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Nuclear Batteries

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Abstract: ***The potential scope of a nuclear battery for its amazing extended shelf-life and excellent energy density as compared with other modes of energy storage devices makes them an excellent alternative to research. The performance of nuclear batteries can be defined as a function of the radioisotope and radiation transport properties. The energy conversion mechanisms vary significantly between different nuclear battery types, where the radioisotope thermometric generator is often considered a performance standard for all nuclear battery types. This paper presents a review of the recent advances in the technological field to miniaturize nuclear battery systems and a comparative analysis of the energy outputs of different isotopes.***
Keywords: Nuclear Battery, Radioisotope, Transducers, RTG

I. INTRODUCTION

Nuclear batteries have a great potential for a long battery lifetime. As a result, it has attracted the interest of researchers since the early 1900s. There are many competing types of nuclear batteries: thermoelectric, thermo-photoelectric, direct charge collection, thermionic, scintillation intermediate, and directed energy conversion alpha-voltaic and beta-voltaic. In miniaturization of nuclear batteries the concept of 'well-matched' system is a design specification that has to be considered. The range of a given particle in a specific material is referred to as the transport scale length of the radiation (λ Rad Tr) and the relevant physical dimension of the energy conversion volume in the transducer is referred to as the scale length of the transducer (Ltrans). These two scale lengths, λ Rad Tr and Ltrans, should be approximately equal. This fundamental property is the primary and the main factor which influences the efficiency of a nuclear battery. The phrase 'well-matched' is a measure of the extent to which this is complied. 'Well-matched' systems have a higher maximum theoretical efficiency, while the complements of the 'well-matched' have a lower maximum theoretical efficiency. Establishing 'well-matched' scale lengths is one of the fundamental challenges faced by miniature systems in the literature because of the respective parameters which determine each scale length.

II. CONVERSION OF RADIATION INTO ENERGY

A. Characteristics of Radiation sources

Ionizing radiation refers to the fact that different types of radiation will create ion pairs in the matter. Ionizing radiation includes ions such as fission fragments, charges, alpha particles, beta particles, gamma rays, x-rays, and neutrons. Each type of ionizing radiation source possesses its characteristic range. Let us Consider a material existing in the solid phase, for example. Very heavy ions like fission fragments and alpha particles are likely to store their energy within a solid over a range of a few micrometers, while the electrons deposit their energy over a range of few millimeters. Particles which possess high energy and either with no rest mass or with no net charge, such as gamma rays and neutrons, are likely to deposit their energy over a range of meters.

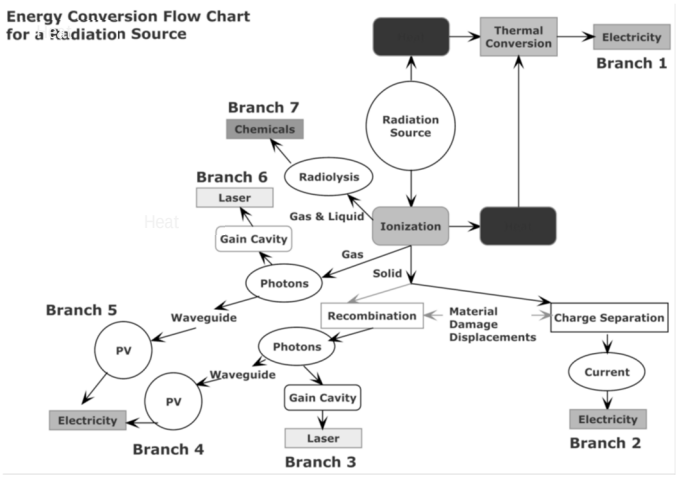

Figure 1. Energy conversion flow chart for radiation sources,

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1) *Branch 1* - Uses the radiation for heat production.
2) *Branch 2* – Uses the production of charged species in a solid to generate current flow.
3) *Branch 3* - Uses the production of charged species in a solid to produce laser photons.
4) *Branch 4* - Uses the production of charged species in a solid to produce photons which are used to produce electricity from photovoltaic (PV) cells.
5) *Branch 5* - Uses the production of charged species in gas to produce photons which then interaction with photovoltaic (PV) cells to produce electricity.
6) *Branch 6*- Uses the production of charged species in gas to produce laser photons.
7) *Branch 7*- Uses the production of charged species in a gas or liquid to produce chemicals through radiolysis.

B. Nuclear Fragments

The shortest transport scale lengths are for ions, and the most massive ions are those fragments which are produced as a result of fission. Fission commonly occurs through spontaneous decay of a heavy atom like californium-252, which releases fast neutron energy and fission fragments. The products of a spontaneous fission event are given in Equation1 and Equation 2, where *ffl* is the light fission fragment, *ffh* is the heavy fission fragment, *nfast*, released during fission and are emitted with a typical fast neutron distribution and *v* is the statistical average number of prompt fission neutrons.

$$KE_{ffl} = \frac{m_l}{m_h + m_l} KE_{ff} \quad \text{..... Eq.1}$$

$$KE_{ffh} = \frac{m_h}{m_h + m_l} KE_{ff} \quad \text{..... Eq.2}$$

For example, consider the specific fission reaction of U-235 shown in Equation 3 which produces La-147 and Br-87. Further, by changing the conditions, we can produce Ba-144 and Kr-89 as shown in figure 2. The kinetic energies of the fission fragments are calculated in Equation 4 and 5, respectively, and the energy from the fission reaction products are shown in Table 1. The ranges of fission fragments in the matter are very short because of their mass and charge. The bromine-87 atom has a range of 6.2 micrometers (μm) in uranium (U) metal and is used in the calculations.

$$_{92}U^{235} + n_{th} \rightarrow {}_{57}La^{147} + {}_{35}Br^{87} + 2n_{fast} + Q\ (195\ MeV) \quad \text{Eq3}$$

$$KE_{La_147} = \frac{87}{147+87} 162 = 60.23\ MeV \quad \text{.....Eq.4}$$

$$KE_{La_147} = \frac{87}{147+87} 162 = 60.23\ MeV \quad \text{.....Eq.5}$$

Table 1. Distribution of energy released during the fission of U-235 which yields the specific fission fragments La-147 and Br-87.

Radiation	Energy in MeV
Kinetic Energy of Fission Fragments	162
Fission Neutrons	6
Prompt Gamma Rays	6
Delayed Gamma Rays from Fission Fragments	5
Beta particles from Fission Fragments	5
Neutrinos	11
Total Energy	195

U-235 can also be collided with neutrons to form Barium and Krypton, Heavy and Light product respectively with energy distribution as shown in Table 2.

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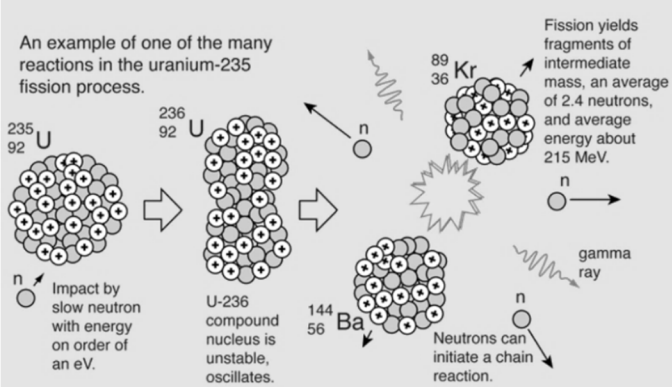

Figure 2. U-235 undergoing fission reaction to produce Ba-144 and Kr-89 with the release of other products.

Table 2. Distribution of energy released during the fission of U-235 which yields the specific fission fragments Ba-144 and Kr-89.

Radiation	Energy in MeV
Kinetic Energy of Fission Fragments	167
Fission Neutrons	5
Prompt Gamma Rays	5
Delayed Gamma Rays from Fission Fragments	6
Beta particles from Fission Fragments	7
Neutrinos	10
Total Energy	200

III. CHOICE OF ISOTOPE FOR NUCLEAR BATTERY

The Selection of the kind of isotope to use in a nuclear battery is a bit complex. There are many factors to be kept in consideration such as,

A. Type of radiation that the isotope emits will determine whether there is a good match between the range of radiation and the scale length of the transducer.
B. The half-life of the isotope determines the activity of the source as well as the effective lifetime of the nuclear battery.
C. The third consideration is the decay energy of the radiation, which, along with activity, determines the effective power density of the source.
D. The fourth consideration is how the isotope is produced, which effectively determines its cost. If the isotope is produced naturally as part of the decay chain of U-238, U-235 or Th-232, then it may be economical if large quantities are not needed as shown in Table 3.

Table 3. The estimated world supply of medium half-life (less than 100 yr) isotopes produced in fission.

Isotope	Atomic Mass of Isotope	Half-Life (yr.)	The activity of World Supply of Isotope (Ci)	World Supply of Isotope (gm)
Eu155	155	4.76	1.18E+08	1.97E+05
Kr85	85	10.76	1.42E+08	2.94E+05
Cd113m	113	14.1	39.97E+05	1.43E+03
Sr90	90	28.9	1.09E+05	6.43E+06

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IV. ENERGY CONVERSION MECHANISM

The theoretical limitation for any energy-conversion device that uses radiation to produce ion pairs in the very first step and then uses those so produced ion pairs for energy conversion is given by the ratio of the ionization potential to the W value (I/W or Eg/W). Thus the last columns of Table 4 represents the efficiency of converting the energy from radiation into ion pairs in these specific materials. This also shows the theoretical maximum efficiency for any energy conversion process that depends on the production of ion pairs from radiation interactions with a gas or solid. Even though this table was developed for alpha particle interactions with the gases, the W value is consistent for any ionizing radiation like heavy ions, light ions, beta particles, gamma rays and neutrons.

Table 4. The average energy required to produce ion pairs in various gases.

Element	Energy per Ion Pair, W (eV)	First Ionization Potential (eV)	Fraction of Energy used in Ionization (I/W)
H_2	36.3	15.6	0.43
He	43	24.5	0.58
N_2	36.5	15.5	.042
Ar	26.4	15.7	0.59
Xe	21.9	12.1	0.55
CO	34	14.3	0.42

V. PERFORMANCE ANALYSIS

Consider the popular radioactive isotopes with half-life period shown in table 5.

Table 5. The half-life of radioactive isotopes

Isotope	Half-life
H-3a	12.32 years
Ru-106a	1.02 years
Ni-63a	100.2 years
S-35a	87.37 days
Pm-147	2.62 years
P-33a	25.35 days
Ca-45	162.61 days
Cs-137	30.08 years
Sr-90a	28.79 years

Whenever an isotope is subjected to nuclear fission reaction, the average energy and maximum energy is obtained for respective isotopes. Average Energy is the statistical average of the kinetic energy possessed by an object during a given amount of time. However, for gases, it can also be the kinetic energy possessed by an average molecule, while Maximum Energy provides information about the rate at which one kind of energy is transformed into another as well as the efficiency of that transformation. The average energy output for different radioactive isotopes is shown in figure 3. Hydrogen-3a Isotope, being the lightest element has the lowest average output of 5.69 eV and Yttrium-90 isotope has a maximum average energy output of 933.6 eV as compared to all the other isotopes considered.

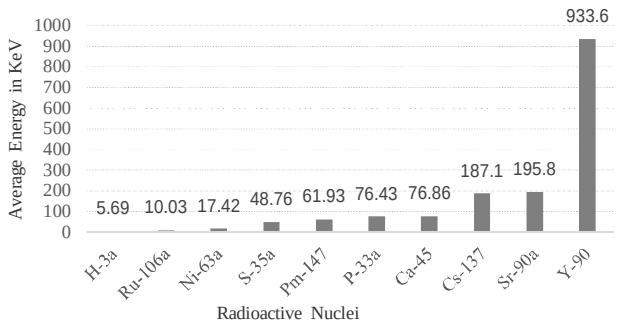

Figure 3. The average Energy output of Radioisotopes

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Analysis of Average output of element with respect to its half-life shows interesting results. In the majority of cases, the Average output energy in KeV is greater than the Half-life period of elements expressed in years except for Hydrogen-3 and Nickel-63a. These elements produce relatively less average output energy when compared to remaining radioisotopes. Figure 4. shows the comparison between the average energy and half-life of radioisotopes.

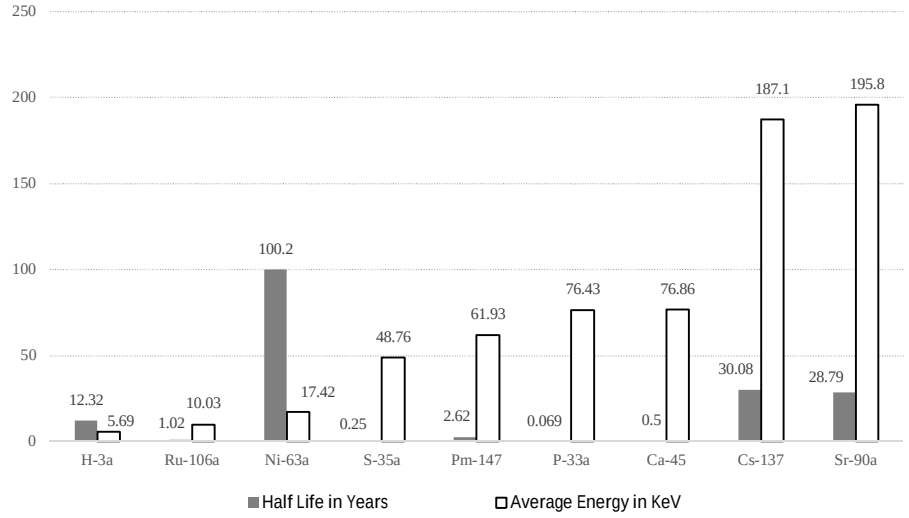

Figure 4. Relative Graph between Half-life and Average Energy output of radioisotopes.

The relationship between the average and kinetic energy of the Radioactive isotope mostly have direct dependency i.e., higher the maximum output energy, higher will be the Average output energy. This proportionality is true for almost all the isotopes, if we represent the maximum output energy in terms of the Average energy output, it can be represented as shown in Equation 6.

$$\text{Maximum Energy} = K \times \text{Average Energy} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq.6}$$

The value of k widely varies depending upon the isotope. Figure 5. represents the value of average energy and maximum energy for the given isotope.

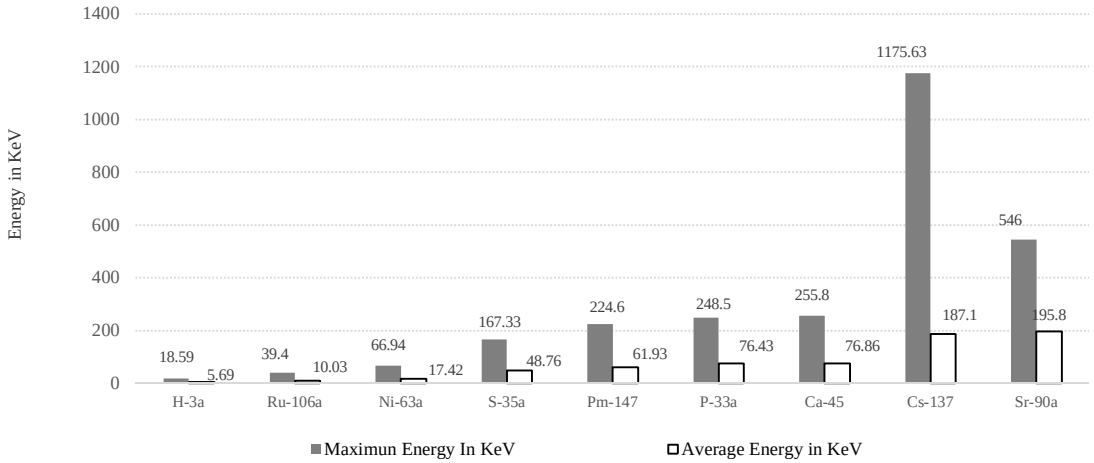

Figure 5. Graph showing value of Average and Maximum Energy for given Radioactive isotope.

VI. CONCLUSION

The efficiency of Micro-scalar nuclear battery is dependent upon the range of the radiation source to the scale length of the transducer used in the energy conversion process. The scale length matchups are in general poor for radiation/transducer combinations based upon current production, and for the most part, are very limited in the maximum energy conversion efficiency. The future of long-lasting battery devices lies in nuclear battery and has a lot of potential for future uses. These batteries deal with safety problems but with further research and development, they can be developed for safe usage to be used everywhere. Replacements of electrodes can make it cheap enough for normal people to use for day to day applications, but for this to occur we have a long way to go in Research and Development.

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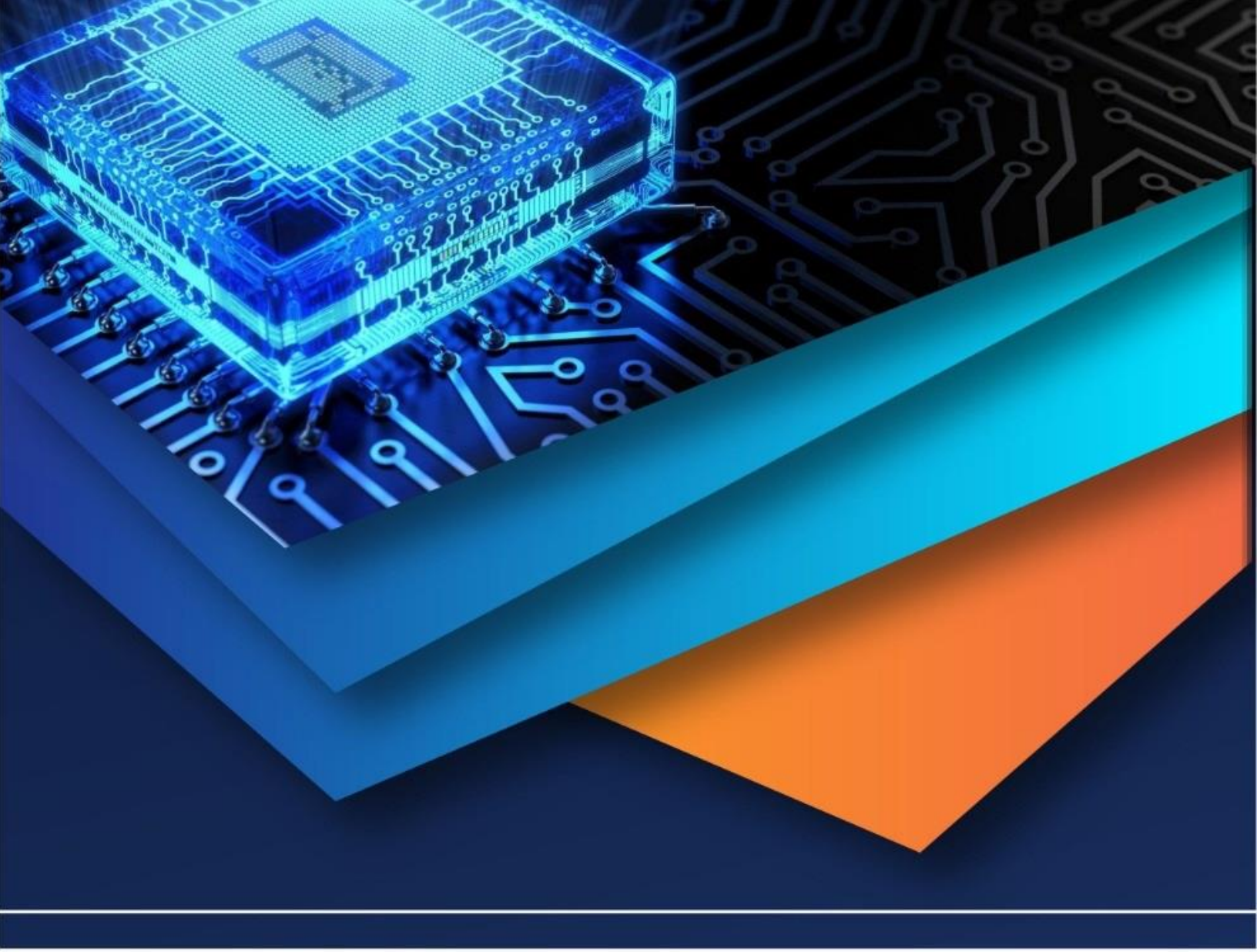

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