

Advances in Betavoltaics, URadioisotope Power Source for Long-Life and High Energy Density Applications

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Abstract: Unlike electrochemical batteries, betavoltaics and other types of radioisotope power sources can meet the demands in applications requiring long operating lifetimes and operation in extreme temperatures. State-of-the-art betavoltaics are being developed with power densities of 0.1 mW/cm^3 and with further refinement, 1 mW/cm^3 is promising. Though the power density is much lower than lithium primary batteries, the amount of energy delivered after 10 years is at least 5000 times more than lithium batteries. A promising fit in DoD exists in smart tags and unattended ground/maritime sensors (field & forget) to significantly extend current mission lives and situational awareness resulting in huge savings while mitigating risk to Warfighters. Center for Strategic and Budgetary Assessments estimated the cost per troop in Afghanistan for 2015 is \$2M. Experimental results and evaluation data will be presented and discussed, with a direction of where this technology may be utilized.

Keywords: Betavoltaic; radioisotope power source; energy harvesting; hybrid battery; solid-state battery; beta emitter; p-n junction; latent power; low power; modelling.

Introduction

Radiation interaction with materials can have beneficial uses, such as in betavoltaic cells, a type of radioisotope power source where the kinetic energy associated with beta (β -) decay is converted into electricity. Novel and compelling need-based applications are emerging in the military, intelligence, commercial, and medical markets that can utilize the diminutive energy produced from such cells. Present-day sensors, medical implants and electronic devices make betavoltaics an attractive alternative to electrochemical batteries enabling applications to perform for much longer periods in extreme temperatures. Unlike conventional electrochemical batteries, commercially available betavoltaics can operate in excess of 10 years over temperatures ranging from -55°C to 150°C [1]. Because the technology is far from mature, many challenges and issues remain to increase energy density, reduce cost, and make them easier to use.

Background

The first betavoltaic battery was developed in 1953 at RCA by Rappaport. The device yielded an efficiency of only 0.2% and degraded rapidly due to radiation damage

from the beta source, strontium-90 [3]. Several others continued research using ^{147}Pm but were only able to achieve <1% efficiency [4, 5]. The most promising effort in the early history of betavoltaic developments occurred ca. 1974 through research led by Olsen at the Donald W. Douglas Laboratories [6, 7]. Olsen's Betacel battery exhibited a 4% efficiency using ^{147}Pm and silicon p-n junctions. Over 285 patients received pacemakers powered by the Betacel batteries, 60 patients inside the United States. German and U.S. medical institutions were seriously considering the Betacel for wider use. The United States Atomic Energy Commission (USAEC) had authorized the licensing in the United States of a Clinical Investigation Program that allowed the implantation of 50 Betacel pacemakers per month [8]. However, strides in lithium battery development entered onto the scene and were subsequently selected for pacemakers instead [9].

Most research and development in the last 10 years has concentrated on designs using tritium; since the radiation damage is low and thus easily shielded, and available. City Labs successfully produced tritium betavoltaic prototypes in 2008 (Figure 1), that are still operating. The NanoTritium™ betavoltaic was granted a NRC General License which is approved for manufacture and sales within the United States.



Figure 1. City Labs' NanoTritium™ betavoltaics.

Theory of Operation

A direct conversion betavoltaic is comprised of two components, the p-n junction and the beta source. Electricity is produced similar to a photovoltaic using the kinetic energy of the beta particles. The basic concept of operation is shown in Figure 2. Beta particles enter the p-n junction and collide with atoms creating electron-hole pairs (EHPs) as they slow down. A 5 keV particle creates

over 1000 EHPs, and deposits some energy into the lattice. In the depletion region, holes are accelerated to the p-side collector and the electrons are accelerated to the n-side collector. With a load connected, the electrons travel from the n-side, through the load and back to the p-side. The voltage developed in a betavoltaic is directly related to the quality of the semiconductor and its band-gap energy.

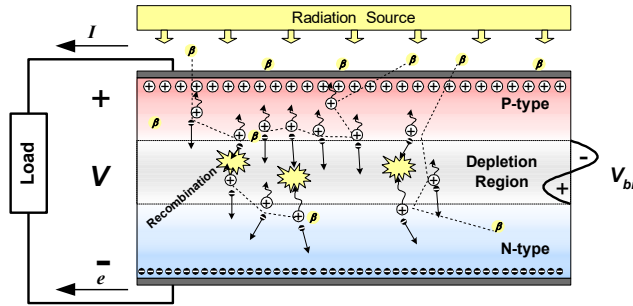


Figure 2. Overview of a betavoltaic cell.

Combining the betavoltaic in parallel with a solid-state lithium rechargeable (secondary) battery can provide latent and burst power for many applications. In a design using a Cymbet 50 μ Ah lithium solid-state rechargeable battery, the operating temperature is limited to 85°C, the maximum operating temperature of the battery.

Beta emitting source

When selecting a beta emitting isotope, the maximum beta energy and decay half-life are the most important criteria. The beta energy from ^{90}Sr and ^{85}Kr exceeds the minimum dislocation energy of 300 keV which results in semiconductor damage and bremsstrahlung [10]. The 25-day half-life of phosphorus-33 is too short for a long operating life. Therefore, of the three potential isotopes in Table 1, tritium is the most attractive. Tritium is readily available from Ontario Power in Canada and is least expensive at \$3.50/Curie (Ci). Russia is the only provider of ^{147}Pm and ^{63}Ni , which are costly at >\$1000/Ci and \$4000/Ci [11], respectively. Reprocessing in the U.S. would alleviate these obstacles making them attractive again for radioisotope power.

Table 1. Potential radioisotopes.

Isotope	$T_{1/2}$ (yr.)	E_{AVG} (keV)	E_{max} (keV)	Ci/g	W/g	Cost/Ci
Tritium	12.33	5.7	18.5	9,664	0.33	\$3.5
Ni-63	100.1	17.1	67	59	0.006	\$4,000
Pm-147	2.6	65	220	600	0.22	\$1,000

In tritium based designs, the substrate material that serves as the sync or storage medium for the tritium has become a significant challenge. Tritium can be efficiently stored as a solid in metal rather than as a compressed gas. Scandium (Sc) and titanium (Ti) can store larger amounts of hydrogen by forming hydrides, ScH_2 and TiH_2 . Recent

designs invoking tritium stored as tritides demonstrated many practical difficulties with loading techniques and substrate damage. Air and moisture contaminate the surface which increases the activation energy necessary for diffusion. Substrates around 500 nm thick are necessary to efficiently fuel betavoltaics due to shielding from the metallic substrate. Models using MC-SET (Monte Carlo Simulation of Electron Trajectories in solids) [2] were developed to predict surface beta flux for storage materials and reported in Ph.D. dissertation.

Temperature Performance Results

Betavoltaics were evaluated under temperature from -30°C to 70°C by applying a voltage and sinking the current using a Keithley 2602B source measurement unit. For individual cells, Current-voltage (I-V) curves were acquired by stepping the voltage from 1.00 V to -0.10 V in steps of 1 mV and measuring the current. Figure 3 shows I-V curves measured on Sample BV07. From cold to hot, the open-circuit voltage, V_{oc} , decreased from 0.95V to 0.65V while the short-circuit current (I_{sc}) increased from 82 to 86 nA.

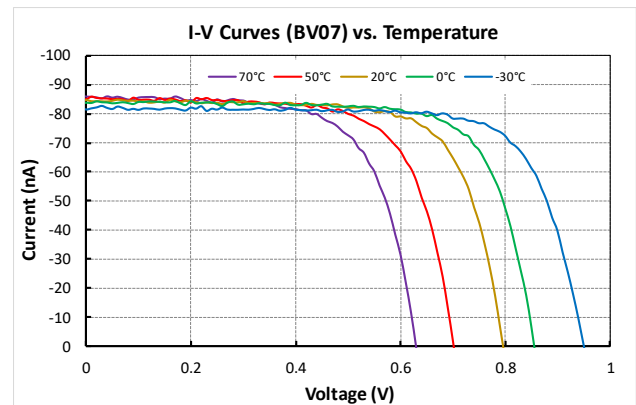


Figure 3. I-V curves of BV07 at -30°C to 70°C

Because of the strong temperature dependence on voltage, the maximum power increases with decreasing temperature. To charge a lithium solid-state rechargeable battery, six betavoltaic cells were connected in series and

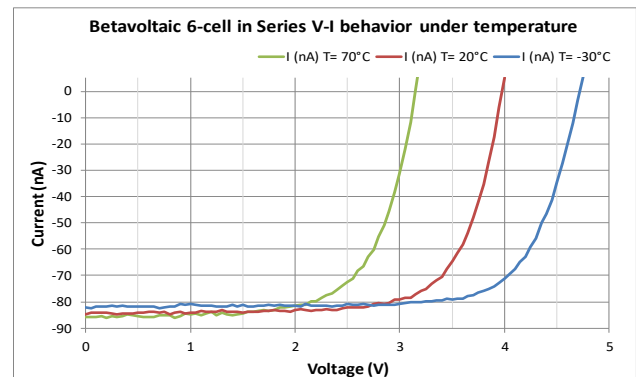


Figure 4. I-V curves of six samples (BV07-BV11) connected in series at temperatures from -30°C to 70°C

evaluated from -30°C to 70°C where they behave similar to individual cells (Figure 4). The six-cell arrangement works for temperature below room temperature but for higher temperatures, another cell is needed to boost the voltage.

The 6-cell betavoltaic was connected to a Li-SS battery in parallel to create a hybrid design. The test was done at 20°C and Li-SS battery was 90 percent charged to determine if full charge can be achieved. The result is shown in Figure 5 where the voltage increased quickly then slowed as the current decreased. The battery approached full charge to 4.0V, but fell short at the current diminished to zero. Adding another cell will provide full charge but will continue to overcharge and cause cell damage. Either voltage on betavoltaic needs to be increased or a clamping circuit needs to be developed.

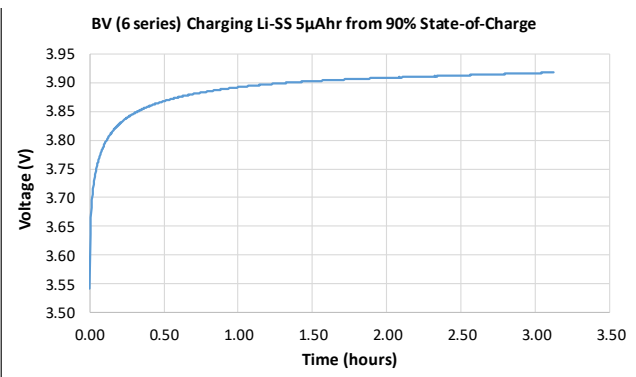


Figure 5. I-V curves of six betavoltaics connected in series at temperatures from -30°C to 70°C.

In another experiment, the internal resistance that affects the voltage was explored using a technique that maintains constant voltage over a temperature of -10°C to 50°C. A shunt resistor was placed in parallel with the betavoltaic to clamp the voltage below open-circuit voltage and cycled over the temperature range. Six betavoltaics were connected in parallel to reduce the value of the shunt resistor to what was available. The voltage followed a single cell but the current was much higher indicating that combining in parallel does not affect performance or integrity.

At 30°C, a potentiometer (outside of temperature chamber) was placed across the betavoltaic parallel stack and adjusted to obtain a voltage of 0.3 V_{oc} . Without changing the potentiometer, the open-circuit voltage was measured at -10°C and 50°C. The test was repeated with the potentiometer adjusted to provide 0.5 V_{oc} . The results in Figure 6 indicate the voltage is stable; it increases benignly as temperature increases, which is due to increasing current. The shunt resistance needed to maintain the open-circuit voltage is shown in Table 2. Higher clamped voltages vary more over temperature as the knee of the I-V curve is approached.

Using the same setup, a test was done to evaluate effects of load current on voltage stability over temperature. This time, the open-circuit voltage was set to 0.2, 0.3, 0.4, and 0.5 V. At temperatures from -10°C and 50°C, load current was increased to 50 nA in steps of 5 nA. Results for tests at 30°C are shown in Figure 7. The voltages under 50 nA remained within 5% of open-circuit voltage.

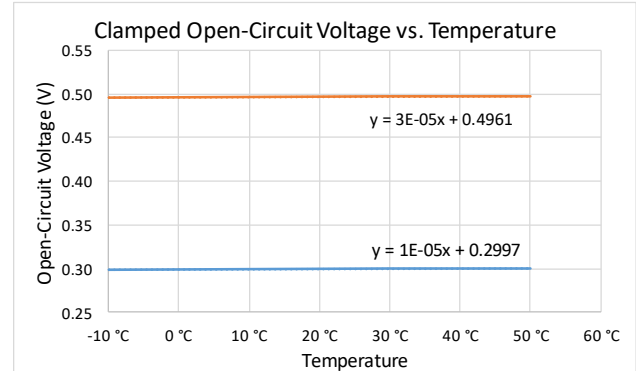


Figure 6. Clamped open-circuit voltage for 6-cell Betavoltaic over a temperature of -10°C to 50°C.

Table 2. Shunt Resistance for V_{oc} Clamping over Temperature

V_{oc}	R_{L-10C} (M Ω)	R_{L30C} (M Ω)	R_{L50C} (M Ω)
0.2	0.506	0.506	0.506
0.3	0.774	0.767	0.768
0.4	1.041	1.042	1.057
0.5	1.322	1.369	1.466

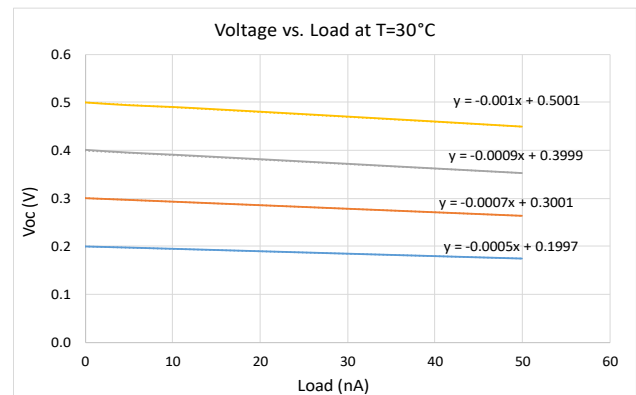


Figure 7. Sensitivity of clamped voltage for 6-cell Betavoltaic under load to 50 nA at 30°C.

Next Generation Betavoltaic

Recent advances at City Labs incorporate tritium metal hydride beta flux density and a reduction of the betavoltaic semiconductor substrate thickness from 625 microns in the P100a units (Figure 1) to 170 microns in the new 100 μ W betavoltaic unit (Figure 8) allowing for an increased power density level through stacking of betavoltaic semiconductors. Recent advances in tritium scandium metal hydride deposition techniques are projected to raise the current density to 100 nA/cm². The projected open circuit voltage for the P200 units are 0.8V,

1.6V, or 2.4V with short circuit current at inception of 156 μA , 78 μA , or 52 μA respectively. The power decay of the 100 μW betavoltaic will follow the natural decay of tritium with a half-life of 12.3 years as shown in Figure 9. On-going developments are being done to reduce the semiconductor substrate down to 10 μm that will enable milliwatt power levels within the same package.



Figure 8. Render of City Labs next generation 100 μW P200 betavoltaic (99mm x 45mm x 8mm, 20.1g)

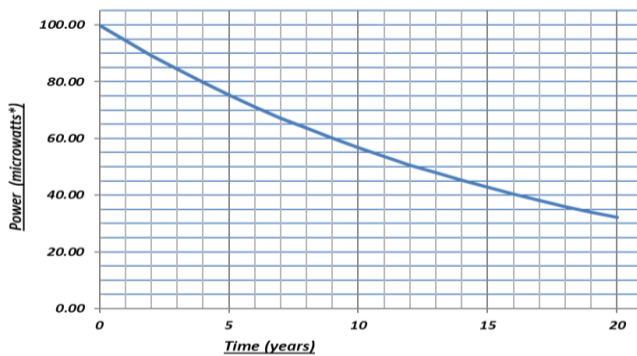


Figure 9. Projected power for Model P200 betavoltaic

Conclusion

Betavoltaics are a safe enabling technology for military and commercial applications, but the technology is far from maturity with much room for improvement. Direct replacement of batteries with betavoltaics is not straight forward and will likely require a hybrid design consisting of a betavoltaic stack and storage device (battery or capacitor) that must be able to operate in the extreme temperatures as betavoltaics. Betavoltaics have an advantage where they can operate in a constant current range with little changes in voltage. Betavoltaics can be placed in parallel and series with one another without adverse effects in performance. Paralleling multiple betavoltaics together reduces the effect of temperature on voltage which is critical in many sensor applications. The technology is developing with higher power devices and

general licensed devices for less restrictive uses. Consortia are being developed by Niowave, Inc., betavoltaic manufacturers, private industry, Department of Energy, Department of Defense, and Academia to address present challenges and advance the technology into military, commercial and medical applications.

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