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Tritium-Powered Radiation Sensor Network

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James C Brent, and James J Carroll**

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14. ABSTRACT Isotope power supplies offer solutions for long-lived (100 years), low-power (100 μW_e) energy sources. The energy density of nuclear batteries uniquely serves applications for sensors or communications nodes that are required to last the lifetime of infrastructure. Efficiencies less than 10% are typical for either direct (or indirect) energy conversion of radiation to electric current. A tritium (^3H) beta-source (12.5-year half-life) encapsulated in a phosphor-lined vial is coupled directly to a photovoltaic (PV) generating a trickle current into an electrical load. An inexpensive design approach is described consisting of commercially available components that generate 100 μW_e for next-generation compact electronics and sensor applications. A total of 15 μW_e electrical power is measured from individual 20-Ci tritium cassettes (80 cc) using gallium arsenide (GaAs) PVs. A compact radiation sensor (400 cc) has been designed and built to operate during long-lived missions. A low-power sensor architecture is described and implemented that uses microprocessor-controlled sleep modes, a judicious choice of low-power electronics, and a passive interrupt driven environmental wake-up. The low-power early-warning radiation detector network combined with a long-lived isotope power source enables no-maintenance mission lifetimes dependent only on the half-life of an isotope of choice.					
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1. Introduction

The size of personal electrical devices is continually shrinking. Unfortunately, the power requirements of sensors, compact communications equipment, and light sources are not reducing as fast as device size and weight. Chemical batteries are the inexpensive mainstay of power for these devices. However, chemical batteries have limited lifetimes (<10 years). The unique opportunity for isotope-based power sources comes in addressing long-lived applications. Eliminating battery replacement means low maintenance and, more importantly, enables new uses previously not considered. Sensors buried in bridges and buildings can last for infrastructure lifetimes. However, licensing is required when using these materials, from the Nuclear Regulatory Commission (NRC)¹ and the Department of Transportation (DOT).²

The use of radioactive materials creates issues that are not strictly technical in nature. These include radioisotope packaging, licensing, biotoxicity, regulation (NRC), transportation (DOT), and the fear carried in our society when we mention the use of radioactive materials. Chemical power sources are inexpensive, offer high power output, and are readily available. Isotope power sources offer greater than 100-year lifetimes (⁶³Ni) opening up operational concepts that include power sources for sensors that can last the lifetime of infrastructure.

Structural material defects that limit safe operation of buildings, bridges, and roadway infrastructure can be measured over their operational lifetime of 150 years. Persistent sensing of the environment with vibration and radiation (electromagnetic [EM], acoustic, gamma, etc.) in urban and remote locations can now be considered where previously chemical battery replacement was either impossible because of remote location or revealing and thus endangering the Soldier or the data value. Reducing the amount of radioactive material to levels as low as reasonably achievable is a common safety goal and a practical step to using the energy released in decaying isotopes. By finding the most efficient path to converting the products of radioactive materials, maximum electrical output is available for minimum isotope mass.

The most compelling reason to use isotope power sources is the long lifetime capability for remotely located or unattended sensors and communications nodes. Isotope-based power sources specifically enable extended lifetime operation. While chemical-based power sources are inexpensive, application independent, and ubiquitous, the value gained from long-lived no-maintenance power is not achievable through chemical energy conversion. The capability to operate in the

field for 15–100 years enables remotely located sensors, embedded sensors, or communications nodes to provide information maintenance-free for decades.

Three primary technical issues must be considered in the process of developing an isotope power source. First is the choice of isotope, second is the choice of energy conversion, and finally, energy storage and load matching must be managed so as not to waste any of the electrical power generated. The material and design choices and tradeoffs, as well as the impact on electrical power output, are discussed in Section 2. Electrical power consumed by many commonly used sensors exceeds energy harvesting power levels ($100 \mu\text{W}_e$). For this reason, the design rules of low-power radiation sensors are discussed in detail in Section 3. We have set a goal of designing long-lived power sources and low-power matching sensor architecture, using commercially available materials and components. Progress and issues are described in Section 4.

2. Isotope Power Source Design

2.1 Isotope Choices

The design goals for this isotope power source is that it be inexpensive, be composed of commercially available components, offers a half-life greater than 10 years, and be practical/usable within the existing code and regulation. Tritium (^3H) represents the low hanging fruit for choice of isotope. Several other beta-emitting isotopes offer long half-life and low energy beta emission so as not to be damaging to conversion materials, and gamma emission less than 5% of the energy exchange so that radiation shielding is not required. Tritium is the least expensive of all isotopes shown in Table 1. Because all isotopes listed are primarily beta decay, the radiation dose at 1 ft is negligible.^{3,4}

Table 1 Candidate beta-emitting radioisotopes with beta emissions <250 keV, gamma emissions <10% of the radiation energy output, and half-life >10 years. The activity (Ci) is shown for $100\text{-}\mu\text{W}_e$ power output assuming generic 10% conversion efficiency.

	HalfLife(yr)	E_{avg} (keV)	Ci
^{151}Sm	90	25.3	6.7
^{193}Pt	50	18	9.4
^{63}Ni	101	17	9.9
^{157}Tb	71	16	10.6
^3H	12.5	6	28.2
^{121m}Sn	55	3	56.3

^{63}Ni is another strong candidate meeting all the criteria described above. However, ^{63}Ni is 5 times more costly than tritium primarily because it is used less in commercial environments.⁹ The cost of 100 Ci ^{63}Ni is \$20k while the cost of 100 Ci of tritium is ~\$6k. While the average beta energy released in a decay of ^{63}Ni is 3 times larger than that of ^3H , ^{63}Ni remains a viable candidate for use with wide band gap semiconductor devices.^{5,6} It has a 99-year half-life, which is perfect for sensors supporting infrastructure lifetimes.^{7,10}

The remaining isotopes listed in Table 1 are available, but have no continuing commercial use, which makes their procurement much more expensive. One notable candidate, $^{121\text{m}}\text{Sn}$, is an isomer with a 55-year half-life and offers the possibility releasing the energy stored in the excited state of the nucleus when stimulated by an electron beam, thus triggering the 55-year half-life power generation phase on-demand.⁸

2.2 Energy Conversion

While there are many energy conversion approaches to using the charge, we discuss 3 in particular: 1) charge collection, 2) direct energy conversion (DEC), and 3) indirect energy conversion. Alphas contain 2 charges and have been used to generate high voltages by collecting and building up the charged particles on the inside of a vacuum chamber.¹¹ Moseley showed how in an evacuated chamber surrounding 20 mCi of radium (Ra), he could develop ~150 kV electrical potential due to the charge collected on the grounded surface of the vacuum chamber.¹¹ Ra has insignificant natural abundance by itself, but is part of the ^{238}U natural decay chain where ^{226}Ra is an alpha emitter with a 1600-year half-life.

DEC of radiation to electrical power uses the internal electric field (E-field) within the physical geometry (Fig. 1a). The internal E-field is required in all configurations to move charge through the volume, sweep carriers out of the active volume, then collect and/or create additional charge carriers for electrical power output. The E-field across the depletion region in a semiconductor is essential in order to pull the free charges created by beta impact through the device, creating a flow of charge. Increasing the depletion region (or intrinsic region in a passive device) creates a larger volume for electron-hole (EH) pair creation and collection. In a chemical battery, the internal E-field is generated by the difference in material work function between cathode-anode, cathode-electrolyte, or electrolyte-anode. In an ion chamber (fluid or plasma filled), both negative and positive ions are created that can be influenced by the work functions of the anode-cathode materials.

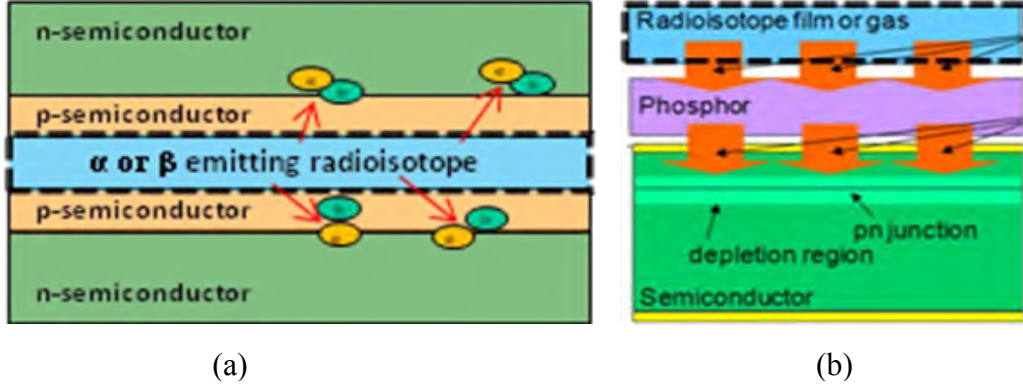


Fig. 1 The energy from nuclear decay products are commonly converted to electrical energy in semiconductors by a) DEC within the junction of the semiconductor or b) indirect energy conversion, which involves an intermediate step using a phosphor

Indirect conversion (Fig. 1b) usually includes phosphors that both shield the direct radiation and fluoresce from the radiation. The optical energy is then converted into electrical energy in the photovoltaic (PV). This 2-step process adds an additional conversion step with additional inefficiencies in the net conversion process. Even though 2 conversion steps are used, the indirect conversion method is chosen as the approach for a practical (NRC/DOT regulated), low-cost (commercially available components) design in order to overcome the non-technical issues described in Section 1. The indirect conversion approach uses tritium-loaded, phosphor-lined, sealed-source components that are commercially available. As sealed sources, they are licensed by NRC for use in night-vision materiel.

While indirect energy conversion is a 2-step process compared to DEC (single energy conversion from β kinetic energy to EH pairs), the semiconductor devices and geometry for conversion are not optimized at this time. Designing the largest possible depletion regions in PN or PIN junctions would enable collection of charge over larger volumes and with greater efficiency than exist today. All DEC approached to date have been less than 3% efficient.^{12–15}

2.3 Energy Balance

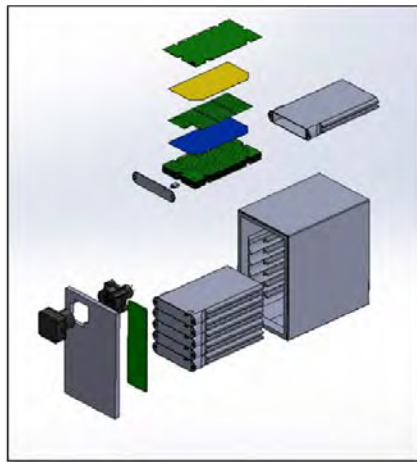
Each nuclear decay of tritium (${}^3\text{H} \rightarrow {}^3\text{He} + \beta + \bar{\nu}$) releases 18.6 keV that goes into the production of a β -particle and neutrino. Only the β -particle interacts with phosphor, as neutrinos rarely interact with matter. The average energy resulting from the spectrum of β -energies released is 5.7 keV.¹⁷ Each tritium vial is loaded with 100 mCi. The nuclear power (P_{nuc}) generated from each tritium vial is 3.37 μW . The surface area of the 2 large sides available to the PV cells (4x20x0.8 mm) is 160 mm². The resulting nuclear decay power available per square cm over both sides of the vial/plate is then 2.1 $\mu\text{W}/\text{cm}^2$. The optical output (P_{opt}) of the phosphor-lined tritium vials was measured using a Newport optical power

meter. The measurement yielded $1.08 \mu\text{W}/\text{cm}^2$ (on one side), or $2.16 \mu\text{W}/\text{cm}^2$ total P_{opt} for both sides. The efficiency of the gallium arsenide (GaAs) PV presently used is 3.2%, converting the P_{opt} into electrical power (P_e).

The $P_{\text{nuc}}/\text{cm}^2$ of $4.6 \mu\text{W}/\text{cm}^2$ produces $P_{\text{opt}}/\text{cm}^2$ of $1.07 \mu\text{W}/\text{cm}^2$. The $P_{\text{opt}}/\text{cm}^2$ produces P_e/cm^2 of $0.034 \mu\text{W}/\text{cm}^2$. The phosphor efficiency is 23% and the PV electrical efficiency is 3.2%, giving an overall measured power source efficiency of 1.48% when using both sides of the tritium plate (tritium plates sandwiched between 2 PV panels).

2.4 Design and Packaging

The power source is designed to be lightweight (taking advantage of the high energy density of tritium), durable (layered packaging for safety), and functional (using a familiar battery format) for plug-and-play capability for the Soldier (Fig. 2a). The power sources are designed into cassettes holding 4 PV- ^3H -PV sandwiches, connected in parallel, and mechanically and electrically connected to printed circuit boards (PCBs). Each cassette converts the decay from 20 Ci ^3H , which is aligned with the DOT regulation for sealed assembly shipping limit of ^3H . The entire enclosure (holding up to 7 cassettes) has dimensions and footprint similar to a BA5590 general purpose communications battery (2 x 4 x 5 inches). The overall design, material selection, and components of the battery offer long-lived power attributes that can benefit the Army's low-power sensor requirements for unattended sensor and communications nodes.



a)



b)

Fig. 2 a) Packaging of tritium isotope power source shows individual sealed modules limited 20 Ci (as specified by DOT) integrated together to compose a single $100\text{-}\mu\text{W}_e$ electrical power source. b) Low-power radiation detector for unattended operation includes global positioning system (GPS) and radio frequency (RF) communications powered by a tritium isotope power source.

The power levels generated by naturally abundant renewable energy are shown in Table 2. These power levels range from less than 1 $\mu\text{W}/\text{cm}^2$ to more than 10 mW/cm^2 . The components being built up around these types of energy sources are having impact on the growing needs of the low-power electronics industry. A 100- μW power level was chosen as a minimum level of power capable of providing useful operational support for small sensors and communications nodes. The constraints on generating power >1 mW power levels are only dictated by the interest in minimizing the activity of the radioisotope inserted into a power source. There is no maximum isotope activity limit based on engineering guidance. For example, radio-thermal generators (RTGs) for space applications use 100 kCi of ^{238}Pu generating 4 kW of heat (only 10% converted to electricity). A 100- μW electrical power output goal is achieved with ~ 140 Ci of tritium.

Table 2 Energy harvesting levels of power are consistent with the power levels supplied by isotope power sources

	Energy Input	Available Power	Harvested Power
PV Outdoor	1 Sun at noon	100 mW/cm^2	10 mW/cm^2
Thermal	Human body	20 mW/cm^2	20 $\mu\text{W}/\text{cm}^2$
PV Indoor	Fluorescent Lamp	0.1 mW/cm^2	10 $\mu\text{W}/\text{cm}^2$
Vibration	Human walking movement	0.5+1 m/s @50Hz	4 $\mu\text{W}/\text{cm}^2$
RF GSM 900Mhz RF GSM 1800Mhz	RF harvester in an office environment	0.3 to 0.03 $\mu\text{W}/\text{cm}^2$ 0.1 to 0.01 $\mu\text{W}/\text{cm}^2$	0.1 $\mu\text{W}/\text{cm}^2$
Isotope	Tritium filled vial and PV converter	1.02 mW/cc 2.03 uW/cm^2	17 uW/cc .035 uW/cm^2

Tritium-filled, phosphor-lined vials are commercially available for night-vision gear applications.¹⁶ The tritium capsules purchased yield as much as 11 nW/mm^2 . The tritium-filled vials of dimension 0.8 x 4 x 20 mm generate total light output of 1.1 μW , as measured with a Newport power meter (model 1916). The geometry of the thin, flat, tritium-filled vials (plates) allow us to characterize the emitted light output over an area. The conversion efficiency of the zinc sulfide (ZnS) phosphor is $\sim 27\%$.

The optical output of the phosphor is in the green (528 $\text{nm} \pm 40$ nm). PV cells sandwich the tritium-filled, phosphor-lined vials. The PV cells are soldered to the electronic PCB, adding mechanical support, alignment, and electrical connection. The sandwiches are supported within rigid cassettes totaling 20 Ci. The cassette

case adds additional mechanical support and are filled with silicon (Si) rubber adhesive producing sealed modules that meet DOT shipping regulations.

The BA5590-style military enclosure houses the tritium- ^3H -PV sandwich cases (Fig. 2a), which includes a military connector and an energy harvester circuit board. The case adds mechanical support and water resistance. The enclosure material is acrylonitrile butadiene styrene (ABS) plastic. The enclosure has self-locating features to allow the user to slide the cassette cases and an o-ring seal for environmental protection. The back side of the enclosure cover has standoffs and plastic supports to mount the energy harvester board.

3. Low-Power Sensor Design

The radiation observations with communications (ROC) sensor (Fig. 2a) can operate on limited 100- μW power supply with energy management tools provided by both the microcontroller and sensor peripherals. The electronics package is designed to reduce the number of power wasting components and therefore reduce the overall power of the radiation sensor by stripping the components down to a minimum set for sensing and communications. Both hardware and software were chosen specifically in order to build a sensor with the minimum acceptable power requirement and the highest efficiency from each component.

The low-power electronic design is centered on the Texas Instruments MSP430 microcontroller. This controller is powered by a lithium ion battery that is currently being used as the power source. The size of the lithium ion battery is based on the trickle charge rate of the isotope battery, presently capable of delivering 10 J per day.

The MSP430 has a variety of sleep modes that allow it to run at ultra-low power when not needed. For the ROC Gen 3 sensor design, the lowest power sleep mode (LPM 4) was chosen, which causes the MSP430 to use only 0.22 μA . The MSP430 requires an external interrupt in order to wake up from this sleep mode. There is also a LPM 3, which allows the MSP430 to wake up periodically; this is maximum sleep with a timer wake up. This LPM uses 0.94 μA when sleeping. The LPM 4 was chosen because the sensor was designed with external interrupts. When the MSP430 is in normal operation, which is when data are being collected and transmitted, it uses 3.34 mA of current. With our 100- μW battery, we will never be able to run the microcontroller freely for long periods of time. Table 3 shows how long the microcontroller runs on 8.64 J per day when each mode is used.

Table 3 Component energy consumption in low-power radiation sensor. These values are based upon the trickle charge of 100 μW , which delivers 8.64 J per 24-h period.

Item	Power	Energy (per min)	Time on Isotope battery (10J)
GPS	65mW	3.9J	2.56 min
MSP430 (NO SEND)	7.28mW	0.435J	23 min
MSP430 (SEND)	82.5mW	4.95J	2 min
Detection (NO EVENT)	221uW	0.013J	769 min (12.8 hrs)
Detection (Continuous Event)	221uW+260uW	0.028J	357 min (5.95 hrs)
All Systems Sleep	1uW	60uJ	166666min (~115 days)

The CC1101 radio chip is part of the low-power communications strategy for the MSP430. It is capable of following the microcontroller into its deep-sleep modes only to wake up and transmit the data wireless to an access point when instructed. The radio chip requires 138 μJ to send the first packet, because of one-time wake-up directives from sleep mode. After this first signal, subsequent packets require 128 μJ per transmission. We currently operate the MSP430 under interrupt control to send 30 measurements over 10 s. This requires a total of 4 mJ of energy for every 10 s of use supporting power needs of the CC1101 transmitter.

A low drop-out 3.3-V regulator gives us dynamic control of the processor voltage, which can operate between 1.7–3.3 V. A load switch on every peripheral allows the MSP430 to not only shut off its own power needs but also control the parasitic load of each of the electrical peripherals in the signal chain. The load switch is simply a P-channel metal-oxide-semiconductor field-effect transistor (MOSFET) that allows a digital pin from the processor to act as a physical disconnect. The MSP430 then sends a low-voltage signal to the MOSFET when electrical components need to be activated. The sensor-chain components are the comparator, digital potentiometer, a 30-V power supply, and a GPS sensor as required.

Data collection starts with the activation of an ultra-low power DC/DC converter designed to boost the voltage from 3.3 to 30 V DC. This voltage is used to feed an avalanche photodiode, which is connected to an ultra-low power comparator. A low-power digital potentiometer sets the reference threshold, which is counted by the microcontroller. A threshold is adjusted automatically to maintain about 150 counts per second. The count data are collected during the small operation window of the boost converter, as it is one of the highest power peripherals in the signal chain after the CC1101 radio. An operational flowchart is shown in Fig. 3.

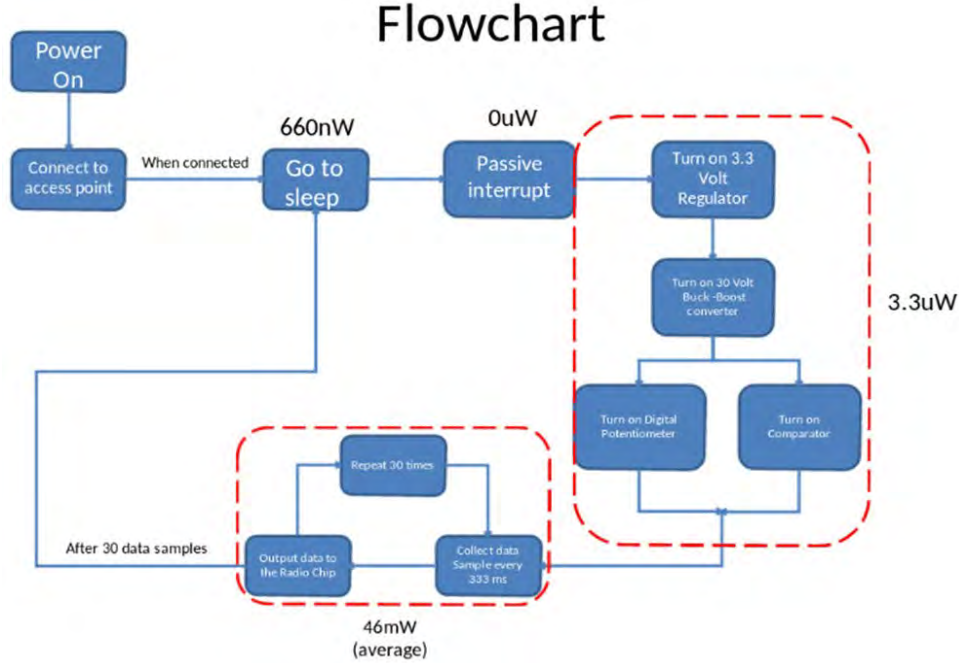


Fig. 3 Power consumption flowchart for the MSP430 microprocessor used in the ROC sensor

4. Results and Performance

The weakest link in the design and energy balance described in Section 2.3 is the unexpected low efficiency of the PV. Commercial vendors of PVs normally achieve $>20\%$ efficiency under 1 sun intensity (100 mW/cm^2) solar spectrum illumination. The 2 distinguishing factors that differ in our application from normal solar PV applications is 1) weak illumination (10^{-5} sun) and 2) narrowband light emission from the phosphor ($528 \text{ nm} \pm 40 \text{ nm}$). Identifying PVs with the largest efficiency under weak illumination and the narrowband spectrum is essential in order to reduce the isotope activity while meeting the $100\text{-}\mu\text{W}$ electrical output goal.

4.1 PV Materials

PV converters work by generating charge carriers when photons interact in materials that form a junction. For an electron to be liberated to pass into an external circuit, there must be an event that raises its energy level within the semiconductor. The amount of energy to boost it to the higher level is called the “band gap” energy. Only photons with the minimum band gap energy will be able to free electrons to create a current. Photons with less than the band gap energy will simply be absorbed as heat in the solar cell. In the case of sunlight, covering the yellow and green spectra efficiently suggests the use of 1.4 eV to optimize the conversion efficiency in a single-junction device.¹⁸

Band gap matching the narrowband phosphor optical output to the PV material band gap (E_g) creates an optimum design. The Si PV (1.1-eV band gap) is most available commercially and offered in many formats including crystalline amorphous, thin film, etc. GaAs thin-film devices with a band gap of 1.4 eV are becoming more available as indoor PV sensor technologies are increasing in use. Indium gallium phosphide (InGaP) has a band gap of 1.9 eV, which offers the closest match to the phosphor used in the tritium vials. The ZnS phosphor emits a 528 ± 40 nm green spectrum (2.375 ± 0.475 eV).

The excess energy of the incoming photon compared to the energy that can be electrically converted in the semiconductor across the band gap is thermalization loss. For an Si PV, the loss amounts to 53% because the 528-nm photon energy is 1.275 eV greater than the Si band gap of 1.1 eV. By using GaAs- and InGaP-based PVs, the thermalization losses are reduced to 41% and 20%, respectively.

The key to high efficiency is to separate the charge carriers in the junction and collect these charges at the terminals of the cell without excessive recombination. Recombination occurs when the charge carriers encounter a defect or trap due to crystal defects on their way through the semiconductor. This requires that we choose high-performance PV cells with high mobility. Theoretically, high efficiency solar spectrum single-junction PV could be made of Si with a lower band gap of 1.1 eV, but the larger photocurrent generated is limited by its low voltage and high recombination.¹⁹ Our goal for this inexpensive first-prototype is to use commercial-off-the-shelf (COTS) cells. Our choices are limited to market dominated solutions. Our expectation was to use space-grade, multi-junction PV cells for our system. It was based on our expectations that the layer with the correct band gap for our narrowband light source would generate the photocurrents needed at the highest efficiency possible.

PV inefficiency (fabrication and materials) presented our team with many challenges in the development of the tritium power source. Commercial and experimental PV cells were tested with the expectation that we could determine a successful PV cell from a few experimental observations. This approach led to the purchase of several PV cells composed of differing materials and fabrication processes. In all cases, PV cells that performed well in standard AM1.5 solar spectrum and intensity were completely ineffective for the monochromatic light at 10^{-5} sun illumination (Fig. 4). Motivated by the use of indoor PVs for sensor applications, measurements as low as 10^{-3} suns have yielded a nonlinear decrease in efficiency with decreased intensity.^{20,21}

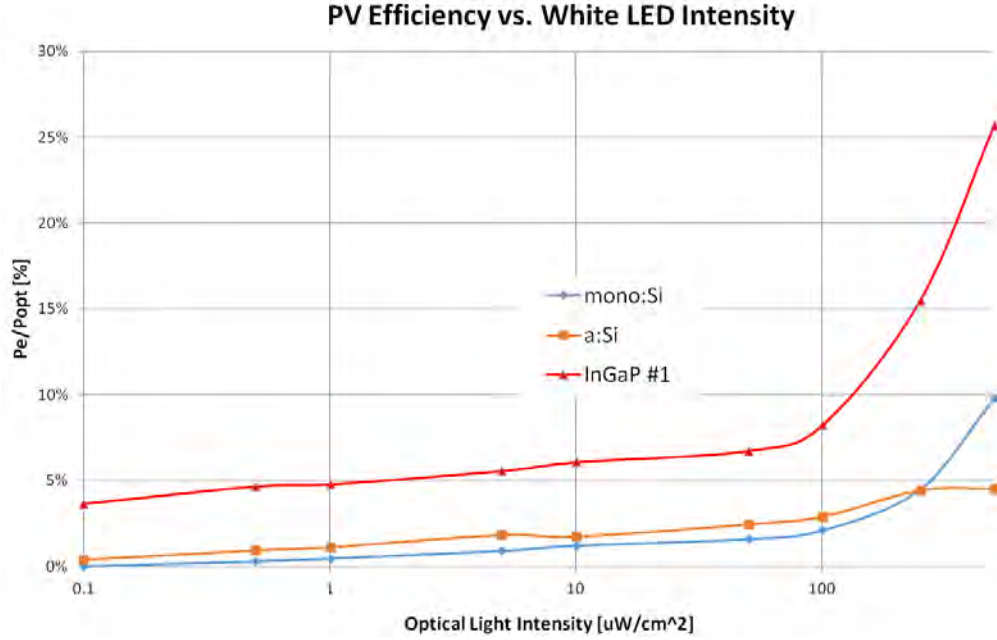


Fig. 4 Efficiency of PV materials as a function of band gap and light intensity

The green light generated by the ZnS:silver (Ag) phosphor in the tritium capsules was not always a spectral match to all PV cells. We discovered that space-grade heterojunction PV cells (multi-junction) were almost useless in monochromatic light (± 40 nm) because all junctions were not turned on. Our investigation then expanded to thin-film amorphous Si PV cells and wide band gap, single-junction cells made of GaAs and InGaP. The amorphous Si cells offered broader spectral response and the GaAs cells promised high quantum efficiency and reduced thermalization loss at the 528-nm green light region.²²

4.2 Sensor System Results and Performance Measurements

Continued reduction of energy consumption in the ROC sensor is limited by several factors. The most significant is the power requirement for the 30-V avalanche photodiode (220 μW). After evaluation of several boost converter power supplies that support 3.3 to 30 V, we were able to reduce power consumption but only to a level that was several orders of magnitude above the average power delivery of the isotope battery.

This necessitates the periodic shutdown of the sensor so that power consumption could drop from an average of 101.5 mW to a sleep-mode level of 22.7 μW . Periodically, the radio must be activated, which increases power consumption up to 44 mW. The overall result is that continuous radiation measurement cannot be performed and must instead be triggered by a different, lower power (or passive) environmental sensor. Thus event-driven detection was implemented through the

use of passive interrupts to the microprocessor by a passive antenna and vibration sensor.

Detrimental to our radiation detection range is the fact that all low-power boost converters operate in burst-type mode that minimizes power consumption at the expense of signal quality and voltage regulation. In our case, the 300-mV ripple of our DC/DC converter creates a 30% reduction in range of minimum detectable activity, limiting the detection range from 3 to 2 m. This ripple may be removed through capacitive filtering.

5. Conclusions

We have designed and built a 20- μ W power source prototype that is easily scaled to 100- μ W electrical output by adding more cassettes into the enclosure. The components are commercially available and when fully assembled represent a practical device for field demonstration. As discussed, this prototype does not use the highest energy density isotope nor is it the most compact configuration, but it does represent a first step in fabricating and licensing a device that can be taken into the field for evaluation in a sensor/communications application. This is an important step as it is not simply an evolutionary increase in battery capacity. An isotope power source creates entirely new long-lived capabilities not accessible in chemical power sources.

The isotope power source design is simple, modular, and feasible for use in long-lived applications that include environmental awareness. The self-identifying package features allow the battery to be easily assembled on location. The materials used in the battery provide protection from mechanical shock and the environment (sand, dirt, water, etc.). The limitations in total power and efficiency in this device, imposed on the design by using all commercially available components, will be explored further by a continued market survey for high intensity phosphors and lower leakage thin-film PVs.

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List of Symbols, Abbreviations, and Acronyms

^3H	tritium
ABS	acrylonitrile butadiene styrene
Ag	silver
COTS	commercial-off-the-shelf
DEC	direct energy conversion
DOT	Department of Transportation
E-field	electric field
EH	electron-hole
EM	electromagnetic
GaAs	gallium arsenide
GPS	global positioning system
InGaP	indium gallium phosphide
LPM	low power mode
MOSFET	metal-oxide-semiconductor field-effect transistor
Ni	nickel
NRC	Nuclear Regulatory Commission
PCB	printed circuit board
Pt	platinum
Pu	plutonium
PV	photovoltaic
Ra	radium
RF	radio frequency
ROC	radiation observations with communications
RTG	radio-thermal generators

Si	silicon
Sm	samarium
Sn	tin
Tb	terbium
U	uranium
ZnS	zinc sulfide

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