Production of Alpha and Beta Radioisotopes for Nuclear Batteries Using a Superconducting Electron Linac

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INTRODUCTION

The Defense Science Board Report on "Technology and Innovation Enablers for Superiority in 2030" identified a clear need for portable and long-lived power sources for unattended surveillance sensors, special operation missions, unmanned sea vehicles, and spacecrafts. Radioisotopes were identified as high density energy sources with "significant untapped potential" (see Fig.1).

Energy Sources	Energy Density (kilojoules per cubic centimeter)	
Solar, Wind	NA (diffuse)	Clean and abundant, with diffuse, intermittent availability Valuable supplemental sources
Electrochemical	3–5	Primary source for personal power Development driven by commercial markets
Fossil fuels	20–35	Gasoline = 35 Primary source for vehicle propulsion and power, base power
Radioisotopes	> 100,000	Significant untapped potential
Compact fission reactor	> 10,000,000	Significant untapped potential

Fig. 1. Various energy sources and corresponding energy densities [1].

Nuclear batteries generate electric current by using energy from a radioactive source emitting alpha or beta particles. Nuclear batteries can have a significantly longer shelf-life and higher energy density when compared with conventional energy storage devices. Several different mechanisms have been proposed and developed for the nuclear batteries. The simplest one is the direct conversion mechanism, similar to that used in photovoltaics, as shown in Fig. 2.

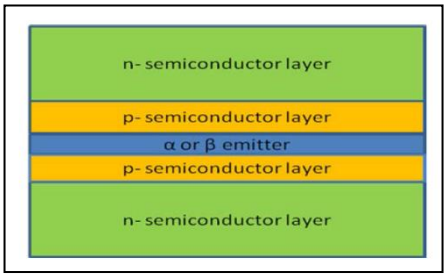

Fig. 2. Direct energy conversion mechanism: alpha, beta, or photon create electron-hole pairs in *p/n*-type semiconductor sandwich. The internal electric field generates the current flow [2].

Various radioisotopes have already been used and proposed for nuclear batteries. All the radioisotopes share some common properties including relatively long half-life (>1 year) for continuous operation, low gamma output (to minimize shielding/detection), high α/β yield, high specific activity, and chemical compatibility with semiconductor matrix material. Tritium (H-3), Ni-63, and Pm-147 have been already used. However, with their benefits, they experience drawbacks. For example, tritium emits the lowest average energy betas (~ 6 keV), but exhibits a high energy density (J/g) and is inexpensive. Pm-147 has 11.4 times higher beta energy than tritium, but has a lower energy density, and is limited and expensive as this radioisotope is exported from Russia. Ni-63 has a long half-life of 100.1 years that reduces decay fade, but has a very low energy density and is expensive to produce.

Considering the trade-offs involved with existing isotopes used for nuclear batteries, exploration into production and testing of other isotopes is warrented. There are a number of other promising radioisotopes which have suitable properties, but have not been produced historically. Among them are beta-emitters, such as Sr-90, Ru-106, Ce-144, and alpha-emitters, such as Ac-227 and Am-214. Use of alpha-emitters is still under development: while they typically produce much more energy per particle, they damage the absorber much more than beta-emitters. Properties of these radioisotopes are listed in Table 1.

Table 1. Some commonly used and newly proposed radioisotopes for nuclear batteries and their properties.

Isotope	Half-life, years	Primary Decay Mode	Average $E_{\alpha/\beta}$, MeV	E_γ, MeV
H-3	12.3	β^-	0.006	No
Ni-63	100	β^-	0.018	No
Sr-90	29	β^-	0.196	No
Ru-106	1	β^-	0.010	No
Ce-144	1	β^-	0.080	0.13
Pm-147	2.6	β^-	0.062	0.12 (weak)
Ac-227	22	α	~5*	No

Niowave formed the Nuclear Battery Consortium (NBC) which includes key players in the beta-voltaics field: Niowave, George Washington University, US Naval

Research Laboratory, US Army Research Laboratory, Naval Surface Warfare Center, Crane Division. Our collaboration is working on developing nuclear batteries based on these novel radioisotopes, which have not been tested yet.

DESCRIPTION OF WORK

Niowave's Radioisotope Production Program started as a result of the American Medical Isotope Production Act (AMIPA 2012) where the goal was two-fold: to eliminate the need for highly-enriched uranium in isotope production, and to establish a domestic supply of molybdenum-99. As of today, Niowave has years of experience in commercializing superconducting electron linear accelerators, obtaining and implementing NRC licenses, maintaining a radioactive material inventory, and producing radioisotopes by either fissioning uranium or by neutron capture. After irradiation, the radioisotopes are extracted from the matrix and purified and contained in the radiochemistry laboratory.

For the nuclear batteries project we are employing the same two major routes of production: neutron capture and uranium fission (see Fig. 3). For example, Sr-90 which is a nearly pure beta-emitter can be efficiently produced by fissioning uranium – it has a high cumulative fission yield of 5.6%. On the other hand, Ac-227, which is an interesting alpha-emitter can be produced via neutron capture of Ra-226 creating a short-lived Ra-227 which naturally decays into Ac-227.

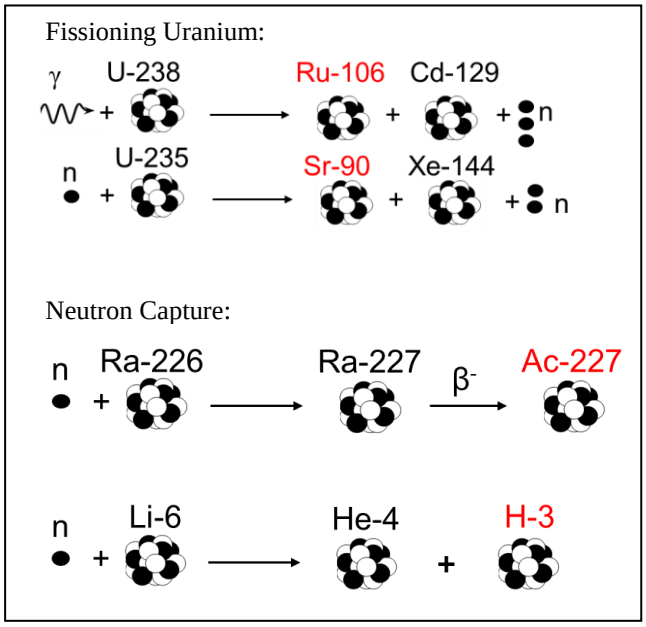

Fig. 3. Schematic production of radioisotopes for nuclear batteries via uranium fission (top) and neutron capture (bottom).

Both types of radioisotope production are done using the Uranium Target Assembly (UTA-1), a pool-type low enriched uranium subcritical assembly designed and built at Niowave and licensed by the NRC. UTA-1 is driven by an external neutron source: a superconducting electron linac equipped with a photoneutron converter. Alternative neutron sources, such as Cf-252 or a D-D neutron generator can also be coupled to UTA-1. UTA-1 consists of uranium pellets that are filled into aluminum cladding rods, which are loaded into a stainless steel tank filled with light water, which serves as a coolant, moderator, reflector, and shielding. UTA-1 has the versatility to vary the core configuration and moderating materials to operate as a thermal or fast core. UTA-1 has 1.8 kg of LEU and 4.6 kg of natural uranium loading. For production of radioisotopes through neutron capture, the seed nuclide is put inside UTA to maximize the exposure to thermal neutrons. For radioisotopes produced through uranium fission, the fuel pellets are dissolved and desired isotopes are extracted with radiochemistry techniques.

DEMONSTRATION AND TESTING

Niowave has made significant progress on our feasibility study for accelerator-based production of alpha and beta emitters for radioisotope sources. Niowave is in a unique position to supply various accelerator-based radioisotopes for national security. Other members of the NBC have capabilities and expertise developing various applications of radioisotopes. They will use Niowave's isotopes for prototype systems and Niowave's facilities and infrastructure for testing.

Currently, Niowave is expanding the scope of this project by producing radioisotopes not only for nuclear batteries, but for other applications in nuclear security (see Fig. 4). Among the additional applications is production of nuclear isomers for energy storage [3]. Production of radioxenon is another promising application. Measuring the ratios of specific radioxenon isotopes allows distinguishing between different sources of fission, such as nuclear power plants, medical isotope production facility, or nuclear weapons detonation [4]. Production of radioxenon is necessary for developing sophisticated monitors that can distinguish the source of radioxenon. Finally, production of strategic radioisotopes (such as tritium) is the third additional application we are planning to pursue. According to the DOE report to Congress, "Tritium and Enriched Uranium Management Plan through 2060" [5], the need for tritium remains one of the most pressing defense missions and alternative methods of its production (including accelerator-based) should be investigated.

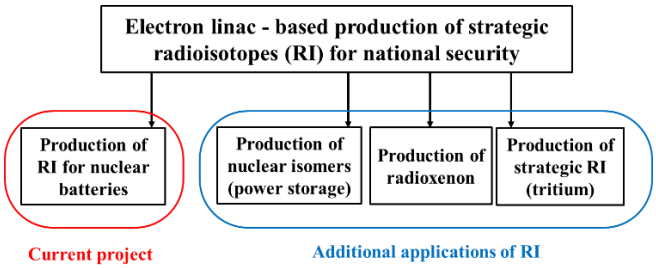

Fig. 4. Production of various radioisotopes for national security.

ACKNOWLEDGMENT

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