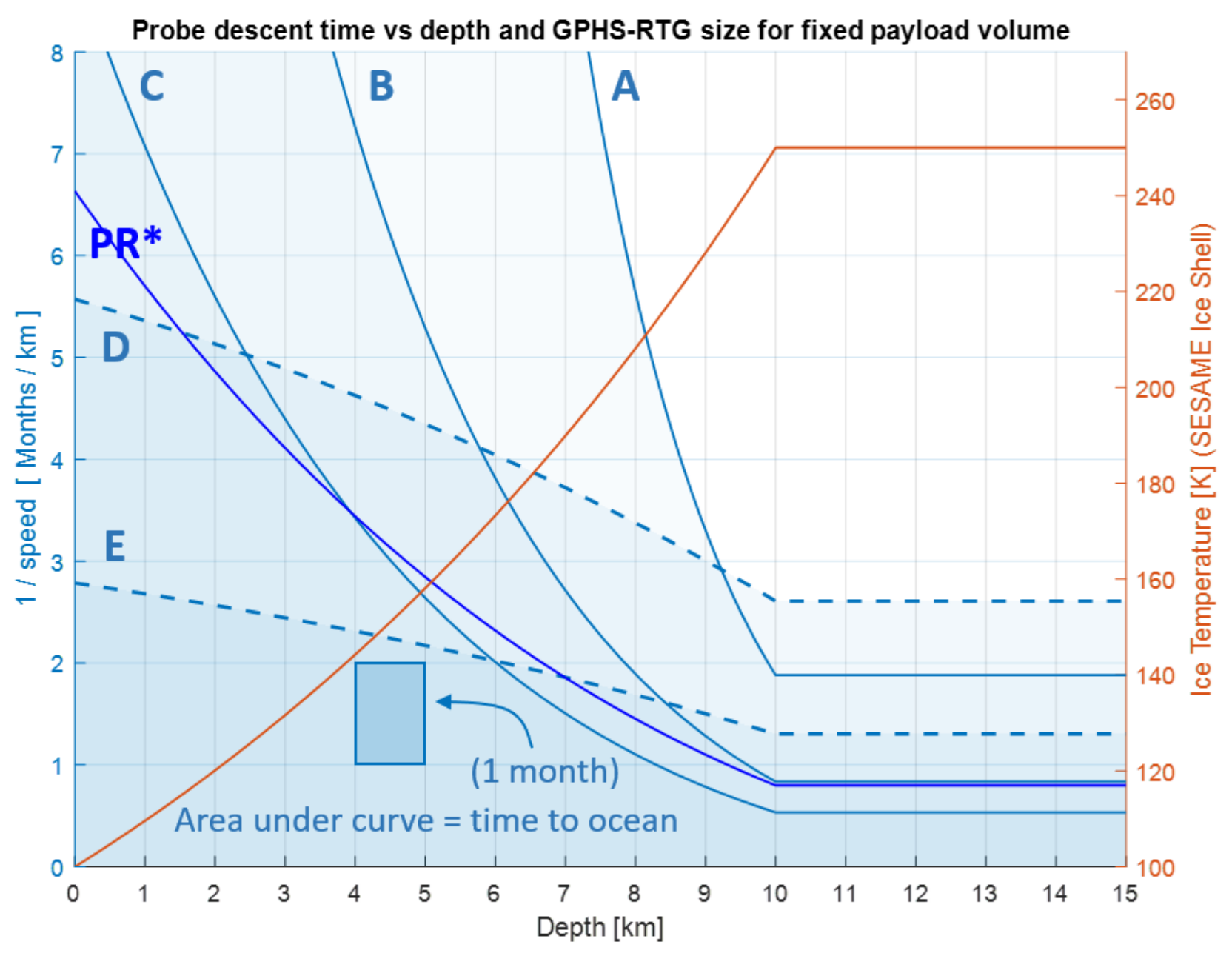


**Figure 5.** A performance comparison of steady state cryobots and the pulse-power cryobot concept investigated in this study. **Right**: Descent time (1/speed) vs depth in Europa's ice shell for different cryobot designs, which corresponds to the baseline ice shell temperature profile proposed by the SESAME program shown on the right axis. Areas under the blue curves correspond to the descent time. Probe designs A-E are summarized in the table on the left. This analysis assumes a 20 cm diameter probe with a fixed 65 L "carrying capacity" (Probe minus RTG = 2.1 m length). Steady state curves reflect "Aamot++" model and Pulsed probe curves reflect estimates from this study. RTG power assumes 10-year degradation.

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## Acknowledgements

We would like to thank Mike Durka (3464) for his help in applying his two-phase CFD code for modelling the water-jet-induced growth of the forward melt pool, as well as Miles Smith (394D), Bailey Cassler (353K), and Ben Furst (353K) for their periodic feedback and guidance throughout the project.

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**Clearance Number: URS303672**
**RPC/JPL Task Number: R21261**