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SELECTION OF RADIATION SOURCES FOR THE CONCEPT OF NUCLEAR BATTERIES AS ENERGY SOURCES

Cahyo Ridho Prabudi[1], Bambang J. Suroto[1], and Topan Setiadipura[2]

[1]Faculty of Defense Technology, Indonesia Defense University, Jakarta, 10430 Indonesia
[2]National Nuclear Energy Agency, Banten, 15310 Indonesia

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ABSTRACT

Batteries are an efficient medium for storing energy. Its small size, reliability and light weight make batteries a widely used choice as a power source for small electronic equipment. Currently existing nuclear battery technology can only produce very little electrical power. Even so, nuclear battery technology is predicted to develop rapidly in the next few years. This article discusses the characteristics of radioisotopes which are suitable for making nuclear batteries. The characteristics considered are the type of radiation, other types of radiation emitted by the radiation source, the production method of radioisotope, the half-life of the radioisotope, and the decay energy of the radiation.

KEYWORDS: alternative power sources, characteristics of radioisotopes, nuclear battery.

1. INTRODUCTION

The need for energy is increasing over time. Currently, many potential energy sources have been developed for future use. The battery is widely used because of its relatively small size so that it can be easily carried or moved. Generally, batteries are used as a medium for storing energy, that's why today's rechargeable battery technology is developing rapidly because it is considered more efficient. The nuclear battery is another alternative that can outperform rechargeable battery technology because it has a high energy content.

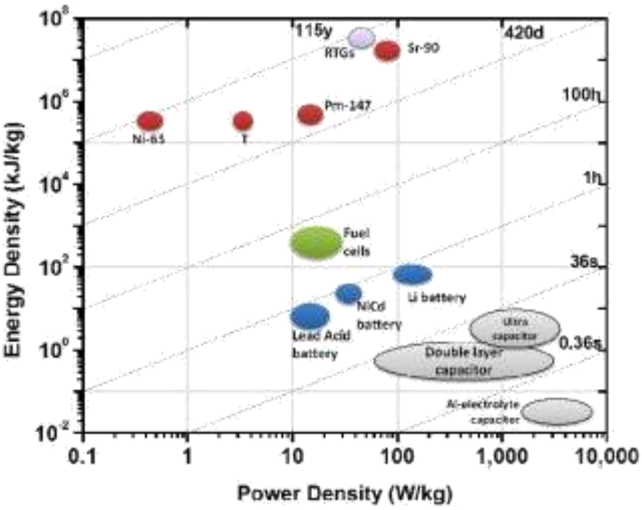

FIGURE 1. Comparison of Power Density and Energy Density on Various Types of Batteries [1]

Table 1 comparison of energy content in various batteries per 1milligram [2]

Source	Energy Content (mW-hr)
Chemical Battery (Li-ion)	0.3
Fuel Cell (methanol,50%)	3
Po-210 (5% - 4 years)	3000
H-3 (5% - 4 years)	500

Energy density states the nominal battery energy per unit volume expressed in Wh/L. Power density states the maximum available power per unit volume which is expressed in W/L [3]. The gray color in the graph shows capacitors, green for fuel cells, red for various radiation sources for nuclear batteries, and purple for RTG (Radioisotopes Thermoelectric Generator). The advantage of nuclear batteries compared to other types of batteries is that they have a large energy storage capacity due to their high energy density, so they can last for a long time even if they are not recharged.

A nuclear battery is not a miniature nuclear reactor because there is no fission or fusion reaction in the battery. Nuclear batteries utilize spontaneously emitted energy from the decay of radioactive isotopes (radioisotopes) to generate electricity. Radioactive sources used for nuclear batteries are usually sources that emit alpha or beta radiation. Gamma radiation sources are not considered for use as nuclear batteries because of their high particle penetration power so that their application will require a large radiation shield. Currently, the use of nuclear batteries is still limited as a resource for tools that use microelectromechanical systems (MEMS).

II. EKSPERIMENTAL METHOD

This research was conducted by studying literature related to various types of radioisotopes that have the potential to be used in nuclear batteries. The data obtained from the literature study of previous studies were collected and then analyzed for the characteristics of each radioisotope. Until finally it was narrowed down to obtain radioisotopes that meet the requirements for nuclear batteries.

The performance of a nuclear battery is determined by 3 factors, namely radioisotope characteristics, radiation transport, and energy conversion mechanisms. This study will limit the problem to the criteria for radioisotopes which are expected to be used as energy sources in nuclear batteries. Expected nuclear battery criteria:

- Portable, can be carried or moved easily
- Safe from radiation emitted by radiation sources inside the battery
- Low production cost
- Long battery life/effective life
- Big battery effective power

The main consideration criteria for the selection of radiation sources for nuclear batteries:

- Radiation type
- Other types of radiation emitted by radiation sources
- production method of radioisotope
- half-life of the radioisotope
- Radiation decay energy

III. RESULT AND DISCUSSION

A. CONSIDERATION OF RADIATION TYPE

Nuclear batteries use the decay energy of radioisotopes/ radiation sources to generate electricity. Radioisotopes emit ionizing radiation when they decay, the decay energy of which is used as a battery energy source. Some types of ionizing radiation include alpha radiation, beta radiation, neutron radiation, and photon radiation.

Alpha particles have a large ionizing power, meaning that they can ionize very strong materials but the kinetic energy of alpha particles is lost quickly because of the large particle size. Thus, alpha particles have a very short radiation range. An alpha particle with an energy of 5 MeV is only able to penetrate 0.002 cm of aluminum plate and only about 3.5 cm in the air.

Beta radiation has two forms, namely electron particle radiation ($\beta-$) and positron particle radiation ($\beta+$). When compared with alpha radiation, beta radiation has 100 times less ionizing power in the air but has a higher penetrating power. Because it is very light, beta particles are easily scattered when passing through a medium and will also be deflected when passing through magnetic and electric fields. A beta particle with an energy of 1 MeV can travel 3.5 meters in the air.

Neutron particles are neutrally charged particles, which is why they cannot directly ionize atoms. However, neutrons can ionize materials indirectly when they are absorbed by a stable atom, this will cause the atom to become unstable and have a tendency to emit ionizing radiation. It can be said, neutrons are the only type of radiation that can change the material in its path into radioactive material. Photon radiation is divided into 2 types, Gamma Radiation and X-Ray Radiation. X-Ray generally has a longer wavelength and lower energy when compared to Gamma Radiation. Gamma rays have no mass and no charge so the radiation emitted is also known as Electromagnetic Radiation. Gamma radiation has high energy and has the greatest penetrating power when compared to alpha and beta radiation. Gamma radiation generally accompanies alpha and beta decay. Gamma radiation travels at the speed of light and can reach thousands of meters in the air to exhaust its energy [4].

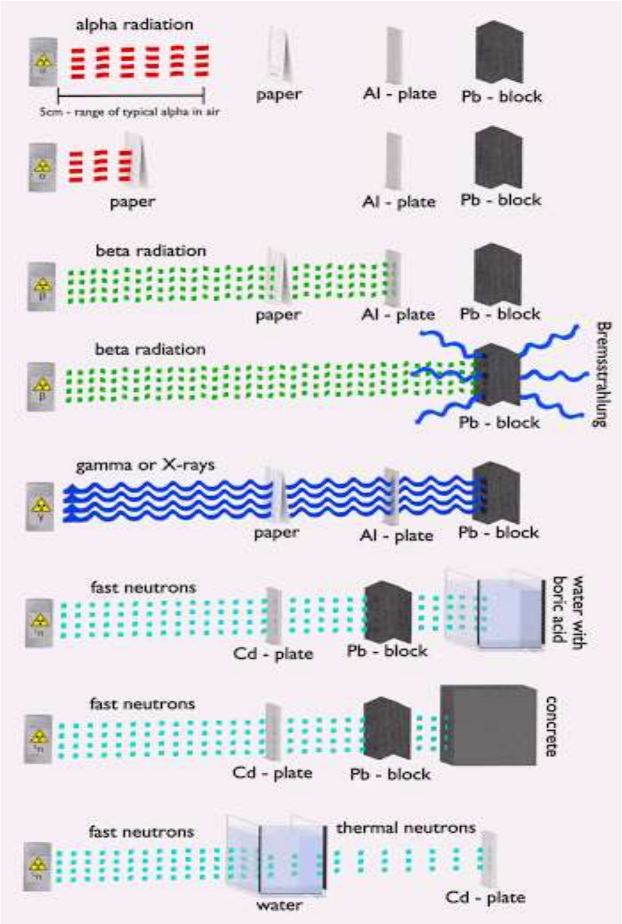

FIGURE 2. Illustration of the translucent power of various types of ionizing radiation [5]

Based on the characteristics of each type of radiation above, what needs to be considered in choosing a radiation source for a nuclear battery is the penetrating power of the radiation. The penetration of the particles will affect the type of material used for shielding and wrapping the battery. Nuclear battery applications are intended to be portable, can be carried and moved easily. Photon and neutron radiation has a very high penetrating power that requires a shield that is thick enough to protect humans and electronic devices. The selection of materials for nuclear batteries needs to consider the safety aspects of radiation hazards so that radioactive substances must be selected whose radiation is easily restrained by a light radiation barrier. To be able to withstand gamma radiation, lead (Pb) beams are required which are quite thick and heavy, which will directly increase production costs as well, so that they do not meet the demands of economical and portable criteria. The best option for application to nuclear batteries is to use isotopes that emit alpha or beta particles when decaying because they have low penetrating power so that only using aluminum plates can block radiation from leaving the battery, as shown in Figure 2.

Table 2 Potential Radioisotopes for Nuclear Batteries [6]

α	β	
Gd-148	H-3	Pm-147
Po-208	Ar-39	Sm-151
Po-210	Ar-42	Eu-152
Th-228	Co-60	Eu-154
U-232	Kr-85	Eu-155
Pu-236	Sr-90	Tm-171
Pu-238	Ru-106	Os-194
Am-241	Cd-113m	Tl-204
Cm-243	Sb-125	Pb-210
Cm-244	Cs-134	Ra-228
Bk-248	Cs-137	Ac-227
Cf-250	Pm-146	Pu-241
Cf-252		
Es-252		

Table 2 shows the types of radiation emitted by different types of radioactive isotopes. These isotopes are potential alternatives that can be selected for the manufacture of nuclear batteries based on previous studies.

B. CONSIDERATION OF THE EXISTANCE OF OTHER TYPES OF RADIATION EMITTED BY RADIOISOTOPE

Gamma radiation generally accompanies alpha and beta decay. Meanwhile, as discussed earlier, nuclear batteries avoid the presence of gamma radiation in the decay process of radioisotopes because gamma radiation has a high particle penetration power. So, the best isotopes for nuclear batteries are isotopes that emit only alpha radiation or beta radiation or a mixture of both.

Table 3 Other Types of Radiation Emitting on Potential Alpha Nuclides [6]

α nuclide	**Other radiation (MeV, %)**		
	Type	**Energy**	**%**
Gd-148	N/A	N/A	N/A
Po-208	β^+:	0.3783	0.00%
Po-210	γ:	0.803	0.00%
Th-228	α:	5.34	27.20%
		5.423	72.20%
	γ:	0.216	0.25%
U-232	α:	5.263	31.55%
		5.32	68.15%
	γ:	0.1 – 0.3	low %
Pu-236	α:	5.721	30.56%
		5.768	69.26%
Pu-238	α:	5.456	28.98%
		5.499	70.91%
Am-241	α:	5.442	13%
		5.485	84.50%
	γ:	0.05954	35.90%
Cm-243	α:	5.742	11.50%

		5.785	72.90%
		5.992	5.70%
		6.058	4.70%
	γ:	0.2 – 0.3	20%
Cm-244	α:	5.762	23.60%
		5.805	76.40%
	γ:	low percentage	
Bk-248	N/A	N/A	N/A
Cf-250	α:	6.0304	84.60%
		5.989	15.10%
	γ:	0.04285	0.01%
Cf-252	SF:	FF	3.09%
	α:	6.0758	15.70%
		6.118	84.20%
	γ:	0.043-0.155	0.02%
Es-252	α:	6.5762	13.60%
		6.632	80.20%
	γ:	0.043-0.924	25%

Table 4 Other Types of Radiation Emitting on Potential Beta Nuclides [6]

β nuclide	Other radiation (MeV, %)		
	Type	Energy	%
H-3	N/A	N/A	N/A
Ar-39	N/A	N/A	N/A
Ar-42	N/A	N/A	N/A

Co-60	γ:	1.17	99%
		1.33	0.12%
Kr-85	γ:	0.514	0.40%
Sr-90		2.281	Y-90, daughter
Ru-106	N/A	N/A	N/A
Cd-113m	N/A	N/A	N/A
Sb-125	γ:	0.5	5 – 20%
Cs-134	γ:	0.6 – 0.8	97%
Cs-137	γ:	0.6617	93.50%
Pm-146	γ:	0.747	33%
Pm-147	N/A	N/A	N/A
Sm-151	N/A	N/A	N/A
Eu-152	γ:	0.1 – 0.3	
Eu-154	γ:	0.123	38%
		0.248	7%
		0.593	6%
		0.724	21%
		0.759	5%
		0.876	12%
		1	31%
		1.278	37%
Eu-155	γ:	0.086	30%
		0.105	21%
Tm-171	γ:	0.0667	0.14%
Os-194	γ:	0.01 – 0.08	

Tl-204	N/A	N/A	N/A
Pb-210	γ:	0.046	4%
Ra-228	γ:	low E	low%
Ac-227	α:	4.953	47.70%
		4.94	39.60%
	γ:	0.1-0.24 γ	
Pu-241	α:	4.853	12.20%
		4.896	83.20%

The red color in the Table 3 and 4 are radionuclides that does not meet the criteria needed for the manufacture of nuclear batteries because it emits gamma radiation.

C. CONSIDERATION OF RADIOISOTOPE PRODUCTION METHOD

There are several ways to obtain radioisotopes, including radioisotopes derived from nuclear fission products, radioisotopes derived from natural products, or neutron capture processes using an accelerator. The method of radioisotope production is one of the considerations for determining the right isotope for a nuclear battery because it will affect the production cost of making the battery itself. Radioisotopes that come from natural products are products of the natural decay of a radioactive element. This type of radioisotope is an ideal choice for nuclear batteries because it only costs a relatively small amount of money to obtain. The problem is that this type of radioisotope that is available in nature is very limited.

Table 5 Potential Radioisotope Production Methods [6]

Nuclide	Production method
Gd-148	Sm-147 (α,3n)
	Eu-151 (p,4n)
Po-208	Bi-209 (d, 3n)
	Bi-209 (p,2n)
Pu-236	Np-236 (β)
	U-235 (α, 3n)

Pu-238	Np-238 (β) Np-237 (n, γ)
Cm-244	Multiple-n capture U-238, Pu-239, Am-243
Bk-248	Cm-246 (α,pn)
H-3	Li-6 (n, α)
Ar-39	Ar-38 (n, γ) KCl (n, γ)
Ar-42	Ar-40 (n, γ) Ar-41 (n, γ)
Sr-90	Fission product
Ru-106	Fission product
Cd-113m	Cd-112 (n, γ) Cd-113 (n, n’)
Pm-147	Nd-146 (n, γ)
Sm-151	Fission product
Tl-204	Tl-203 (n, γ)
Pu-241	Multiple-n capture U-238, Pu-239

On the other hand, radioisotope which is a product of nuclear fission becomes economical when the isotope is a byproduct of fission so that it can be obtained from spent nuclear fuel from nuclear reactors. In this case, the nuclear reactor functions as a power generator and produces isotopes used for nuclear batteries, so the cost of producing nuclear batteries can be reduced because they do not require other facilities to produce the required isotopes. Meanwhile, radioisotopes produced using accelerators will require relatively expensive costs because they require separate particle accelerator facilities to produce isotopes.

On this basis, the selected method of isotope production is radioisotope produced from fission products. This is based on the difficulty of obtaining natural radioisotopes because of their limitations in nature. In addition, for Indonesia, currently, the most economical and possible way to obtain isotopes is to make radioisotopes using our research reactor.

By eliminating radioisotopes that do not meet the criteria in the previous Table 3 and 4, the data as shown in Table 5 is obtained and then selected radioisotopes that can be produced by the neutronic fission process.

D. CONSIDERATION OF RADIOISOTOPE HALF-LIFE

Radioactive substances are unstable elements because they try to form new stability by releasing the emission of particles called the decay process. Decay is a spontaneous and natural process for radioactive elements. All types of radioactive elements will lose half of their mass and emit only half of their radiation in a given time. The time it takes for a radioactive element to decay by half is called the half-life, or it can be said that the half-life is the age for a radioactive substance to be reduced by half.

The half-life of radioactive substances varies depending on the type of isotope. For example, polonium-214 has a very short half-life of 0.16 milliseconds, while other radioisotopes such as plutonium-238 have a half-life of about 78 years [2]. The characteristics of the half-life of radioactive elements are one of the things considered for application in nuclear batteries.

Table 6 Half-Life of Potential Radioisotope [6]

Nuclide	Half-life (year)
Gd-148	74.6
Po-208	2.8979
Pu-236	2.857
Pu-238	87.74
Bk-248	9
H-3	12.33
Ar-39	269
Ar-42	32.9

Sr-90	28.77
Ru-106	1.0234
Cd-113m	14.1
Pm-147	2.624
Sm-151	90
Tl-204	3.78

Nuclear batteries are required to have a long effective battery life, ideally, radioisotopes with long half-lives are the choice. However, it turns out that in general the longer the half-life of a radioactive substance, the lower its radiation power. With this in mind, the selection of radiation sources is limited to radioisotopes which have a half-life of 1 to 270 years. Radiation sources that meet these criteria are shown in Table 6.

E. CONSIDERATION OF RADIATION DECAY ENERGY

As explained earlier, the advantage of nuclear batteries compared to other types of batteries is the large energy density as shown in Figure 1. Then what about the power density of nuclear batteries? Because as can be seen in Figure 1, the power density of nuclear batteries is generally smaller than batteries that use capacitors. Radiation decay energy, together with radioactive activity, will determine the power density of a nuclear battery. The greater the decay energy of a radioactive substance, the greater its power density.

Table 7 The Relation of Decay Energy and Power [6]

Nuclide	Decay energy (MeV)	Specific power (W/gr)	Power (W/Ci)
Gd-148	3.182	0.61057	0.01884
Po-208	5.216	17.96949	0.03088
Pu-236	5.867	18.0322	0.03473
Pu-238	5.593	0.55559	0.03311
Bk-248	5.793	5.49388	0.03429

H-3	0.019	0.3606	0.00034
Ar-39	0.565	0.03711	0.01003
Ar-42	0.6	0.30674	0.01066
Sr-90	0.546	0.14898	0.0097
Ru-106	0.039	0.25396	0.00069
Cd-113m	0.58	0.25714	0.0103
Pm-147	0.225	0.41193	0.004
Sm-151	0.076	0.00395	0.00135
Tl-204	0.763	0.67819	0.01355

The power output per gram of the isotope means the maximum achievable power density of the isotope. The interaction of the isotope surface to the nuclear battery will further limit the power density. For example, Gd-148, the power produced per gram of material is 0.61 W. The density of Gd is 7.90 g/cm3. The absolute maximum power density of metal Gd-148 is 0.61 W/g times 7.9 g/cm3 which is 4.8 W/cm3. If the surface of the nuclear battery chip is coated with Gd-148 metal, the coating thickness should be on the order of 5 m to minimize self-absorption. So, the surface area of a layer of 1 gram of metal Gd-148 with a thickness of 5 m on the chip is 25.32 cm2. This chip will have 0.61 W of power from the alpha particles emitted by Gd-148. If the chip efficiency is optimized, the efficiency can be about 1%. Thus, the output power of a 25 cm2 cell will be approximately 6.1 mW. The effective power density will be on the order of broad multiplied by the range of alpha particles (~20 m) divided into 6.1 mW or about 0.12 W/cc. Isotopes are usually sold in quantities measured in Curie (Ci), so the amount of power produced by Gd-148 per Ci is 0.019 W/Ci. If the chip efficiency is 1% then the cell will produce 0.19 mW/Ci.[6]

By using these calculations, the power for each radiation source will be obtained as shown in Table 7. It can be seen that the greater the decay energy of the radioisotope, the greater the power generated.

III. CONCLUSION

After analyzing the literature study to determine the appropriate radiation source for nuclear batteries, it can be summarized as follows,

1. Radiation type: alpha radiation or beta radiation or a combination of both
2. Radiant decay energy: the bigger the better
3. Radiation of other types: does not contain radiation of photons and neutrons

4. Production method: neutronic fission reaction product or spent nuclear fuel
5. Half-life: 1 year to 270 years.

The radioisotope criteria suitable for nuclear batteries based on the above considerations are summarized in the Table 8.

TABLE 8 RADIATION SOURCES ELIGIBLE FOR NUCLEAR BATTERIES

Nuclide	Radiation type	Decay energy (MeV)	Half-life (year)	Other radiation (MeV, %)			Production method
				Type	Energy	%	
Gd-148	Alfa	3.182	74.6	N/A	N/A	N/A	Sm-147(α,3n) Eu-151(p,4n)
Po-208	Alfa	5.216	2.8979	β^+:	0.3783	0.00%	Bi-209(d, 3n) Bi-209(p,2n)
Pu-236	Alfa	5.867	2.857	α:	5.721 5.768	30.56% 69.26%	Np-236(β) U-235(α, 3n)
Pu-238	Alfa	5.593	87.74	α:	5.456 5.499	28.98% 70.91%	Np-238(β) Np-237(n, γ)
Bk-248	Alfa	5.793	9	N/A	N/A	N/A	Cm-246(α,pn)
H-3	Beta	0.019	12.33	N/A	N/A	N/A	Li-6(n, α)
Ar-39	Beta	0.565	269	N/A	N/A	N/A	Ar-38(n, γ) KCl(n, γ)
Ar-42	Beta	0.6	32.9	N/A	N/A	N/A	Ar-40(n, γ) Ar-41(n, γ)
Sr-90	Beta	0.546	28.77		2.281	Y-90, daughter	Fission product

Ru-106	Beta	0.039	1.0234	N/A	N/A	N/A	Fission product
Cd-113m	Beta	0.58	14.1	N/A	N/A	N/A	Cd-112(n, γ) Cd-113(n, n')
Pm-147	Beta	0.225	2.624	N/A	N/A	N/A	Nd-146(n, γ)
Sm-151	Beta	0.076	90	N/A	N/A	N/A	Fission product
Tl-204	Beta	0.763	3.78	N/A	N/A	N/A	Tl-203(n, γ)

To become a recommendation for stakeholders to apply nuclear batteries, further research is needed on radiation transport and the mechanism of energy conversion from radioisotope decay into electricity.

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