

Nuclear Batteries: Harnessing Energy of Radioactive Materials for Long Lasting Low Power Applications

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Abstract

Nuclear batteries are devices that generate electric power by harnessing the energy of particles (alpha or beta) and radiations (gamma) emitted during nuclear decay. Interest in these batteries has been driven by a prospect of long-life, high energy density and applicability in extreme conditions where refuelling/battery replacement may be unviable. The term nuclear battery encompasses a variety of devices such as thermoelectric, thermophotovoltaic, scintillation intermediates, and those based on direct energy conversion like alphavoltaic/betavoltaic, each with unique advantages and limitations. While these applications have been well known, interest in these devices has waxed and waned over the years due to challenges associated with energy conversion devices, reduced operating-life due to radiation damage, limited supply of radioisotopes and design complexities. However, nuclear batteries are seeing a renaissance as “sustained low power sources” for various applications. The present article explores nuclear batteries, a field where interest has varied over the decades and is witnessing a new resurgence. Harnessing the concept of wealth from waste, nuclear batteries using

radionuclides from nuclear waste promise sustained power sources for various low power applications.

Keywords: Nuclear battery, alphavoltaic, betavoltaic, radioisotope thermoelectric generator

1. Nuclear batteries

Nuclear batteries convert the energy of radioactive decay into electrical energy [1]. The primary attraction of nuclear batteries remains their potentially long operational life, making them suitable for applications where recharging and/or refuelling is not viable. Unlike nuclear reactors, nuclear batteries do not rely upon nuclear fission for power production.

Radioisotope decay can be harnessed to yield electricity using either thermal or non-thermal conversion as depicted in Figure 1. Indeed, all nuclear batteries require energy conversion devices such as thermoelectric, thermo-photoelectric, scintillation intermediates or those designed for direct radiation energy conversion. Of course, the use of such conversion devices reduces efficiency, which together with low energy density in comparison to chemical batteries limits their application. There is also the acceptability constraint of having nuclear materials in the public domain. The advent of high energy density, relatively long life Li-ion based battery packs had also diverted interest away from nuclear batteries. Nevertheless, nuclear batteries remain attractive for applications where sustained power sources are de-rigueur such as remote applications, exoplanetary probes and vehicles, sensors for remote areas such as pack ice monitoring units near the poles etc. where frequent battery/power source replacement is unviable as mentioned previously. More recently, nuclear waste is available as a promising and abundant source of radionuclides with potential battery applications.

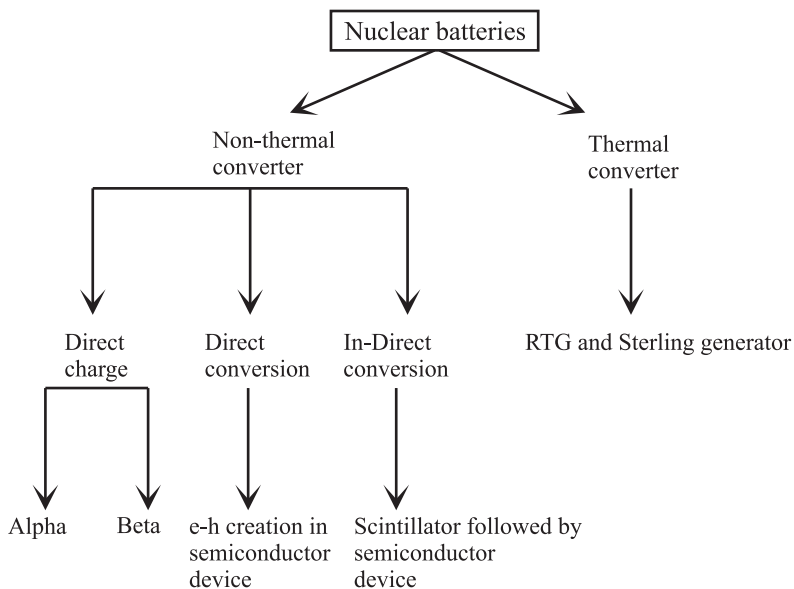


Figure 1: Different types of nuclear batteries

2. Conversion of radioactive energy

Nuclear batteries allow direct harnessing of nuclear energy from radioactive decay and can be thermal or non-thermal as presented in Figure 1. A breakthrough in harnessing the decay heat produced by a radioisotope towards generation of electricity occurred in 1954 when Kenneth Jordan and John Birden (Mound laboratories, USA) constructed a device that exploited the Seebeck effect (i.e., development of a voltage difference when junctions of two dissimilar metals are kept at different temperatures). The patent they received for the use of thermocouple principle has been the basis of all subsequent Radioisotope Thermoelectric Generators (RTG)[2]. By virtue of having no moving parts, RTGs have high reliability and long service life. The fundamental building block of a RTG is a radioactive heat source (alpha emitter) and thermoelectric converter based on semiconductors. RTGs, like usual thermoelectric power generators, comprise a large number of p - n legs that are serially connected to add the voltage produced by each leg and placed thermally in parallel so that each leg faces a uniform temperature gradient. Design of a typical thermoelectric power generator (TEG) consisting of one p - n leg is shown in Figure 2(a). When a temperature difference is maintained between both the ends of a RTG, charge carriers in both p - and n - thermoelements move from hot-end to the cold-end; this separation of charge carriers generates a voltage that can be used to provide power. However, to create a sufficiently high temperature difference at both the ends, a large amount of radioactive material is required in RTGs, which restricts the usage of RTG in commercial applications. The energy conversion efficiency of a RTG depends upon properties of constituent's p - and n -type material as well as on the temperature difference and in best cases it can reach up to 8-10%. An efficiency of 6% (equivalent to that reported by NASA, US) has been achieved in case of modules developed with n -PbTe and p -TAGS 85 alloys as thermoelements. A linear shaped TEG based on these thermoelements is shown in Figure 2(b). The concept of using radioactive material such as the alpha emitter Am-241 (that is recovered from partitioning of high level liquid waste) as a heat source in these TEGs is also a focus of on-going research at BARC, Mumbai (Figure 3).

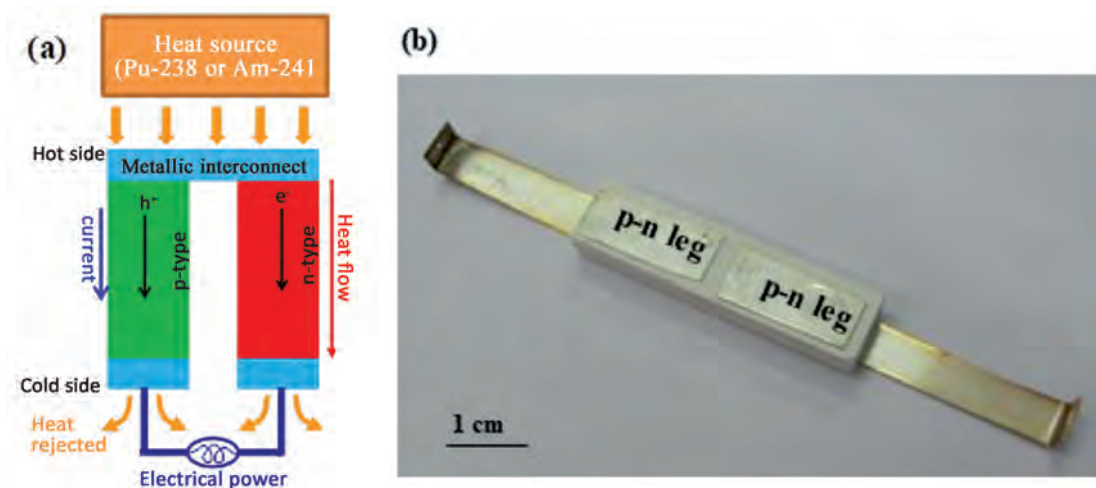


Figure 2: (a) Schematic showing working of a Radioisotope Thermoelectric Generator (RTG) with an alpha emitter such as Am-241 as heat source, (b) Photograph of a linear shaped TEG developed at BARC with n -PbTe and p -TAGS 85 semiconducting alloys as thermo-elements.

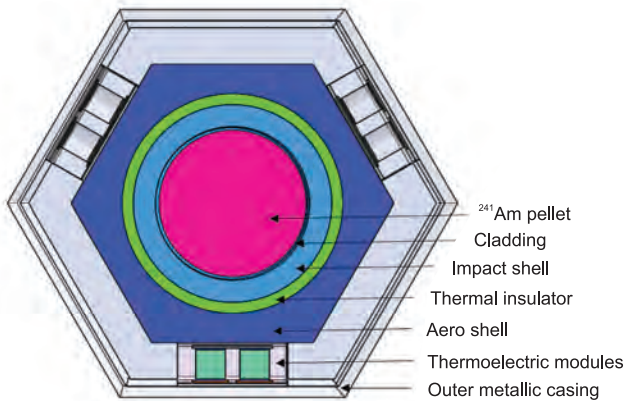


Figure 3: Configuration of an RTG based on Am-241 (left), RTG assembly (right)

Alternately, in *non-thermal convertors*, radiation energy is tapped via two ways: direct and indirect. Non-thermal (indirect) convertors harvest the energy of the radioisotope into electrical power in two steps. In the first approach, the alpha- or beta- particles originating from the radioactive material fall on a scintillator to produce photons, and using a photovoltaic device, the photons in turn are converted to electricity. In this approach, the spectral response of the scintillator and the photovoltaic device must be carefully matched for obtaining high conversion efficiency. In this case, battery life depends on the half-life of a radioisotope as well the stability of the photo luminescent material under high energy radiation. Indeed, the latter limits device life more often than the former. Non-thermal indirect conversion becomes more significant when the decay involves emission of high energy particles.

In case of non-thermal (direct) convertor, the radioactive particles falling on a semiconductor device directly creates electrical current. Typical methods include the betavoltaic effect. The

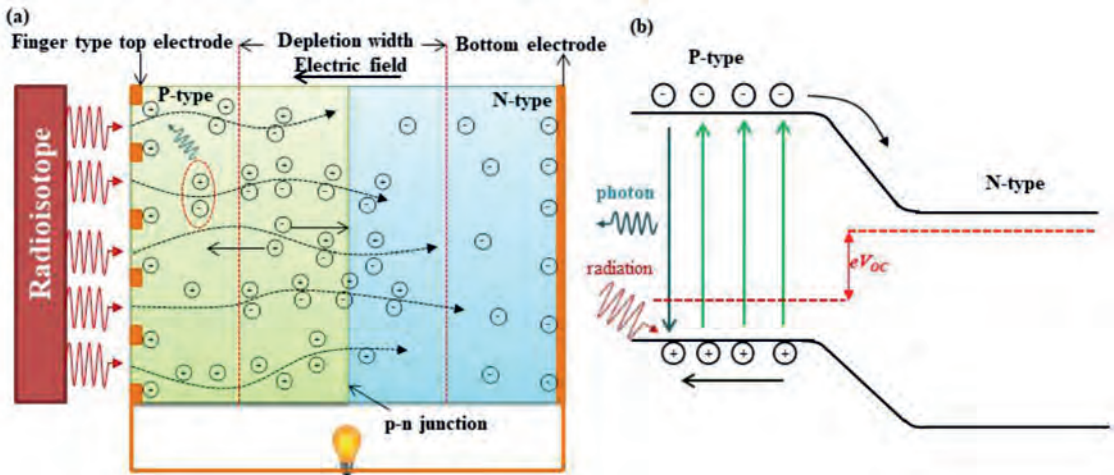


Figure 4: (a) Schematic showing a p-n junction based betavoltaic battery where radiation generates electron-hole pair and built-in electric field in the depletion region provides a driving force for current to flow (b) the band diagram demonstrating the betavoltaic process

working principle of betavoltaic convertor is very similar to that of photovoltaic cells (as shown in Figure 4), and it consist of a semiconductor p-n junction and a beta source. The beta particle falling on the semiconductor junction creates electron hole pairs and it gets separated by the built-in electric field at the junction (consequently generating current). Some of electron-hole pairs recombine again and leads to the radiative losses in the betavoltaic device. Most of the semiconductor junction devices have electron–hole collection efficiency of $\sim 50\%$.

Experiments studying non-thermal conversion at BARC involve both direct and indirect approaches and have been carried with electrodeposited ^{106}Ru source (with a half-life of 1.02 y and emitting beta particles having average energy of 1.6 MeV). The ^{106}Ru used was recovered from high level liquid waste. This radioactive material layer is sandwiched between two p-n junction devices connected either in series or in parallel. Ce-doped $\text{Gd}_3\text{Ga}_3\text{Al}_2\text{O}_{12}$ (GGAG) single crystal scintillator grown at BARC, Mumbai was used in Ru-battery for generation of photons using energy of Ru decay. Figure 5 shows the device in two configurations *i.e.* without scintillator (Device-1): direct conversion and with scintillator (Device-2): indirect conversion. The electrical output of both these devices is shown in Figure 5(d). From this experiment the research group conclusively proved that in case of beta particles having high average energy ($\sim \text{MeV}$), a scintillator in between the semiconductor converter and radioactive source is mandatory to avoid degradation of the semiconductor device.

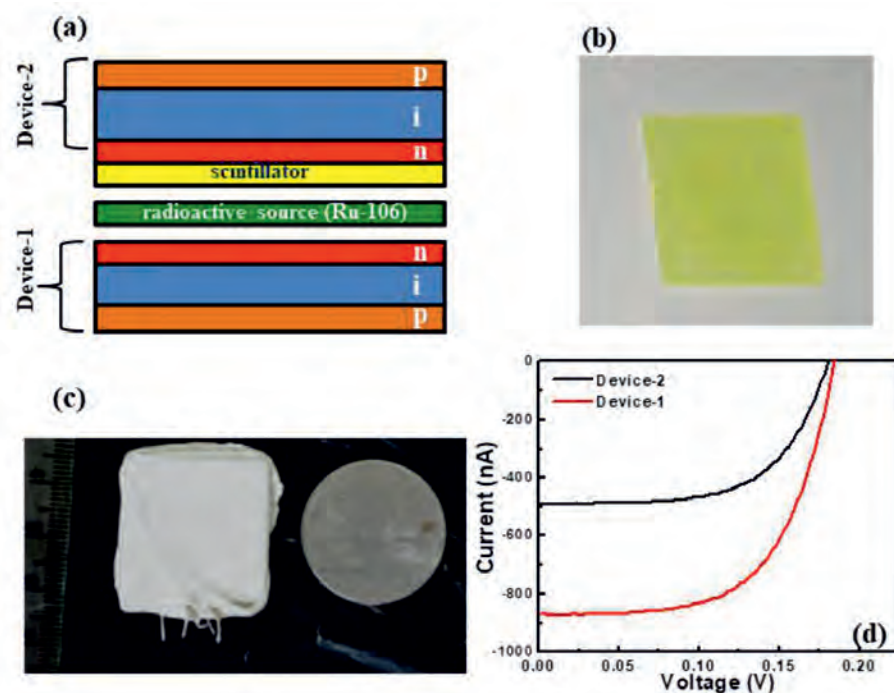


Figure 5: Betavoltaic device development work at BARC (a) Schematic showing two different configuration of betavoltaic device with (device-2) and without scintillator (device-1) between source and device, (b) Ce doped GGAG single crystal scintillator grown at BARC, (c) Photograph of the prototype betavoltaic power source using electro-deposited Ru-106 source of 3 mCi strength, (d) Current-voltage characteristics of device in both configurations.

3. Suitable radioisotopes for nuclear batteries

Choice of a radioisotope material is very significant while designing and developing a nuclear battery. Typically, the radioisotopes chosen for nuclear battery applications are preferably alpha or beta emitters. The beta emitters are usually the choice for non-thermal type converter.

In contrast, alpha emitters are preferred in case of thermal conversion, where the high energy alpha particle generates heat upon hitting the walls of a metallic container, which can then be used to generate electricity. Alpha particles, being massive, generate radiation induced damage in the converter material, reducing their utility and hence popularity. Moreover, proper shielding is needed against Bremsstrahlung and (alpha, n) reactions. Gamma emitters are generally avoided as a source in nuclear battery to preclude bulky shielding requirements. Table 1 shows some typical alpha- and beta- emitting radionuclides that are being widely used for battery applications.

Table 1: Typical radioisotopes used for nuclear battery applications

Radioisotopes	Type	Average energy of emitted radiation (keV)	Half life (year)	Specific activity (Ci/g)	Specific Power (W/g)
⁶³ Ni	β	17	100	57	0.0067
³ H	β	5.7	12	9700	0.33
⁹⁰ Sr/ ⁹⁰ Y	β	200/940	29/2	140	0.98
¹⁴ C	β	156.5	5730	4.5	0.004
¹⁴⁷ Pm	β	61.9	2.62	800	0.29
²¹⁰ Po	β	5300	0.38	4500	140
²³⁸ Pu	α	5500	88	17	0.56
²⁴¹ Am	α, γ	5500	432	2.91	0.097

From Table 1, it can be observed that the half-life and specific power of radioactive source are inversely correlated. Therefore, optimization of specific power and operational life is important for making a selection of a suitable radioisotope. It is evident from Table 1 that although Sr-90 seems to be a promising radioisotope with synergetic combination of both specific activity and specific power, the average energy of the beta particles emitted by Y-90 exceeds the displacement energy of Si atoms (~400 keV) in commonly used semiconductor material. Consequently, direct use of Sr-90 as a betavoltaic source leads to significant reduction of battery life. Nevertheless, these sources have been used to power remote light houses in Soviet Russia. Such high beta energy produces Bremsstrahlung, necessitating heavy shielding. However, for most remote terrestrial applications, weight is not a significant limitation. In addition; incidents of pilferage of the sources and accidental exposure on breaching the containment have resulted in the withdrawal of these sources from active operation.

4. Issues of Concern, Constraints and Challenges

The process of conversion of energy of an alpha/beta particles into electron hole pair involves certain losses. The imperfection in the semiconductor device can trap the excited electrons and accelerate the recombination of generated electron-hole pairs to produce a photon. In addition the inelastic scattering of beta particles may also result in the heating of the semiconductor device. Therefore, engineering of the material in terms of improving crystallinity

for reducing losses by minimizing the dark as well as surface leakage current through the semiconductor device becomes a primary requirement to obtain the high conversion efficiency. The performance of nuclear batteries depends not only on the isotope used but also on the radiation transport properties and energy conversion devices. Energy conversion devices must be efficient and compatible to convert energy of nuclear decay products such as alpha particles, beta particles etc. into electrical energy. The converter device based on compound semiconductors (III-V materials) like GaAs, InGaP etc. are preferred for betavoltaic application due to their high threshold energy for damage as well as tunable band-structure. By improving the semiconductor crystallinity and reducing the surface leakage the conversion efficiency for a single converter device can reach 30%. The product of source efficiency and semiconductor conversion efficiencies can reach 10%, but experimentally observed efficiencies are usually < 2%. The performance of these materials depends more on the degradation (of the material) upon irradiation rather than the half-life because the process of degradation is faster than the radioactive decay; like in case of RTGs. Despite that betavoltaic batteries show promise as 'on-chip' batteries because they can be made small, reliable and have very long lifetimes. It is pertinent to mention that the research on nuclear batteries has once again gained momentum in recent years due to focus on long-lived devices and the push towards miniaturization. Table 2 summarizes some of the main comparisons between betavoltaic and chemical batteries.

Table 2: Comparison of a betavoltaic and chemical battery

Parameters of betavoltaic battery	Parameters of Chemical battery
Performance Life time: Quite Long, can be 15 - 20 years	Performance Life time: Short, typically ≤ 3 years
Operational under extreme temperatures from -40°C to 80°C	Performance diminished at extreme temperatures
Thermally & Environmentally independent lifetime, corrosion resistant	Lifetime susceptibility to extreme temperatures, humidity & corrosive environments
Suitable for low power robust applications (nW - μW), however in Power burst mode it can deliver mW	Suitable for higher power applications with power requirement in mW – W range

It can be concluded that nuclear batteries have great potential in powering small devices for prolonged periods; diverse applications include long-life sensors for remote sensing, animal tracking, and remote/military low power communications. However, smaller dimensions of devices require careful matching of length scales between the range of the radiation in the conversion material and the thickness of the conversion material used for the device. Such a matching is possible through comprehensive modelling approaches and thus, can result in improved devices.

5. Potential applications

Nuclear batteries are known as useful power sources since past many decades. In the 1970s it has been used as power source for cardiac pacemakers but after the development of lithium-ion batteries their demand has decreased. However, the nuclear batteries are still being used in crucial defense applications. In spite of length scale mismatch issues i.e. penetration depth of alpha/beta particles and the thickness of semiconductor device the development of nuclear battery in micro and nano-dimensions was initially started (60 years back) by the Radio Corporation of America (RCA). Later Sandia lab in the 1960s developed a direct charge nuclear

battery (DCNB) which could produce an electrical output of 20 kV and currents in nA range using Kr-85 radioactive source. While, as a part of ongoing research programme since 2005, City lab Inc (a US based firm) has developed commercially available tritium betavoltaic battery (life time ~ 20 years) producing few hundred nW to μ W power and finding use in diverse applications including environmental pressure/temperature sensors, intelligence sensors, medical implants, trickle charging lithium batteries, RFIDs (radio frequency identification), silicon clocks, SRAM memory backup, deep-sea oil well sensors and lower power processors (e.g. ASICs, FPGAs, Micro Controller Units). It is important to mention that the P100 model of city labs that uses 225mCi of H-3 has typical open circuit voltage of 0.8 V, current ~60 nA. For higher current, the company offers other model P200 that uses 100 Ci of H-3 with typical open circuit voltage of 0.8 V, current ~ 165 μ A and power ~100 μ W. Some of the specialized applications for which nuclear batteries can serve as promising and reliable power sources are discussed as follows:

5.1 Power source for deep space mission

Space missions are in continuous search of promising alternative energy conversion technology to solar cells for deep space exploration (i.e. planets Mars and beyond it in the solar system), where the available solar flux is not sufficient. Hence, Radioisotope Thermal Generators (RTGs) are being used for such missions. Though RTGs can reach only upto 6% of efficiency, they are reliable and have been extensively flight tested. In addition radioisotope based heating unit (RHU) is also used to keep optimal thermal environment for various electronic components used in space missions. The NASA RTG technology is based on isotope Pu-238 as the radioactive source. Due to scarcity of Pu-238 in other countries (other than USA), Am-241 is the next alpha emitter isotope of choice. Am-241 has a longer half-life than Pu-238 (433 years vs. 88 years) and thus, more mass (~5 \times) is needed to produce the same amount of activity. To support the deep space mission program of Indian Space Research Organization (ISRO), BARC has taken up an initiative to develop a power source and heating unit based on Am-241 recovered from high level liquid waste through actinide partitioning.

5.2 Defense Missions

For various defense missions there is a need for portable and long lived power sources. Technical advancement has made battlefields more complex and digital with new and advanced technologies that include Global Positioning System (GPS), night vision, radio communications, smart-phones, tablets, helmet mounted screens, imaging devices, laser guided weapons, arrays of sensors, drones, robotmules, and wireless devices. Such devices and technologies need a sustained and reliable power supplies. Therefore, nuclear batteries serving as continuous sources of power can really be useful in the defence sector. Moreover, nuclear batteries if designed to micro/nano scales can result in compact and light weight modules that can be easily transported and carried by soldiers for their military operations.

6. Summary

The present article gives a brief account on the radioactive material based nuclear batteries. Research on nuclear batteries from the ancient times highlights them as a promising technology for tapping the energy of radioactive materials. The nuclear batteries besides offering a solution to radioactive waste can act as a 'sustained power-source' for electronic circuits and compact devices. However, their practical use demands attention toward certain issues such as efficient and compatible energy conversion materials, their capability to bear battered radiation and designing them to scale of micro- and nano-dimensions for miniaturization of devices. Different types of nuclear batteries can be deployed in specific applications. For instance radioactive

thermoelectric generators which can be loaded with a large amount of radioactive material can be used to provide power in space and remote applications. Direct and indirect conversion type nuclear batteries can provide open-circuit voltage of few volts but have efficiency of only 2%. In short, ongoing research on nuclear batteries at BARC along with advancement in technologies can potentially revolutionize energy harnessing from radioactive materials.

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