Milli-watt Radioisotope Power to Enable Small, Long-Term Robotic "Probe" Space Exploration

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Abstract—**Milli-watt Radioisotope Power Systems (RPS) based on Radioisotope Heater Units (RHUs) could be an ideal power source for certain spacecraft that cannot use solar power due to large distances from the sun, or other environmental constraints, and where they enable or significantly enhance the ability of a mission to meet its scientific or operational goals. Various modular, compact RHU-based thermoelectric (TE) generator concepts developed or derived from current NASA Small Business Innovation Research (SBIR) projects satisfying this need have been investigated. These modular, compact and low mass power systems could support small, highly-mobile robotic exploration packages, and could be incorporated into different robotic package concepts, spacecraft or satellites. Current modular RPS design concepts with 40mW, 80mW and 120mW power levels use RHUs and Bi_2Te_3 TE converters. Skutterudites materials could be used in the future if new higher thermal energy output and higher temperature miniature heat sources were developed, for example, using technologies currently in the General Purpose Heat Source (GPHS) used in higher electric power output RTGs. Small (a.k.a., "mice-like") robotic packages could effectively utilize these RHU-driven power levels to accommodate crawling, climbing, monitoring, taking measurements, and communicating during long-term planetary missions aimed at gathering environmental and geologic data (i.e., over multiple decades). Waste heat from the cold side of the TE converter could also be directed toward the electronics and / or energy storage (e.g. batteries) to keep them within design temperature ranges. In addition to power generation and electronics / battery heating, the RHU / TE configuration could be designed to survive an external 500°C bake out procedure for critical spacecraft sterilization, environmental certification and planetary protection. Analytical studies have been performed to optimize various design configurations for power, mass, volume and robotic mobility. Specific power (mW/kg) and volumetric specific power (mW/cm^3) characteristics of various design configurations will be presented and key conceptual design tradeoffs will be discussed. Hot- and cold-side thermal interfaces required to meet power and mass goals and associated design sensitivities will also be discussed. RHU / TE systems must overcome critical design challenges to survive high-g loadings in some robotic applications and we will examine the mass impacts required to satisfy various dynamic loading environments up to 10,000 g's. Power can be generated for a minimum of 30 years or more using plutonium-238 dioxide heat sources (given that Pu-238 has an 87.7 year half-life) with some reduction in power as the heat source naturally degrades.**

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1. INTRODUCTION

Radioisotope Power Systems (RPSs) using Radioisotope Heater Units (RHUs) are possible power sources for small spacecraft that are unable to use solar power due to large spacecraft-to-sun ranges, environmental constraints, or where they enable or significantly enhance the ability of a mission to meet its scientific or operational goals. RPSs using RHUs could have various modular, compact integrated RHU / thermoelectric (TE) design configurations developed or derived from current NASA SBIR projects that could satisfy this need. These modular, compact and low mass power sources are ideal for small spacecraft, robots, CubeSats and could be incorporated in a large number of small spacecraft and/or landed robotic packages (impactors), micro landers, rovers and satellites enabling further space exploration and science return [1]. These power sources would enable modular RPS designs providing 40, 80 or 120mW power levels by combining RHUs with Bi_2Te_3 TE converters in various combinations. The waste heat from the cold side or outboard end of the TE converter can also be directed toward the electronics and/or batteries to keep them within a suitable temperature range. Power can be generated for more than 30 years using the baseline Pu-238 (87.7 year half-life) isotope. RPSs using RHUs can satisfy spacecraft electrical and thermal requirements for missions with a low power demand, limited need for Pu-238 and a limited stowage volume.

Compact, lightweight RHU / TE systems have a rich history of development addressing key design challenges to demonstrate their capabilities and performance. The Jet Propulsion Laboratory (JPL) and Hi-Z Technology Inc.'s predecessor, General Atomics, have been developing and testing 75mWe class radioisotope thermoelectric generators since the 1960's. JPL developed thermal / electrical computer models to analyze the performance of some of the earliest milli-watt power systems using the ~1.1 W_{th} space

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qualified Light Weight Radioisotope Heater Unit (LWRHU) (in early 1990s) and a BiTe TE converter. This conceptual design had a projected performance of ~25 mW using Min-K insulation and a projected performance of ~40 mW when operated in space vacuum with multi-foil or multi-layer insulation. JPL purchased and tested converters provided by a supplier in the Ukraine and from Hi-Z Technology, Inc. in San Diego, California. The four Ukrainian couples were very inexpensive, but did not have the lifetime, reliability and performance that were demonstrated by the single Hi-Z Technology couple.

Swales Aerospace under contract to JPL in about 1997 developed the first prototype design of a milli-watt power system using an electric resistance heater in the volume where the LWRHU would have occupied, and a single piece of BiTe material to simulate the thermal characteristics of where the TE converter would be located. The unit was tested as a complete thermal system and the concept seemed to be practical. [2]

NASA Ames Research Center (ARC), JPL, Hi-Z Technology, and DOE teamed and submitted a NASA Discovery Mission proposal (Pascal) using these types of power systems in a 10-Mars-years weather climate network distributed over multiple locations. Ames Research Center (ARC) conducted impact tests on the Hi-Z prototype. The temperature range in the RHU system were from Thot = 250°C to Tcold = 25°C, the power expected to be generated was around 40mW. That system survived multiple ever-increasing impacts until failure eventually occurred in the 500g's range [3]. This Discovery Mission proposal was not selected primarily due to the perceived technical risk of launching a new RHU / TE design that had never flown in space.

In the early 2000s, the Department of Energy (DOE) supported work at the Oak Ridge National Laboratory (ORNL), Mound, ARC, JPL and Hi-Z Technology to support a 120mW Cryo-Hydro Integrated Robotic Penetrator System (CHIRPS) concept that evaluated using either three 1.1 W_{th} RHUs or one 3 W_{th} RHU [4]. Other issues addressed included insulation outgassing and thermoelectric material sublimation. These problems and minimizing heat transfer loses were essentially accommodated using a xenon cover gas.

In 2005, DOE released a Financial Assistance Application requesting design concepts for both milli-watt and multi-watt power systems. Two teams were selected for each power range and inputs were provided until 2007 when the project was terminated due to lack of funding.

An SBIR requesting the design and development of a baseline 40mW power system capable of surviving 10,000 g's impact was released and the Hi-Z Technology team was awarded Phase 1 in 2014. This team was subsequently selected for Phase 2 in 2015 after completing a design trade study and down selecting to one or two designs (10,000g's) with improved shock resistance and power output. The Phase 2 effort is ongoing, and should result in a down select to a single design fabricated for environmental testing. Following discussions with future potential mission users, a separate internally-funded Internal Research and Development (IR & D) activity at Hi-Z Technology resulted in a design matrix consisting of both <1,000 g's and ~10,000 g's impact resistant designs for 40, 80 and 120mW power outputs. The results of this work are shown in Tables 1 and 2.

2. System Description

Various low-g (<1000 g's) and high-g (~10,000 g's) RHU / TE system concept designs have been investigated at JPL and Hi-Z Technology. Figure 1 through 3 show different low-g, cylindrical, modular RPS designs generating 40, 80 or 120mW power levels, respectively. Detailed thermal, thermoelectric, structural and performance analyses have been performed to establish potential system mass and power levels. The design and development should continue, and as the design matures toward flight qualification it should ultimately be under a Department of Energy (DOE) funded subcontract. In Figure 1 through 3 heat flows through the thermoelectric couples from the hot side to the cold side. The estimates for the total masses for the 3 configurations are shown in Table 1 and range from about 800g to 1.4 kg for the 40mW to the 120mW systems. The system concept in Figure 4 is probably best suited for impactors or penetrators on various planetary bodies. This high (~10,000 g's) impact resistant design will require the longest lead time to develop than all the other (<1000 g's) designs presented in this paper that can easily handle almost all other spacecraft impact or vibration loads.

Table 1. Latest Estimate System Power & Mass Budgets for Envisioned RHU / TE System Design Configurations (<1,000 g's)

	Component Mass (grams)		
Component Name	40 mW	80 mW	120 mW
Module Compression Assembly	15	30	45
RHU	40	80	120
Fuel Capsule Holder	28	45	77
Rigid Frame	0	0	0
Base Top	189	189	230
Base Bottom	189	189	230
Cylinder Wall	121	150	300
Aerogel, Polyimide	178	240	350
Total mass (grams)	760	923	1352
Height (cm)	13	16	12
Diameter (cm)	12	12	13

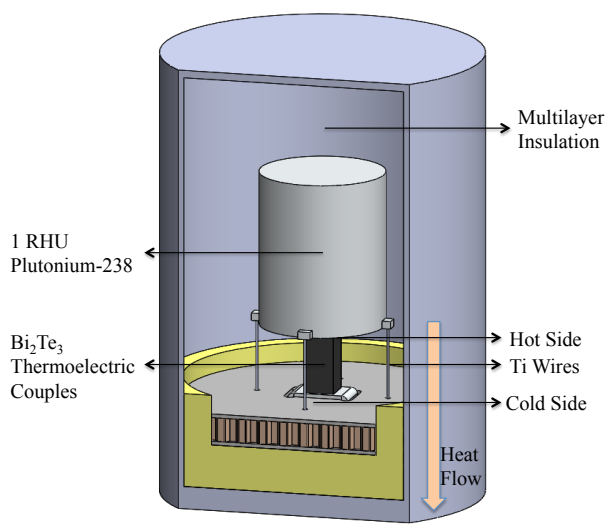

Figure 1. RHU / TE Concept Latest Design (<1,000 g's) Configurations for Small Robotics and CubeSats (40 mW)

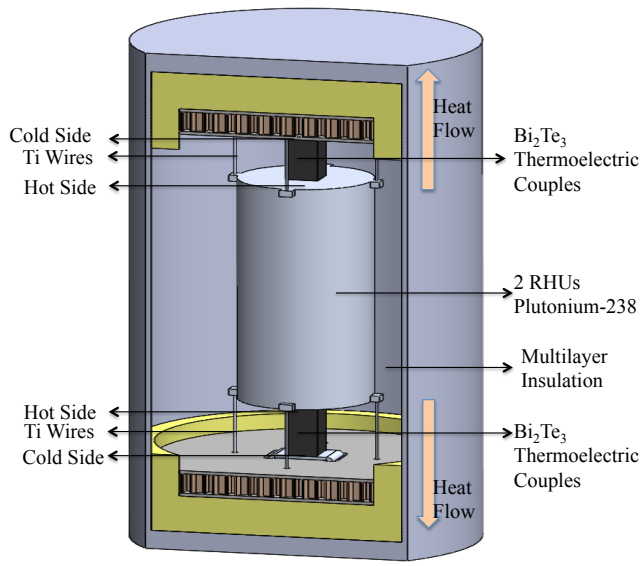

Figure 2. RHU / TE Concept Latest Design (<1,000 g's) Configurations for Small Robotics and CubeSats (80 mW)

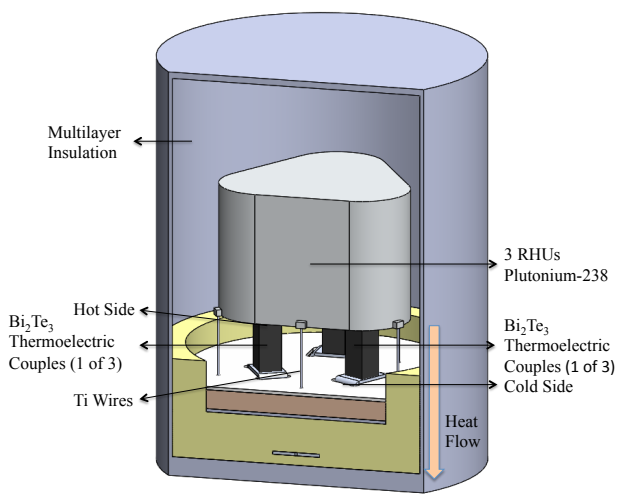

Figure 3. RHU / TE Concept Latest Design (<1,000 g's) Configurations for Small Robotics and CubeSats (120 mW)

For the low-g's impact designs, multilayer insulation thermally isolates the Fuel Capsule Holder (FCH) but isn't shown in Figures 1, 2 & 3 while titanium wires provide structural support. Both the p- and n-leg thermoelectric materials are fabricated from Bi_2Te_3. The LWRHU is contained within the FCH. The FCH and the thermoelectrics are directly connected, but in the high-g RPS they are connected via thermally and electrically conducting compliant graphite straps shown in Figure 4 to the cold and hot side of the thermoelectric couples. The hot and cold side temperatures are at approximately 200 and 0°C, respectively.

Table 2. Latest Estimate System Power & Mass Budgets for Envisioned RHU / TE System Concept Design Configurations (~10,000 g's)

	Component Mass (grams)		
Component Name	40 mW	80 mW	120 mW
Module Compression Assembly	15	30	45
RHU	40	80	120
Fuel Capsule Holder	35	52	87
Rigid Frame	120	240	350
Base Top	189	189	230
Base Bottom	189	189	230
Cylinder Wall	121	150	300
Aerogel, Polyimide	178	240	350
Total mass (grams)	887	1170	1712
Height (cm)	17	17	17
Diameter (cm)	12	15	17

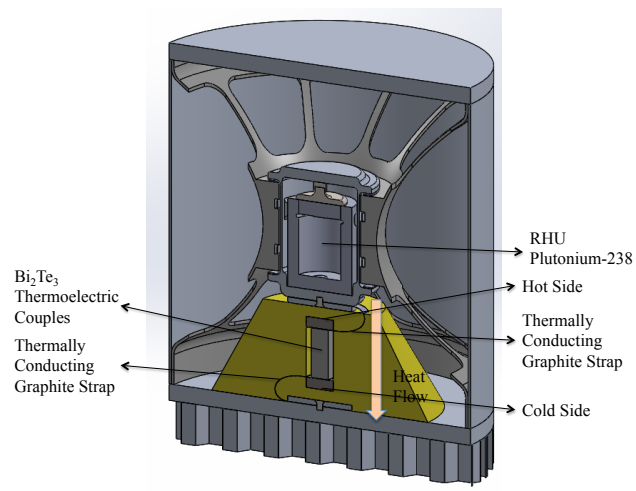

Figure 4. Baseline SBIR Concept Latest Design for ~10,000 g's

The mass for the 40mW to 120mW high-g RHU / TE system is shown in Table 2 and will be approximately 900g to 1.7kg. Power levels from the previous Mars weather station concept designs seem achievable with a single RHU, while the transceivers for the Europa cryobot concept would require power levels closer to 120 mW, which would be more suitable for the 3 RHU configuration.

RHUs generate heat from the natural radioactive decay of a small pellet of plutonium dioxide (mostly plutonium-238). This heat transports to the TE device which converts a fraction of the heat to power and leaving a significant waste thermal energy dissipated on the system cold side This waste thermal energy can be transferred to the spacecraft structures, systems, and instruments directly without moving parts or intervening electronic components. Heat and electricity flow through the graphite straps on both the hot and cold sides of the thermoelectric couples. RHUs are very compact, 3.3 centimeters (1.3 inches) long and 2.6 centimeters (1 inch) in diameter. The fuel pellet is about the size and shape of a pencil eraser weighing approximately 2.8 grams (0.1 ounces). All together each RHU weighs about 40 grams (1.4 ounces). Bi_2Te_3 TE materials are commercially available and used extensively for heating and cooling of automobile passenger seats and automobile portable coolers to replace ice chests. The material used by Hi-Z

Technology is more efficient than most other BiTe suppliers because they have a fine grain material that improves the system efficiency. The combination of existing hardware, components and previous system successes with similar designs including high impact loading make this a low risk technology development.

3. System Tradeoffs

System tradeoffs are very mission specific, but can be addressed using a typical spacecraft systems engineering approach where we maximize the flexibility of the design from the beginning. There is a tradeoff for the modular system concept between the electrical power outputs, the mass and the dimensions of the different configurations and the impact g' levels. Table 3 and Figure 5 are summaries of Table 1, which represents Figures 1, 2 and 3. Table 4 and Figure 6 represent the high g' system in Figure 4 and the data summarized from Table 2. Both tables are the latest power-mass ratio and power-volume ratio estimates for high g' and low g' RPS concepts.

Table 3. Latest Estimate Power-Mass, Power-Volume Impact Level System Tradeoffs for Low g's RHU RPS System concepts

	40 mW	80 mW	120 mW
Power/kg [mW/kg]	52.6247	86.6551	88.7377
Power/Volume [mW/cm^3]	0.0272	0.0442	0.0753

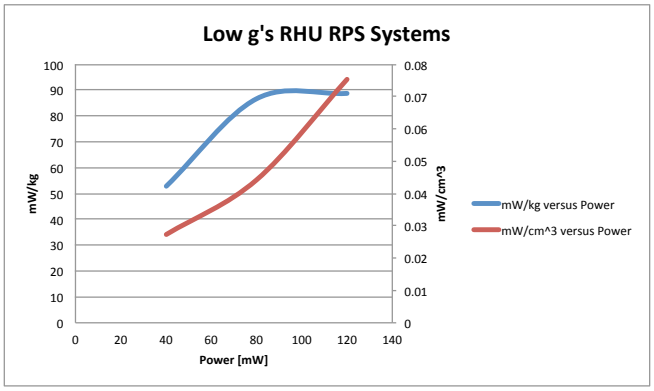

Figure 5. Latest Estimate Power-Mass, Power-Volume Impact Level System Tradeoffs for Low g's RHU RPS System concepts

Table 4. Latest Estimate Power-Mass, Power-Volume Impact Level System Tradeoffs for High g's RHU RPS System concepts

	40 mW	80 mW	120 mW
Power/kg [mW/kg]	45.0958	68.3761	70.0935
Power/Volume [mW/cm^3]	0.0208	0.0266	0.0311

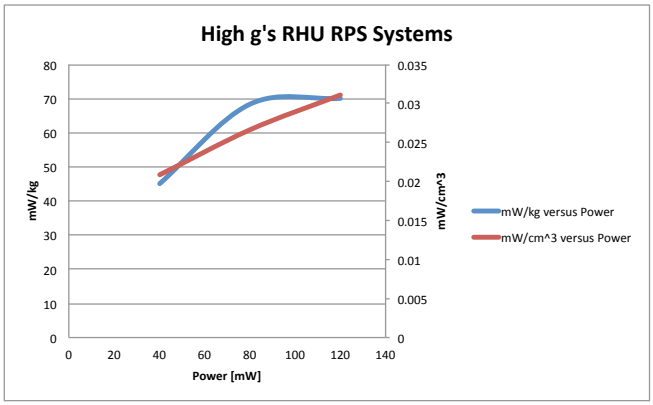

Figure 6. Latest Estimate Power-Mass, Power-Volume Impact Level System Tradeoffs for High g's RHU RPS System concepts

The masses of both the low-g and high-g designs increase by several hundred grams as the electrical power output increases. Concerning Table 1 the mass increase between the 40mW system and the 80mW system is in the range of 160gr and about 430gr from 80mW to 120mW. In Table 2 from 40mW to 80mW and 80mW to 120mW the mass increase is about 280gr to 540gr, respectively. The volume also increases as the electrical power increases. It's interesting to note that the specific power (mW/kg) for both designs (1000g's and 10,000g's) seem to reach asymptotes of 90 and 70 mW/kg, respectively, which is approximately the power density of the 2 RHUs design with a power of approximately 80mW. If the mission is volume or mass constrained one might select the 120mW design in both cases. If the mission is concerned about lifetime, redundancy and reliability, the use of three 80mW units instead of two 120mW units to achieve a 240mW power system to minimize system power loss in the case of a failure of a single unit, is another alternative. The RHU / TE concept can be configured with batteries and/or supercapacitors to meet peak power demands like telecommunications between a surface package and an orbiter.

For the low g' impact design, either polyimide aerogel or Min-K could be used for the insulation and structural support. For the high g' design, polyimide aerogel may be used for the insulation but a design addition for the structural support is required. For the structural support, a fiberglass holder and aluminum honeycomb structure are under consideration. In that particular case, the thermal design characteristic would be to minimize the heat lost from the holder and structural support of the radioisotope heater unit casing. The honeycomb structure addition would add a fairly small amount of extra weight compared to its directional structural benefits.

The high g' concept at 40, 80 and 120mW would have a slightly heavier Fuel Capsule Holder on the order of 10gr when compared

to the low g' Mini-RPS concept at 40, 80 and 120mW. Another addition for the structural integrity of the high g' design is the rigid frame, which adds 120, 240 and 350grams, respectively, as the power increases from 40, 80 and 120mW.

4. POTENTIAL APPLICATIONS

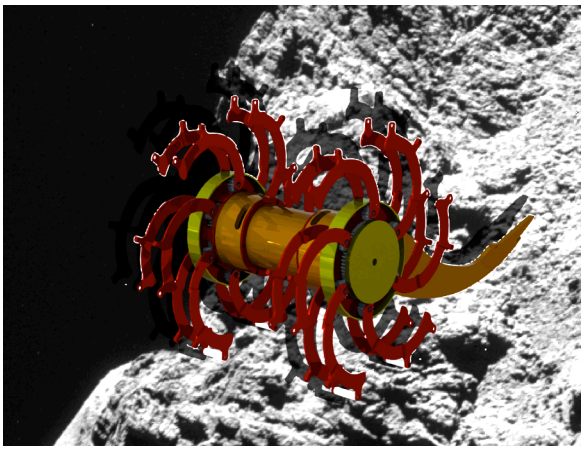

Figure 5. Artist's concept of a two wheeled design with variable radius wheels

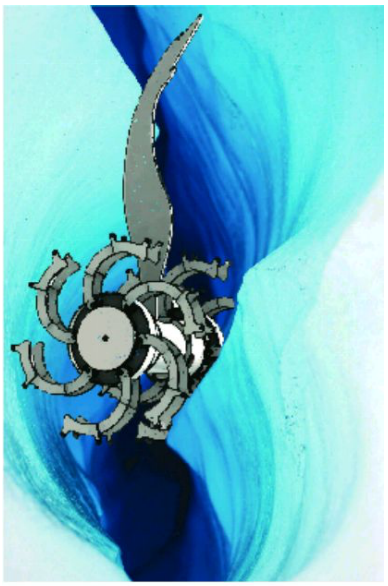

Figure 6. Artist's concept of a two wheeled design with variable radius wheels

By incorporating RPS into small deployable rovers, long duration missions beyond the usable range of solar power, subterranean locations and cryo-world explorations would become possible. Decadal 2013-2022 survey [5] had shown interest in Titan and Europa, and some of the herein incorporated RPS design concepts might be suitable for those types of environments. A simple two-wheeled design with variable radius wheels (See Figure 5 and 6), which stow in a compact volume or can be actuated into a variety of configurations to overcome mobility challenges, would be well suited to incorporate an RHU/TE RPS. The RPS could be mounted in the middle of the body with the electronics and motors mounted inside the insulation. The incorporation of radioisotope power systems using radioisotope heater units would create a robust architecture that keeps key components such as batteries, motors and electronics at operating temperature using the waste heat from the heat source. The batteries or supercapacitors, mounted inside the insulation, would slowly charge allowing for approximately four hours of operation or data transmission each day. These would potentially enable the exploration of asteroids, the mapping of lava tubes, the traversing down chasms or vents and the scouting of cryo-worlds.

Alternate configurations are being explored which use a flywheel induced tumbling architecture. These would use the RPS to slowly spin up the flywheels storing power as kinetic energy, which could be harvested for electrical or kinetic power for mobility.

Several recent small robotic missions concepts expressed interest in the mW power technology for Mars, Europa and other small bodies [1]. Such mission's concepts include among others a Europa Impactor Micro-lander needing an electrical power level of 10mW to approximately 100mW and an RTG configuration of 1 to 4 RHUs. These spacecraft would be experiencing g-loads of less than 5000g's [1].

Another mission concept would be a Titan Micro-Rover needing an electrical power level of 10mW to approximately 100mW and an RTG configuration of 1 to 4 RHUs [1]. The spacecraft would experience g-loads from 40 to 600g's [1]. Other such mission concepts would be a Lunar Micro-Rover, a Mars Micro-Rover and a Pascal Micro-lander for a Mars mission. The electrical power level required, the RTG configuration and the spacecraft g-load experienced would be similar to the previous mission stated [1].

Other missions would be a Mars Deployable Micro-Payload Concept requiring 1 to 2 RHUs configurations for an electrical power of 27 to 40mW for a spacecraft g-load of less than 40g's [1].

Another type of possible mission concepts of interest include The Mars Deployable Micro-Seismic Station and the Mars Science Micro-Instrument [1]. The electrical power respectively are 10 to approximately 100mW and 5 to 50mW; 1 to 4 RHUs for the first mission and 1 to 2 for the second [1]. The specific g load for both missions would be less than 40g's [1].

The Europa Impactor Micro-Lander, the Mars Science Micro-instrument and the Mars Deployable Micro-Payload concepts discussed previously would all be mission piggybacks [1] onboard other missions which would make them more economically feasible. An RHU / TE system discussed herein would enable long duration small robots to explore solar and wind power denied environments.

One of the most recent near term RHU / TE systems with one of the lowest risk design is the baseline 10,000 g's system discussed herein; currently on schedule and on budget with no major technical issues or concerns as of today. In general, it is extremely important to demonstrate the RPS long before a mission needs it because Mission Project Managers are extremely risk averse to unproven technologies that are mission critical like the power system. This technology has experienced this once in a sense that it was not selected for a proposed Discovery Mission it was supposed to fly on primarily due to the lack of a demonstrated small RPS design. This paper therefore recommends planning and executing a funded demonstration project on the small RHU / TE system

designs discussed herein to bring them to an acceptable TRL for the potential missions highlighted above.

5. CONCLUSION

The milli-watt RPS could enable a number of low power demand small missions in the future not the least of which could be providing a possible communication link from the surface of Europa to notional cryobots and hydrobots searching for extraterrestrial life within our solar system. This type of power system would need to be funded to assure the success of these extremely challenging potential future missions. The current baseline funding should provide a high impact system for future penetrators; however, the SBIR phase 2X proposed activities would be much closer to what would be required for many other missions with lower impact load requirements. As miniaturization technologies and robots continue to evolve these small power systems linked with small CubeSat technologies could represent the real future of deep space exploration.

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BIOGRAPHY

Poyan Bahrami *is a Mechanical Engineer in the Thermal Energy Conversion Applications and Systems Group at JPL. He has been working at JPL since 2008 as a student and as an employee. His work focuses mostly on the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) and as a system engineer on the enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG).*

Bill Nesmith *is a Power System Engineer in the Jet Propulsion Laboratory's (JPL's) Thermal Energy Conversion Applications and Systems Group and has 37 years of experience developing nuclear (radioisotopes and reactors), solar (concentrating and non-concentrating) space and terrestrial power system technologies using various types of static and dynamic energy conversion. His work experience outside JPL includes DOE's Los Alamos National Laboratory, DOE's Energy Technology Engineering Center, JPL's Parabolic Dish Test Site at Edwards AFB, NASA-HQ and DOE HQ in Germantown, MD.*

Kalind Carpenter *is a Robotics Engineer in the Robotic Vehicles and Manipulators Group (347B). The lab he works in focuses on rapid technology development and end effectors specifically tailored to gripping and rough surface mobility. He completed his thesis work on rotary microspine rough surface mobility at JPL while earning his master's degree from California State University Los Angeles. His current work includes coinvestigator on the pop-up flat folding explorer robots (PUFFER), designing the mobility system and thermal testing the motors for Mars. On PUFFER he is the Principal Manager of the snow mobility sub task. For the Ocean Worlds Mobility Study he is lead engineer on the ice gripper, designed to react sampling loads, he is also aiding in the design and fabrication of a small scale gossamer rover for long range ocean world surface mobility. Kalind is supporting the micro ground vehicles task designing platforms and gripping prototypes for the wall climbing robots that utilize microspines, electrostatic and dry adhesives (Gecko adhesive) to climb vertical surfaces.*