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THE DEVELOPMENT, PROTOTYPING AND TESTING OF A SHOCK TOLERANT MILLI-WATT RADIOISOTOPE POWER SYSTEM

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Hi-Z Technology, Inc. has recently built, developed and tested a new milliwatt radioisotope power system (mW-RPS) after more than a decade of dormancy. Using a single 1.1W$_t$ radioisotope heater unit (RHU), it will provide steady electric power of about 35 mW at 5 volts while also providing heat to the surrounding system components. Recent work has improved and validated the impact tolerance of the device. Development continues toward flight readiness.

I. INTRODUCTION\BACKGROUND

As outlined in a previous NETS conference submission[1], the device described here traces its lineage to a RPS designed and built by General Atomics for the Atomic Energy Commission in the 1970's. Some units were monitored for ten years and exhibited a power decay rate no greater than that accounted for by the ^{238}Pu they contained. The original design concept, which still applies, is to surround the heat source with high-efficiency multilayer insulation (MLI) in vacuum and allow only one-dimensional escape of heat through a bismuth telluride thermoelectric (TE) module.

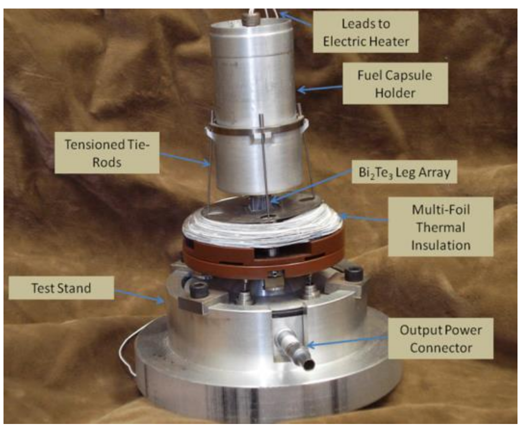


Fig. 1. "Y2K" RPS prototype without insulation and housing.

Fig. 1 shows a prototype RPS built around the year 2000 ("Y2K") that represents the system design before its development went into hiatus. In this design, the fuel capsule holder (FCH), which contains the RHU, is held in compression against one end of the thermoelectric (TE) module by four tensioned titanium rods. The remaining mechanical support for the FCH comes from the TE module itself, which is held in compression between the FCH and a base structure, facilitating heat transfer. This arrangement leaves the relatively brittle module to support the full inertia of the FCH and RHU during a shock event, limiting the system to a < 2,000G on-axis impact.

In 2014 and 2015 Hi-Z won a Phase I & II NASA SBIR to develop a shock-tolerant variant of the milliwatt-RPS. Several new design concepts were considered, all of which mechanically separated the module from the FCH using flexible thermal straps. The design evolved during development and prototyping which resulted in the system described in this paper.

II. CURRENT RPS DESIGN

The most recent configuration of the RPS is illustrated in Fig. 2. The diagram shows a cross-section of the RPS with MLI removed for clarity. It should be understood that the FCH as well as the TE module are surrounded by MLI in all directions except for cutouts that accommodate the thermal strap.

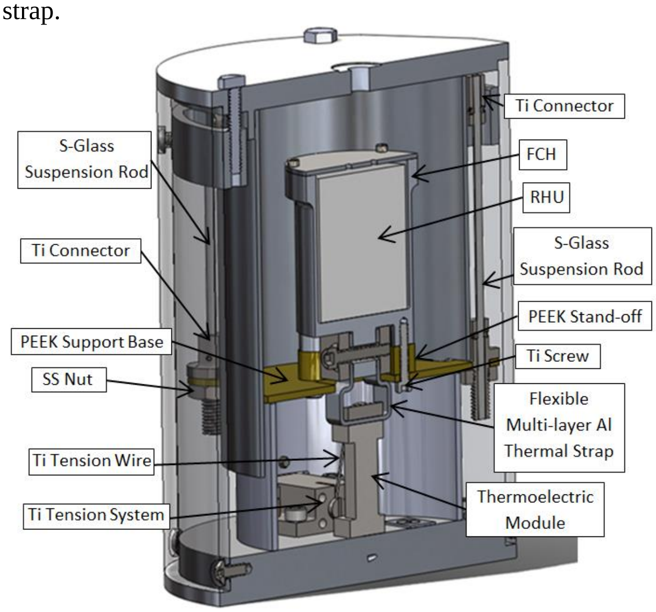


Fig. 2. Model of Current RPS shown without MLI package for clarity.

The FCH is mounted to a PEEK support base which is suspended in the center of the RPS by S-glass composite rods. The S-glass rods have threaded titanium mounts which are secured to the PEEK support base with stainless steel nuts. The other ends of the s-glass rods terminate in titanium T's, which fit into a slot cut into the top Support Ring. All materials were selected to minimize the ratio of thermal conductivity to strength.

The TE module is independently fastened to the base of the RPS with a titanium wire and a special tensioning system designed to minimize heat loss, survive impact loads, and to maintain constant pressure including compensation for creep and thermal expansion.

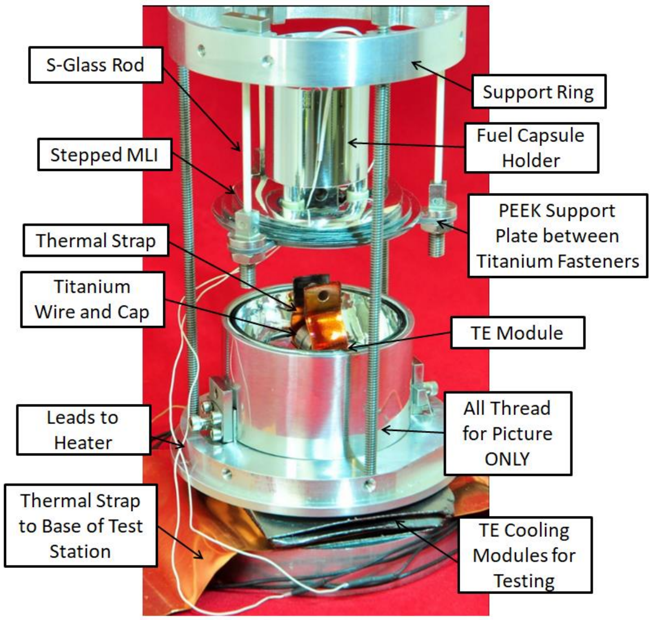


Fig. 3. Current RPS without insulation and housing recently built and tested.

The TE module and FCH are connected by a thermal strap which allows the module to remain mechanically isolated while maintaining the desired heat flow. This vastly improves the system's shock tolerance over the previous version RPS. Fig. 3 shows the FCH suspension system, elevated for staging the photograph by all-thread rods, hovering over the base of the RPS. The two parts are joined by a multi-layer aluminum thermal strap, which provides better flexibility and near equivalent thermal performance as the earlier single piece copper seen in Fig. 4.

For testing purposes, the prototype was outfitted with wire-wound vacuum-qualified resistors in lieu of a RHU pellet. Also for testing, two cascading thermoelectric cooling modules were mounted to the base of the RPS to control the "environment" temperature.

The full system and MLI packages are laid out in Fig. 4. The shell on the far left is the RPS outside housing, the shell to the right of that encloses the FCH. Concentric cylindrical MLI packages on the right of the picture surround the FCH during normal operation. The stacks of circular MLI are representative of packages that sit on the top and bottom of the cylinders; the bottom layers have a cut-out for the thermal strap. A similar MLI package was adopted for the lower section of the RPS seen in Fig. 3.

Fig. 4. RPS, shell and MLI packages.

The design concept was and still is to surround the heat source with high-efficiency multilayer insulation (MLI) in vacuum and allow only one-dimensional escape of heat through a bismuth telluride thermoelectric module.

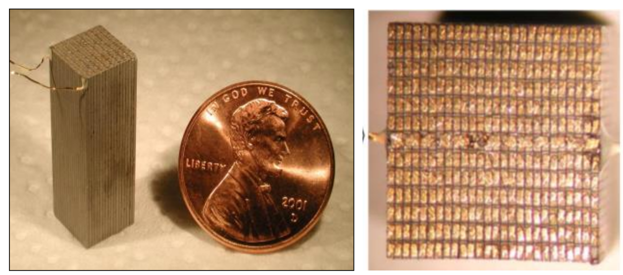


Fig. 5. High Aspect Ratio Bismuth Telluride Thermoelectric Module.

The core technology of the RPS is the Bi_2Te_3 thermoelectric module shown in Fig. 5. The thermal resistance of Hi-Z's TE module is engineered to give a 200°C temperature drop for the expected heat flux of $1.1W_t$. If the cold side can be maintained between -100 and +50°C, this enables the thermoelectric material to operate in the temperature range for its peak conversion efficiency.

To achieve high thermal resistance, the module must have a high aspect ratio. In this case, the module measures 7 x 7 x 20 mm. It consists of an 18 x 18 array of Bi_2Te_3 legs, each measuring 356 x 356 µm in cross-section and 20 mm long, separated by a 25 µm polyimide insulating layer. The legs are alternating N & P type connected by jumpers to form an electrical circuit. The high leg count enables it to produce an open-circuit potential of 10 volts, and matched-load output of 5 volts. This circuit may be one continuous series in its most basic configuration, or it may be made to be some combination of series and parallel circuits to provide redundancy.

III. System Testing

A vacuum test station dedicated to life-testing the RPS is shown in Fig. 6 that maintains a pressure of < 10^{-4} torr. A pre-determined system requirement established an RPS chassis temperature of 0°C to simulate an operating environment. This temperature was achieved in the test station using two cascaded Peltier modules cooled on their hot side by plant cooling water.

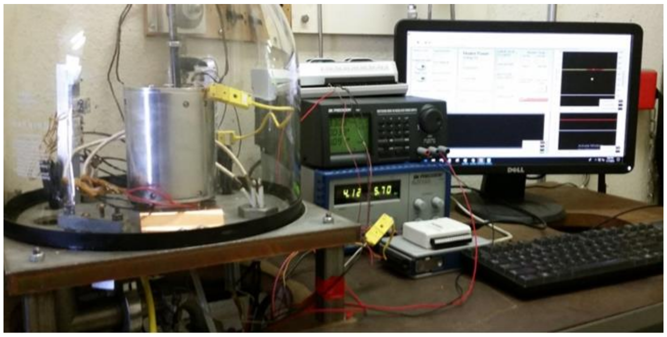


Fig. 6. RPS Life Test Station.

A data acquisition and control system logged system power output, maintained matched-load condition, and controlled periodic breaking of the circuit to measure open-circuit voltage.

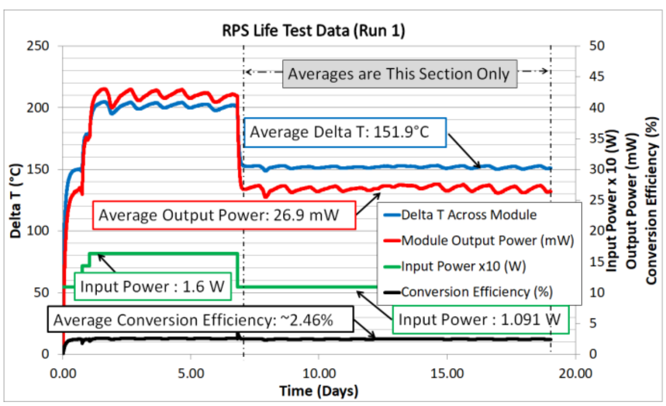


Fig. 7. RPS Thermal Performance Test 1.

The first results from this life test are shown in Fig. 7. The oscillation seen in power is caused by temperature cycling from a closed-loop water cooling system exposed to the outside environment that fluctuates in a diurnal cycle. The stepped decrease in ΔT and power output was due to a manual change in power input to the heater. At the beginning of the test, the input power was modulated until the desired ΔT was achieved. With ~1.6W_t of input power the system achieved a ΔT of 200°C and made ~42 mW_e, however when lowered to the designed 1.1W_t of input power it produced ~27 mW_e of power. Based on an assumed TE conversion efficiency of 4%, this heat should produce 44 mW_e. This suggests that 425 mW of thermal power were lost as by-pass heat, nearly double the expected amount. The radiant heat losses are attributed to suboptimal implementation of the MLI. It is projected that the MLI system can limit the radiant heat losses to < 150mW, and total radiant plus conductive parasitic heat losses to under 250mW.

A subsequent design iteration improved the mechanical structure of the MLI package as well as adopting an embossed MLI technique instead of using an insulating separator. This raised the hot-side temperature and resulting power to ~30mW, seen in Fig. 8.

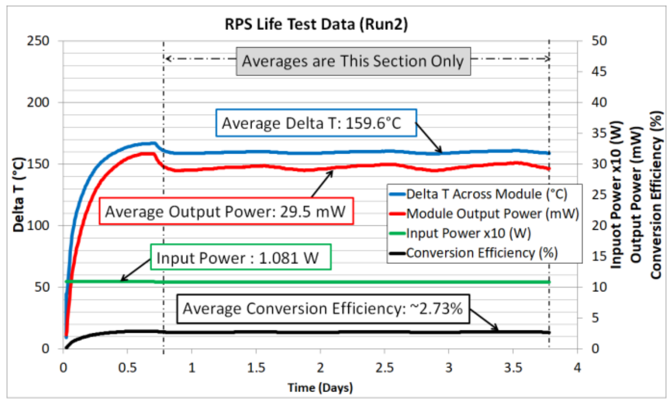


Fig. 8. Improved MLI package RPS Thermal Performance Test 5.

Fig. 9. Solid Work Rendering of In-house Shock Test Setup.

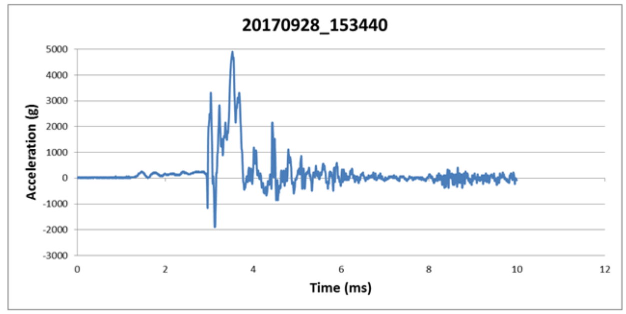
Both computer simulation and laboratory shock testing were used to validate the impact tolerance of the system. A shock-test apparatus was designed and built as shown in Figures 9, 10 and 11. Because the RPS design is not mission-specific, the shock-test parameters were designed to be generically useful, based on assumptions made in conjunction with the NASA program monitor.

Destructive compressive strength testing was performed on 4 Hi-Z TE modules to determine their ultimate strength. Results showed an average compressive failure stress of 15,800 psi. Simulations conducted by ATA Engineering showed that an on-axis shock of 4,000 g would result in peak stress spots of 4,350 psi. All shock simulation and testing work assumed the module to be the weakest point in the system, so module fracture was the failure mode most studied.

Fig. 10. In-house Shock Test Setup.

Fig. 11. RPS with Cardboard Gaskets inside PVC Shock Test Tube.

The shock acceleration peak was taken from design criteria which specified that the RPS should survive a 10,000 g shock. It was agreed that the shock target would be a half-sine pulse, 1-5 milliseconds in duration with a peak acceleration of 10,000 g. It was later decided to use aluminum honey comb to reduce the initial impact to accommodate the shock tolerance of sensors it would inevitably be coupled with. As such, the shock was limited to 5,000 g with a 1 millisecond pulse. The actual maximum shock measured was 4,907 g. Continuity of the module's electric circuit was monitored during the shock tests, and it never failed during any of the applied test conditions and retained full functionality.



- Max acceleration during testing 4,907g's
- Roughly 2ms pulse width
- With Al Honeycomb 10,000g
- Never tested to failure, could survive larger impacts

Fig. 12. Shock Test Data.

IV. Current Work

Work now continues under NASA's SBIR Civilian Commercial Readiness Pilot Program ("CCRPP"), whereby NASA provides 1:1 matching funds with our commercial partner, Aerojet Rocketdyne. This ongoing program is focused on improvements to the module manufacturing process, the effectiveness of the MLI insulation package and the outgassing of materials before and after hermetic sealing. The current prototype has not been hermetically sealed, and one of the major challenges ahead will be the ability to maintain a good vacuum after final sealing of the system. Investigations are being undertaken for selecting and sizing getters as well as developing procedures for inert atmosphere assembly and vacuum bake-out before RHU insertion and final system sealing.

V. Mission Concepts

A compact, lightweight, and durable single-RHU, mW-RPS has the potential to support numerous missions previously limited by batteries and solar arrays. A multi-year seismic investigation on a planetary body such as the Moon or Mars is a well-suited application for the mW-RPS. A Design Reference Mission (DRM) was assembled by the NASA RPS Program Mission Analysis Team which outlined a Mars Network Science Mission enabled by Hi-Z's milli-watt RPS.

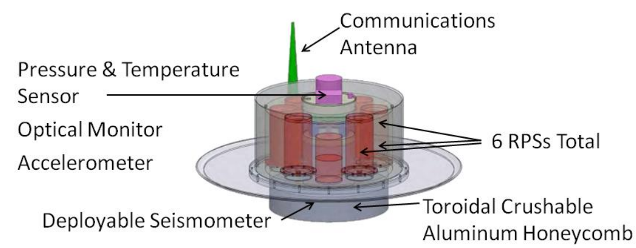


Fig. 13. Probe Concept.

That concept paper[2] describes a network of landed probes on the Martian surface, each powered by six mW-RPS units. Each probe has an Entry, Descent and Landing (EDL) system consisting of a backshell, heatshield, parachute, skid-plate, and crushable glass-phenolic honeycomb which limits deceleration to 600 g. Each probe is also equipped with a pressure and temperature sensor, seismometer, optical monitor, accelerometer package, wind sensors, and atmospheric pressure sensors.

Seismometers would be responsible for identifying the source locations and propagation speeds of seismic events. This can only be done determinately with 4 stations; otherwise weak assumptions must be made. Another study[3] suggests that 12 sites and 24 probes would be needed to properly understand Mars' global seismic activity. The probes would also help determine safe landing spots for long-term human outposts safe from quakes.

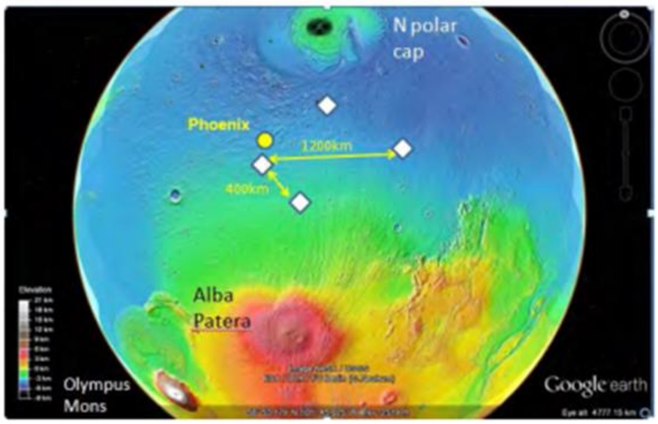


Fig. 14. Recommended Landing Sites on Mars.

Continuous multi-year pressure data would give insight to the CO_2 frost cycle, atmospheric waves, the passage of frontal systems, and the presence of dust devils. Optical monitors would take measurements of dust and ice and the column abundance of water vapor. Wind speed and direction will improve our understanding of meteorological processes as well as improve our inventory of surface wind speed measurements which are important for Entry, Descent and Landing (EDL) and surface operations for future missions[2].

The paper describes how each probe would have six 40mW RPSs for a total of 240mW. The current predicted output of the RPS is 35mW rather than 40mW, which would require a 7th mW-RPS to achieve 245mW. The provided power would run continuous loads such as computers, pressure sensors and seismometers, while also trickle-charging a set of ultra-capacitors for peak loads such as communication. RPS output heat would maintain baseline temperatures for all probe electronics.

One could imagine probes for similar missions on various bodies in the solar system. Some examples of high-priority science enabled by the mW-RPS are mapping the interior of the moon with a seismic network or the characterization of water ice inside Permanently Shadowed Regions (PSRs) on the moon.

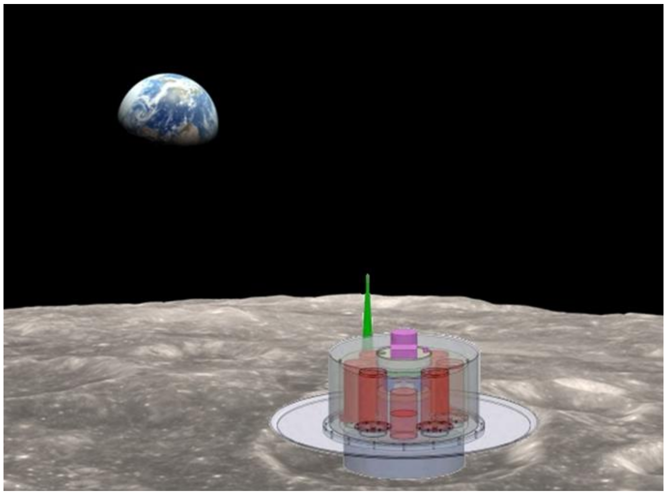


Fig. 15. Hypothetical Mission to the Moon.

VI. CONCLUSIONS

Hi-Z is developing a single-RHU radioisotope thermoelectric generator for use in space that fills an otherwise vacant slot in the spectrum of available power systems. It will provide about 35 milliwatts of power reliably for a life-span limited primarily by the half-life of the radioisotope. It generates electric power from an RHU that may be already required for system heating. This may represent an enabling technology for missions without enough sunlight to support PV power, and where distributed small probes must report or relay data for multiple years.

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