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# 25.5 Betavoltaic Power Cells

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**Abstract:** *Betavoltaic power cells utilize beta-emitting radioisotopes and semiconductor devices to produce long-lived power in a variety of small form factors. Qynergy is developing betavoltaic power cells based on silicon carbide junction converters and $^{85}Kr$ and $^{147}Pm$ isotopes for a variety of applications.*

**Keywords:** betavoltaic; silicon carbide (SiC); $^{85}Kr$; $^{147}Pm$

## Introduction

Because of their high energy density, radioactive power sources should be considered as an alternative to next generation battery and fuel cell technologies, especially for applications where volume is at a premium and long lifetime without recharging is important. Energy from radioactive decay can be converted into electric power by several methods, including thermoelectric conversion, direct charge collection, direct energy conversion, and indirect energy conversion [1]. One promising direct energy conversion technique employs a semiconductor pn junction and a radioisotope that emits high energy electrons or "beta particles". The direct conversion betavoltaic was first patented by Rappaport at RCA in 1956 [2], and many researchers have investigated betavoltaics in the years since [3-13]. Recently, with the increased availability of high quality, wide bandgap semiconductor materials such as gallium phosphide, silicon carbide (SiC), and gallium nitride, there has been a renewed interest in betavoltaic technology. Wide bandgap semiconductors are more radiation resistant than their narrow bandgap cousins (such as silicon, indium phosphide, and gallium arsenide) and are inherently better at converting energy from ionizing radiation into usable electric power.

## Theory

A betavoltaic converts a portion of the energy carried by beta particles into electric power in much the same way a photovoltaic converts energy from light. As each beta particle travels through a semiconductor material, it gives up kinetic energy along its entire path until it is ultimately absorbed in the material. A portion of each beta particle's kinetic energy is lost to the lattice as heat (approximately two-thirds [14]), while the remainder is used to create electron-hole pairs (EHPs). The betavoltaic device itself is a pn junction designed to capture as many of these newly created EHPs as possible. A very high percentage of EHPs created in or near the depletion region of the pn junction will be collected as so-called "generation current" at the contact terminals of the device. This current is the manifestation of the energy conversion process. The betavoltaic device operates at a voltage that is dependent on several factors, including: the generation current, the semiconductor bandgap, the p and n doping levels, and the load impedance. Typical voltages for SiC-based betavoltaics operating near the peak power point are approximately 1.5 V. The conversion efficiency ($\eta_{conv}$) of a betavoltaic refers to the peak electrical power output divided by the beta power entering the semiconductor device. The theoretical $\eta_{conv}$ increases sub-linearly with increasing semiconductor bandgap, saturating at around 30% for bandgaps above 4 eV [4]. Silicon carbide is an ideal candidate for betavoltaics because of its high bandgap (3.2 eV) and radiation hardness. The power cells described in this work utilize SiC betavoltaic devices.

## $^{85}$Kr QynCell

Qynergy has been in the process of developing power cells known as QynCells based on wide bandgap semiconductor betavoltaic technology for the past 1½ years. Two beta-emitting radioisotopes that are of particular interest in these devices are $^{85}Kr$ and $^{147}Pm$. $^{85}Kr$ has several qualities that make it a good candidate for QynCells in addition to some that hinder its usefulness.

*Advantages:* The half-life of $^{85}Kr$ is quite long: 10.78 years. In other words, the output power of the cell will decrease by 50% every 10.78 years, assuming no other degradation mechanisms are at play. The fact that $^{85}Kr$ is a gas is advantageous in many applications, because the power cell can be designed for just-in-time $^{85}Kr$ loading, enabling the cell to have an effectively infinite shelf life. In the unlikely event of a package breach, because $^{85}Kr$ is a noble gas, it easily disperses without chemical reaction, minimizing radiation dose to those nearby. $^{85}Kr$ emits very high energy beta particles (251 keV average), and therefore offers the highest power per Curie (Ci) of radioactivity available in a beta emitter with a reasonable half-life.

*Disadvantages:* Unfortunately, these high energy betas are also difficult to absorb in the betavoltaic effectively, so $\eta_{conv}$ tends to be lower in $^{85}Kr$-based betavoltaics than in others. Another side-effect of the high energy betas is degradation of the semiconductor betavoltaic material. With our SiC converters degradation is reduced relative to other materials, but it still exists, and the end result is the need to load the QynCells with increased $^{85}Kr$ at beginning-of-life to meet a particular end-of-life power requirement. Finally, $^{85}Kr$ is not a pure beta-emitter; it emits a 514 keV gamma particle with an abundance of 0.434%. For this reason, $^{85}$Kr QynCells require additional shielding for applications in constant proximity to humans or sensitive electronics.

*Experimental Data:* We have fabricated and tested approximately 50 SiC betavoltaic devices with a variety of pn junction designs. Testing is accomplished by placing each 1 cm$^2$ device under a $^{85}$Kr sealed source and sweeping voltage in 0.01 V increments while measuring output current and then calculating power. The $^{85}$Kr source was loaded on 12/15/03 with approximately 1.2 Ci of radioactivity, which is equivalent to 4.44x10$^{10}$ betas/sec. A thin (1 mil) titanium "window" allows approximately 10% of the betas through. Figure 1 displays the power vs. voltage characteristics for many of these devices. Based on Monte-Carlo modeling, we estimate the $\eta_{conv}$ of the best devices to be between 0.75% and 1.15%.

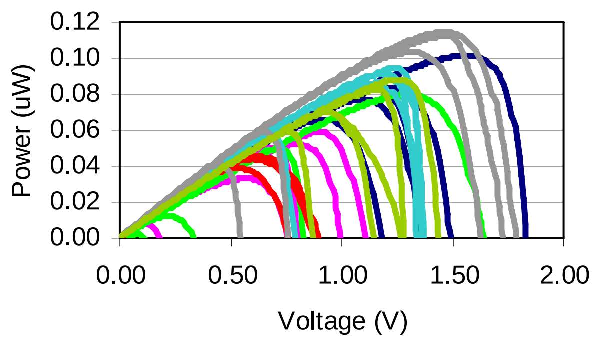


**Figure 1.** Power vs. voltage data for $^{85}$Kr-irradiated SiC betavoltaic devices.

We have gathered degradation data on two of these devices, each with a different pn junction design, as shown in Figure 2. This data was collected by measuring the power vs. voltage characteristics of the device-under-test once per day for an extended period of time.

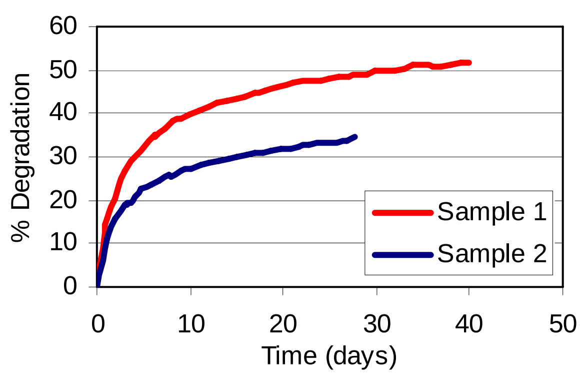


**Figure 2.** Peak power degradation of two different SiC betavoltaic designs.

Interestingly, the absolute value of the peak power degradation depends strongly on the pn junction design, although the general shape of the two characteristics is similar. Both devices exhibit an initial period of increased degradation rate which slows down after approximately 10 days. Although the degradation has not stopped, it has slowed to the point where lifetime extrapolations can be attempted. For both curves, the data beyond the first 10 days can be well fit with logarithmic functions ($r^2 > 0.99$ in both cases). If the degradation rate continues to follow the same trend, samples 1 and 2 will operate at 1% and 8% of their respective initial powers after 20 years (these values already account for the decay of the isotope). For reference, sample 1 delivered approximately 26% more power initially than sample 2.

*Cell Design:* We have designed and fabricated prototype $^{85}$Kr QynCells which will undergo extensive performance and environmental testing at the Naval Surface Warfare Center in Crane, Indiana (NSWC Crane). Figure 3 displays renderings of the latest QynCell design along with a cutaway.

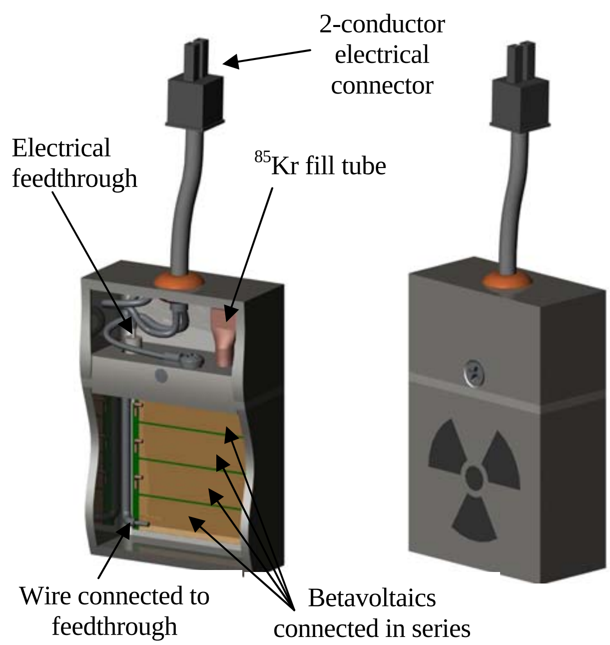


**Figure 3.** SolidWorks renderings of $^{85}$Kr QynCell and cutaway.

The manufacturing process for this power cell proceeds as follows. The betavoltaic devices are soldered to a printed circuit board (PCB) that enables them to be connected in series with one another via wire bonds. The populated PCB is soldered to the inside of the case to make one electrode, and a wire is soldered between the feedthrough and the last betavoltaic device to make the other electrode. There are two such PCBs (one on each side of the case) connected in parallel. The case is welded closed and pressurized with $^{85}$Kr gas. The fill tube is crimped and cut, and a cap is screwed onto the case to protect the feedthrough and fill tube stub. This particular device was designed to deliver up to 50 μW continuous power at beginning-of-life (BOL), depending on the enrichment and pressure of the $^{85}$Kr gas as well as the efficiency of the betavoltaic devices.

### $^{147}$Pm QynCell

Another radioisotope that Qynergy is exploring for use in betavoltaic power cells is $^{147}$Pm. The advantages and disadvantages of this isotope are discussed below.

*Advantages:* $^{147}$Pm is a solid phase radioisotope that is compatible with thin film deposition. The thin film form factor translates into high power density and also enables the exploration of unique applications (i.e. directly integrating power with an integrated circuit). It decays by emitting moderate energy beta particles (62 keV average) which are much easier than $^{85}$Kr betas to capture and convert. $^{147}$Pm is essentially a pure beta emitter, with only a 121 keV gamma particle with an abundance of 0.00285%. This gamma does not drive the shielding considerations for $^{147}$Pm QynCells. In fact, typical devices can have radiation doses below background at contact with only 1-3 mm of tungsten shielding.

*Disadvantages:* The primary disadvantage of $^{147}$Pm is that its half-life is only 2.62 years. The consequence of this fact is the need to add additional isotope at BOL so that the desired output power is still delivered at the desired lifetime. For 5 - 10 year applications, the additional isotope is manageable, but for 15 - 20 year applications it becomes more of a problem. Another issue that $^{147}$Pm has in common with all solid phase beta emitters is known as "self-shielding". Self-shielding refers to the absorption of betas within the isotope film itself.

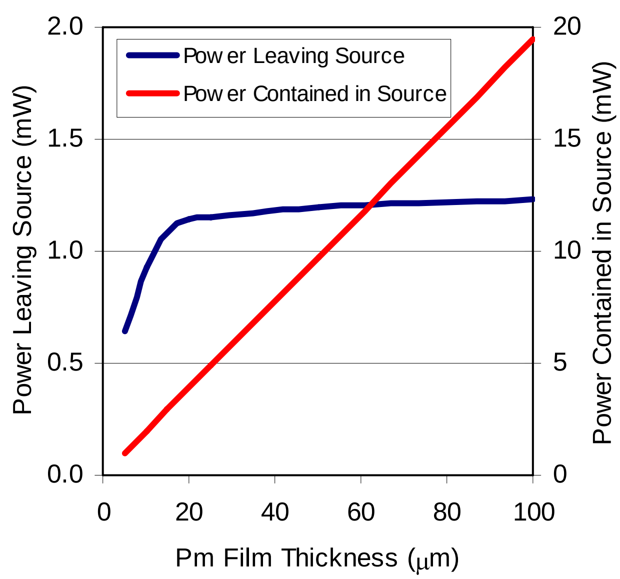


**Figure 4.** Self-shielding in Pm thin films.

Figure 4 demonstrates the effect of self-shielding in Pm thin films, as determined by Monte-Carlo modeling. The source efficiency, $\eta_{source}$, accounts for the effect of self-shielding as well as reflection at the semiconductor/isotope interface. The overall efficiency of a betavoltaic power cell is then $\eta = \eta_{source}*\eta_{conv}$. Values for $\eta_{source}$ range between 5% and 70% depending on Pm film thickness and semiconductor contact material.

*Experimental Data:* To date, Qynergy has performed experiments with $^{33}$P which has a beta spectrum very similar to $^{147}$Pm (77 keV average energy). $^{33}$P is a readily available pure beta emitter with a half-life of 24 days. We believe that conversion efficiency and degradation measurements made with $^{33}$P sources offer reasonable approximations to $^{147}$Pm betavoltaic behavior. Initial experiments, which have been published elsewhere [15], demonstrated a $\eta_{conv}$ of 4.5% and no measurable degradation. Subsequent experiments have produced higher efficiencies (up to 11%), and we are currently gathering degradation data on these samples.

### Applications

Betavoltaic technology has a very high energy density and a moderate to low power density. In other words, although a large amount of energy is stored in the radioisotope, it can only be extracted at the rate of beta decay (best-case). For this reason, coupling a QynCell with an energy storage device to make a long-lived, hybrid power source makes sense. Indeed, our simulations show that using an appropriately designed QynCell to trickle-charge a Li-ion battery can extend the lifetime of the battery by more than a factor of 10 for the same total power source volume. Such a QynCell-battery hybrid would be well-suited to applications where on-demand power is required for a long time (20+ years) and human access is limited or undesirable.

Other hybrid QynCell-based technologies can also be envisioned. For high powers (mW to W) with very low duty cycles (i.e. munitions triggers), coupling with a low leakage super capacitor or high power battery is an obvious choice. Betavoltaic cells could also be used in conjunction with radioisotope thermoelectric generators (RTGs) to improve overall system efficiency (i.e. directly convert excess radiation to electricity). For low power (μW to mW), long-lived applications, a stand-alone betavoltaic or a hybrid betavoltaic/energy scavenging technology would be useful. Energy scavenging technologies involve reclaiming kinetic energy from routine activities and converting it to small amounts of distributed electrical power. Such techniques are inherently long-lived and would work well alongside a QynCell to provide distributed power throughout an entire system.

Another technology that is well-suited to the high energy density that betavoltaics can provide is micro-electro-mechanical systems (MEMS). QynCell technology is potentially enabling to some MEMS applications because of the ease of integration. Small amounts of radioisotope fuel would be required for the typical MEMS application, and the betavoltaic could be attached right to the MEMS substrate. Conventional integrated circuits are also a candidate for this type of “power-on-a-chip” integration.

## Summary

Qynergy is developing power cells based on $^{85}$Kr and $^{147}$Pm radioisotopes and SiC betavoltaic converter devices. Trade-offs between the isotopes, experimental data, cell design, and applications were all discussed. This work was supported by the Air Force Research Laboratory, Space Vehicles Directorate, contract #FA9453-04-C-0066 under the direction of Dr. Paul Hausgen.

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