Non-Solar Photovoltaics for Small Space Missions

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ABSTRACT

NASA has missions planned to targets in the solar system ranging from the permanently shadowed craters of Mercury to the icy reaches of the Kuiper belt and beyond. In 2011, the NASA Office of the Chief Technologist (OCT) requested the NASA Ames and Glenn Research Centers to assess the potential of small power supplies based on direct conversion of energy from radioisotope sources for future NASA missions; and in particular to assess whether alphavoltaic and betavoltaic power sources could be of potential benefit in small missions, as well as examining the use of miniaturized thermophotovoltaic power supplies. This paper summarizes the results of that assessment.

INTRODUCTION

In 2011, the NASA Office of the Chief Technologist (OCT) requested the NASA Ames and Glenn Research Centers jointly conduct an assessment of the potential of small power supplies based on direct conversion of energy from radioisotope sources for future NASA missions; and in particular to assess whether alphavoltaic and betavoltaic power sources could have potential uses in small missions, as well as examining the potential use of miniaturized thermophotovoltaic power supplies. Thus, the motivation of this study is to study the potential of small radioisotope sources as *amplifying* and/or *enabling* technology for future missions

THE CHALLENGES OF FUTURE MISSIONS

NASA has missions planned to exciting targets in the solar system, ranging from the permanently shadowed craters of Mercury to the icy reaches of the Kuiper belt and beyond [1]. A trend for future scientific probes has been the "nanosatellite revolution," in which probe concepts take advantage of miniaturized electronics and spacecraft component to allow much smaller spacecraft designs than previous mission concepts, such as the 10 cm "CubeSat," and smaller micro- and nano-spacecraft. A key technology for the application of nanosatellite concepts to future probes is the development of small power systems.

Many of these proposed missions go to environments in which solar energy is only intermittently available (*e.g.*, probes to the polar caps of Mars, where the winter is nearly an Earth year long), or has very low intensity (*e.g.,* the moons of Saturn; the Kuiper belt). Some of these missions may be targeted to regions where there is no solar power at all, such as missions drilling below the surface of Mars, melting through the ice layer of Europa, or roving into permanently-shadowed craters of the Moon and Mercury. These nanoprobes may be too small to use conventional radioisotope power systems, but require only a small amount of electrical power.

Figure 1 shows one example mission for which such a nonconventional power supply would be enabling, a Mars penetrator microprobe. The microprobe enters the Mars atmosphere with a heat shield, but dispenses with the conventional landing system of a parachute and braking rockets or airbags; instead it impacts at an entry velocity of 180 to 200 meters per second and penetrates through the Martian soil to probe the subsurface. A small portion of the probe remains at (or near) the surface to allow a radio signal to a communications relay. The penetrator section will experience a deceleration of 300,000 m/s^2 (30,000 g), and penetrate between 0.2 and 0.5 m, depending primarily on the ice content of the soil. The power source for such a penetrator thus must be extremely rugged, and also capable of operating without solar input. Existing designs for such a microprobe allow only a few days of operation, based on a primary battery [2], but proposals for future missions have proposed using this penetrator technique to put a network of tens of weather stations across the surface of Mars [3], where they would operate for a period of one Martian year in order to give a global weather picture, giving Mars climate models an accurate "ground truth" on which to check the accuracy of the modeling.

Such penetrators have been proposed as a low-cost alternative to conventional landing systems not only for Mars, but as a means to place a network of seismometers on the moon [4], and for probes to asteroids, comets, and the surfaces of the icy satellites of Jupiter, Saturn, and Uranus. Many of these applications are for missions to low temperature environments, ranging from Martian low temperatures of -100 to -150°C, down to cryogenic temperatures on the icy moons. In addition to ruggedness, the capability of devices to operate in environments that are low- or no-light, and low temperature, is a significant operating advantage.

A robust, non-solar power system would be an enabling technology for a wide variety of low-cost missions.

TECHNOLOGIES

NASA is investigating the use of non-solar photovoltaic systems, which convert power from radioisotope decay into usable power. These systems include alphavoltaic converters, where the photovoltaic element produces power from the ionization trail of high-energy alpha particles; betavoltaic converters, where the photovoltaic converter produces power from a beta-emitting source, and thermophotovoltaic conversion, where heat of an isotope source is converted into electricity by an infrared-sensitive photovoltaic cell.

We define the following terms:

A Radioisotope Voltaic (RV) device is defined as a device that uses a semiconductor to generate electric power from a radioisotope source.

Types of energy generation using radioisotopes:

- *Betavoltaic*: a device in which a radioactive substance that emits energetic electrons ("beta particles") is coupled to a semiconductor p/n junction diode or solar cell. (Typical source: ^{3}H) . Beta particles need minimum shielding for containment compared to many other radioactive sources
- *Alphavoltaic*: a device in which a radioactive source that emits energetic alpha particles is coupled to a semiconductor p/n junction diode or solar cell to convert the energy. (Typical source: ^{241}Am)
- *Thermophotovoltaic (TPV)*: a device with the capacity to convert infrared radiation (*e.g.,* from a hot radioisotope source) into electricity through the use of a semiconductor p/n junction. (Typical source: ^{238}Pu)
- *Thermoelectric*: a device using the temperature differential between the hot and cold sides of a material to generate power. (Typical source: ^{238}Pu)

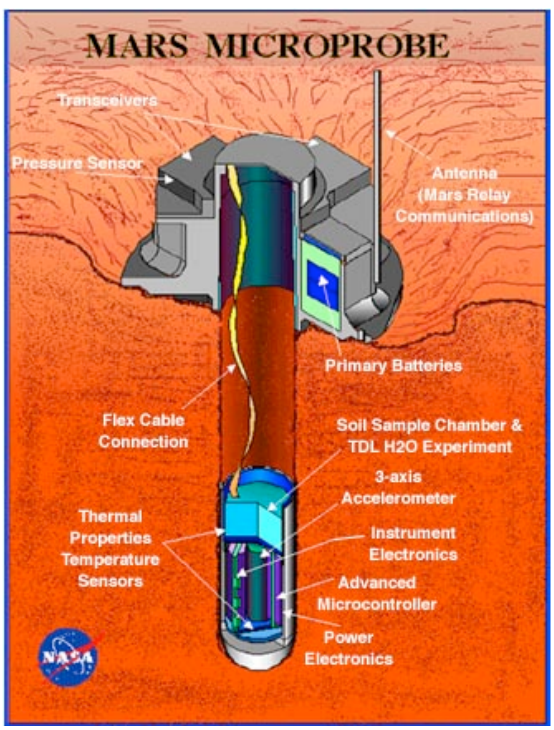

Figure 1: Mars microprobe penetrator [2].

BETAVOLTAICS

The first of the direct conversion technologies, the betavoltaic cell, was first described by Rappaport in 1954 [5]. In a conventional solar cell, a photon from the sun is absorbed the semiconductor to produce an electron-hole pair. In a betavoltaic converter, the electron-hole pairs are produced from the ionization trail of a high-energy electron, which is produced by a radioactive isotope that exhibits by beta-decay, the emission of an electron (or "beta particle"). Thus, the photovoltaic converter produces power from a beta-emitting source. Although in general a solar photon will produce at most one electron-hole pair, a high-energy electron travelling through a semiconductor can produce an ionization trail with thousands of electron hole pairs, depending on the energy.

Early betavoltaic batteries were made using the beta-emitting isotope Prometheum-147, with a half-life of 2.6 years. This technology was developed as long-lived power supplies for implantable pacemakers between 1968 and 1974 [6]. Devices made in the 1970s had beginning of life power levels of hundreds of microwatts. Other beta-emitters investigated include Strontium-90, Nickel-63 and Cobalt-60. The efficiencies of these devices were approximately 2% and typically used only a small amount of the radioisotope [7]. The major limitations for expanding use of such power sources were their low efficiencies, the cost of the radioisotope and the lifetime of the device. The design of radioisotope batteries involves a complex set of tradeoffs between isotope availability and cost, safety, specific power, decay products, semiconductor material and physical device design.

The bandgap of a betavoltaic device need not be matched to the solar spectrum, since the beta emission energies of many keV are high enough to produce an ionization trail in a semiconductor of any bandgap. Compared to solar devices, betavoltaic devices operate at extremely low short-circuit current densities, typically fractions of a microamp per square centimeter. Hence, to achieve high fill factors and minimize the dark current, wide bandgap semiconductors are preferable [6,8,9,10]. Higher bandgap semiconductors also mean that the devices operate with performance independent of temperature, meaning that, in principle, a betavoltaic power supply with a high bandgap converter such as SiC would operate as well on the surface of Venus, at 450°C, as it would on the Earth.

Electron-hole pair production is also independent of whether the bandgap is direct or indirect, and hence the longer diffusion lengths of indirect semiconductors are also preferable.

Current technologies for beta-decay source focus on the use of tritium (^{3}H), which decays into ^{3}He with the emission of an electron with an average energy of 5.7 keV and a maximum energy of ~19 keV. Tritium has a half-live of 12.3 years, which is suitable for the operational lifetime of many space missions. While the low energy of emission from Tritium minimizes radiation damage in the semiconductor, it means that self absorption is significant.

The maximum power density from gaseous tritium gas is 14 μW/cm^2; above this point, increasing the density does not increase power. Other forms of tritium, such as tritiated polymers, have lower power density.

Tritium betavoltaic power supplies are now beginning to become commercialized [11,12,13], with several providers at, or about to enter the market. These power supplies are lightweight and extremely rugged, since the isotope and the converter are typically integrated, and are being manufactured in the form of semiconductor packages in the size and form of an integrated circuit chip, suitable for being integrated directly onto a circuit board [9]. Available devices have power levels slightly less than one microwatt at beginning of life (BOL), with prototype devices at levels of fifty microwatts and higher BOL in progress but not yet in production.

Another device just reaching commercialization utilizes a silicon carbide semiconductor with Krypton-85 isotope source to generate power. ^{85}Kr has a half life of 10.8 years, and an average emission energy of 251 keV. The isotope Promethium-147 (^{147}Pm), with a higher activity but a half-life of only 2.6 years, can also be used to deliver higher power in a smaller package.

A technology that may be useful in the future is the use of liquid semiconductors in betavoltaic devices. Liquid semiconductors have the advantage of being unaffected by radiation damage, and a liquid-selenium based device has been demonstrated, using a ^{35}S isotope source with a half-life of 87.2 days, although so far only at very low power levels [14].

Looking at the trends over the past decades, there does not appear to be a major increase in power density for any direct conversion technology. There has been a continuous slight gradual increase in overall efficiency, but direct conversion devices to date perform in the range of about 5 to 10% conversion efficiency [10]. The best currently reported direct beta device, using a tritium source, has an estimated specific power of about 0.167 W/kg. This is about the same specific power as solar panels at the distance of Uranus.

As an example, a 1-kg CubeSat requiring around one watt of power would require a betavoltaic power source of roughly 6 kg of mass, at an estimated cost of around 3 million dollars. Betavoltaic devices are likely to be most useful for applications for power on the order of milliwatts. Their primary advantage is that they can be made extremely small, and are mostly unaffected by environmental extremes, including temperature and g-loading. The typical mission use of such a device would be to produce a much smaller power level, using the betavoltaic cell to charge a battery or ultracapacitor. This would then be used in “burst” mode to power a transmitter to communicate with an orbiter [3].

INDIRECT CONVERSION

As an alternative to the direct conversion of the ionization trail in a semiconductor, another method of manufacturing an alpha- or beta-voltaic device is for the radioactive decay to be absorbed in a luminescent compound. This luminescence can then be collected and converted to electricity by a more conventional photovoltaic cell. This is shown in schematic in figure 2. Tritium, for example, is often used as an excitation source for luminescence, and applications ranging from self-luminous fire exit signs to night-scopes for rifles are commercially available. The luminous intensity is low compared to sunlight, however, light-trapping techniques can be used in the device design, and the phosphor and solar cell can be optimized for monochromatic conversion, resulting in high efficiency.

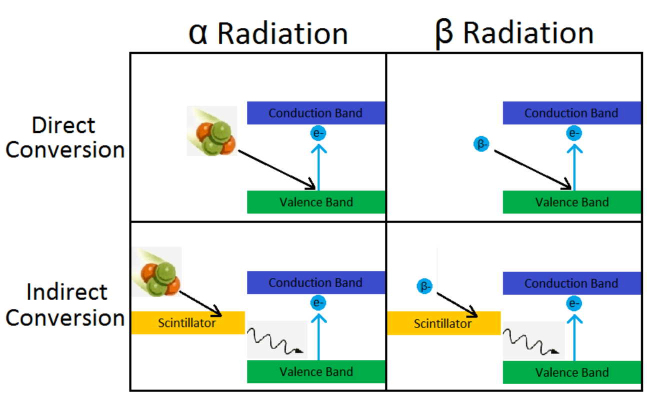

Figure 2: Direct and indirect conversion methods for alpha- and betavoltaic devices. In the direct conversion, the incident radiation directly creates electron-hole pairs in the semiconductor; while in indirect conversion, the incident radiation is absorbed by a phosphor or “scintillator”, which then emits light which is absorbed by the semiconductor.

Figure 3: Schematic of one concept for an alphavoltaic cell using the indirect conversion approach [15], in which the alpha particles produce luminescence, which is converted by the solar cell.

Another possible advantage of indirect conversion is that the semiconductor itself no longer needs to be exposed directly to the ionizing radiation of the source, and hence a device configuration can be made to minimize or eliminate radiation damage.

Conventional phosphors for radioluminescence include zinc sulfide (ZnS) as well as rare-Earth element oxides. An alternate phosphor is the use of semiconductor quantum dots. The use of quantum dots allows the luminescence wavelength to be finely tuned for optimum conversion. Figure 3 shows this concept in schematic.

It has also been proposed to incorporate the radioactive material directly into a thick scintillator crystal. One advantage includes the improved efficiency of the capture of the high energy emissions. These devices are in the development phase.

ALPHAVOLTAICS

A similar technology is the alphavoltaic converter, in which the ionization trail of an alpha particle, rather than an electron, is converted to electricity [15,16]. Alpha emitters such as Americium are available for use in applications such as smoke detectors, and have been flown in space.

The motivation to use alpha-emitting nuclides is the relative ease and light-weight of shielding required. At present, it is possible to construct a 5-mW/cm^3 device. If ten converter of this size are integrated, it is reasonable to believe that we could produce a useful 50-mW module. Table 1 shows candidates for alphavoltaic sources that primarily utilize the ~ 5 MeV alpha particle generated from each isotope.

Nuclide	Half Life (yrs)	Volumetric power (mW/cc)
Am-241	432.2	1,520
Pu-238	87.7	11,200
Ra-226	1600.0	140
Po-208	2.93	165,000
Pb-210	20.4	20,900
Cm-244	17.6	38,600

Table 1. Radioisotope Power and Half-life

For example, 1 Ci of Am-241 will produce 3.7×10^{10} 5.5-MeV alpha particles. If only 50% of those alpha particles are converted, that will yield 1.85×10^{16} electron hole pairs. With a 50% conversion efficiency, this could produce 3.75 mW for 433 years. A 10-mW commercially available alphavoltaic battery has a volume of less that 2 cm^3, a mass of 30 g, and energy density of greater than 50 W-hr/g and an estimated cost of between $100K to $150K.

A critical issue for alphavoltaic converters is radiation damage by the particles; this is a much more significant problem with alpha particles than with beta. One approach to minimizing this is to use radiation-tolerant semiconductors, particularly the phosphorus-containing III-V compounds or quantum dot solar cells that have shown an enhanced radiation resistance. Like betavoltaic devices, alphavoltaic conversion can also be indirect, with the use of a radioluminescent phosphor. This also allows tuning of the emitted light to the wavelength of optimum conversion efficiency. Figure 4 shows a comparison of the current produced by direct conversion of alpha radiation by an InGaP cell, to indirect conversion using a ZnS phosphor, for alpha emission from a ^{210}Po source at 10^7 alphas per second. Clearly, an optimally chosen phosphor can increase the power density.

An alternate approach is to use a suitably structured photovoltaic device shown in Figure 5, with multiple n-i-p junctions structured to minimize the collection distance and hence minimize the effect of shortened diffusion length due to radiation-induced damage. Alpha-generated minority carriers are collected in the spatially separated n and p layers of a "*nipi*" structure [15] and then be transported parallel to the layers to selective ohmic contacts.

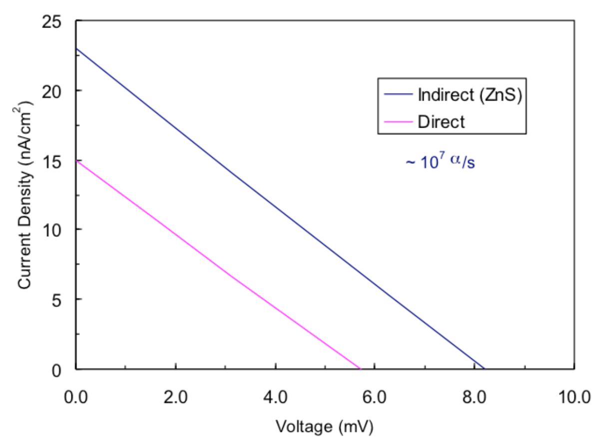

Figure 4. I-V curve for direct conversion of alpha particles to electricity by a GaInP cell, compared to indirect conversion by luminescence of ZnS quantum dots.

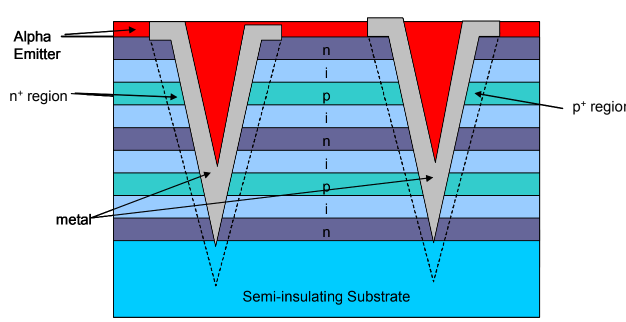

Figure 5. Cross-sectional schematic of "nipi" structured cell for alphavoltaic conversion [15]

THERMOPHOTOVOLTAIC CONVERTERS

In radioisotope thermophotovoltaic conversion, a radioisotope source produces heat. The infrared emission from the hot source is then converted by a solar cell optimized for the infrared spectrum. Typically some combination of spectrum-shaping techniques such as selective emitters, optical filters, and long-wave reflection are used to minimize the absorption of wavelengths to which the cell is not responsive.

Since they are thermal systems, rather than using direct conversion of particle energy, thermophotovoltaic conversion systems optimize for a larger power levels than alpha- or beta-voltaic conversion.

The thermophotovoltaic converters considered primarily use plutonium isotopes (^{238}Pu) as the heat source. This is the same isotope as is used for radioisotope thermoelectric generators (RTGs), although the power levels considered here are considerably lower. It raises the issue of isotope availability, since ^{238}Pu is not currently being produced in the US. While production is scheduled to be restarted, the restart depends on congressional appropriation, which may be difficult in the current budget.

For all thermal conversion technologies, a key issue is minimizing the heat loss through insulation in order to maximize the temperature of the source. Due to surface area constraints, this means that, if other considerations are the same, larger devices tend to be more efficient. The conversion efficiency also increases as the emitter temperature rises, since wider bandgap photovoltaic cells can be used as the converter.

For the infrared wavelengths used in TPV systems, the photovoltaic cells must use a low bandgap semiconductor. Cooling of the cells is a significant issue, and the devices must incorporate cooling fins, or some other approach to reject waste heat. For many of the missions of interest to low-temperature or cryogenic environments, this waste heat can be used to stabilize the temperature of spacecraft systems.

TPV systems seem to be a good choice for missions in the small power category, but still higher in power than the microwatt levels of alpha- and betavoltaic sources. NASA Glenn is developing TPV systems based on a single General-Purpose Heat Source (GPHS) ^{238}Pu source. This is designed to produce >38W (electric) at beginning of life, at a spacecraft standard bus voltage of 28V, using 0.60 eV InGaAs PV Cells with Monolithic Integrated Module (MIM) structure and a conversion efficiency of about 15%. The system is shown in figure 7. The mass of the prototype converter is about 6.78 kg.

Even smaller radioisotope TPV systems are in development at General Atomics [17], with power in the range of 100 mW to 2 watts. The smallest of these systems about the size of a small battery. Lower power devices, in the 1-100 mW range, are also being developed.

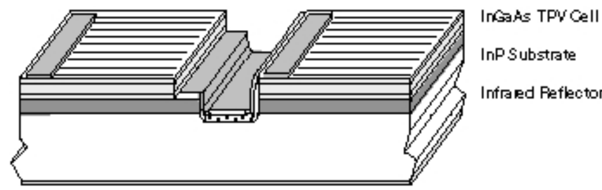

Figure 6: InGaAs thermophotovoltaic cell in the Monolithic Integrated Module (MIM) configuration, developed by NASA Glenn, incorporating a back-surface infrared reflector to reject long-wavelength photons back to the source.

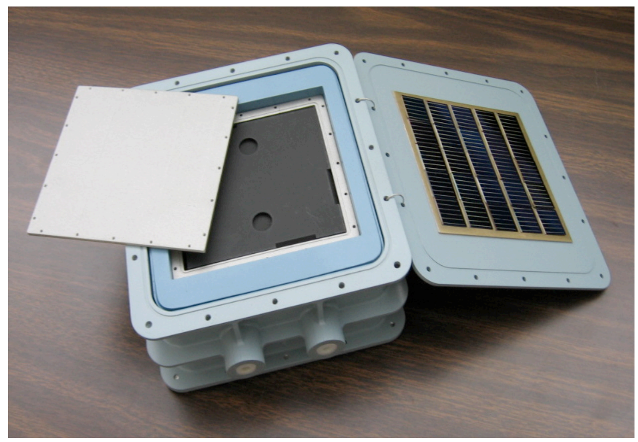

Figure 7. Small thermophotovoltaic power source, designed for operation with a single 240 $W_{(thermal)}$ GPHS unit, being developed by the GRC RTPV Technology Development Project.

A possible alternative isotope heat source, ^{241}Am, is also being considered for some applications. The Americium isotope has the disadvantage of slightly lower power levels as well as a higher neutron flux, which results in displacement damage to the semiconductor. However, the availability of ^{238}Pu as a heat source depends on production facilities that are currently not in operation, and ^{241}Am may be more easily available, since it is a byproduct of reactor operation.

ISSUES

Each of these technologies has different capabilities and different amounts of development needed. Some of the critical issues include launch safety, isotope availability, and the ruggedness of the conversion system to high-impact deployment and landing systems. Another significant issue for such direct conversion technology is the power system degradation produced by radiation-induced damage to the semiconductor.

Another significant issue is the flight approval. Approval to launch any radioisotope source rests with the executive branch. Small Americium sources, such as might be used with a betavoltaic power source, have been launched to orbit in smoke detectors on previous missions. The larger Pu sources must undergo the rigorous launch approval process used with the isotope sources used on Cassini or Mars Science Laboratory. This process is designed to ensure that even in a worst-case launch accident, the isotope source will remain intact and source material will not be dispersed into the Earth's environment. For this reason, radioisotope sources are encapsulated in highly-durable ceramic casings, allowing intact re-entry even for an entry into the Earth's atmosphere at orbital velocities.

CONCLUSIONS

"Photovoltaics" are not always synonymous with "solar energy," and non-solar photovoltaic technologies, including alphavoltaic, betavoltaic, and thermophotovoltaic conversion, may have distinct advantages as the power source for future NASA missions. Betavoltaic and alphavoltaic power supplies are beginning to reach the commercial market, with several suppliers bringing out product in the next few years. These power supplies are lightweight and extremely rugged, sufficient to produce power at the microwatt to milliwatt level, which may be enough to trickle-charge small batteries or capacitors for brief low-power transmission of data from a small probe to a nearby relay, but would not be sufficient to power a conventional mission. Radioisotope thermophotovoltaic power supplies fill in a slightly higher power range, in the 1-100 watt range, which may be suitable for small missions to regions with no availability of solar power.

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