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SLW Chemistry and Biology Webinar Series

Nuclear Batteries: Past, Present and Future

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What is a Nuclear Battery?

- A nuclear battery is any device that harnesses energy from radioactive element isotope decay to generate electricity. Nuclear batteries do not rely upon nuclear fusion or fission. As particles are emitted from the isotope, they stir electrons in a battery system to create a current.
- Some batteries use radioactive decay to generate heat and then harvest with thermocouples; others harness diode junctions to facilitate non-thermal conversion. Regardless of the method, all nuclear batteries draw energy from a radioactive source.

Types of Nuclear Batteries: Thermal and Nonthermal

Components common to both thermal and non-thermal:

- Radioisotope Fuel
- Radiation/Heat Management Structure
- Energy Conversion Transducer
- External Interfaces

Types of Ionizing Radiation

Alpha Particles

- Alpha particles (α) are positively charged and made up of two protons and two neutrons from the atom's nucleus, making them identical to the nucleus of a helium-4 atom. Alpha particles come from the decay of the heaviest radioactive elements, such as uranium, radium and polonium. Even though alpha particles are very energetic, they are so heavy that they use up their energy over short distances and are unable to travel very far from the atom.
- The health effect from exposure to alpha particles depends greatly on how a person is exposed. Alpha particles lack the energy to penetrate even the outer layer of skin, so exposure to the outside of the body is not a major concern. Inside the body, however, they can be very harmful. If alpha-emitters are inhaled, swallowed, or get into the body through a cut, the alpha particles can damage sensitive living tissue. The way these large, heavy particles cause damage makes them more dangerous than other types of radiation. The ionizations they cause are very close together - they can release all their energy in a few cells. This results in more severe damage to cells and DNA.

Beta Particles

- Beta particles (β) are small, fast-moving particles with a negative electrical charge that are emitted from an atom's nucleus during radioactive decay. These particles are emitted by certain unstable atoms such as hydrogen-3 (tritium), carbon-14 and strontium-90.
- Beta particles are more penetrating than alpha particles, but are less damaging to living tissue and DNA because the ionizations they produce are more widely spaced. They travel farther in air than alpha particles, but can be stopped by a layer of clothing or by a thin layer of a substance such as aluminum. Some beta particles are capable of penetrating the skin and causing damage such as skin burns. However, as with alpha-emitters, beta-emitters are most hazardous when they are inhaled or swallowed.

Radioisotopes Used in Nuclear Batteries

Table 1: Radioisotopes Used in Nuclear Batteries

ISOTOPE	TYPE	MAXIMUM DECAY ENERGY (KILOELECTRON VOLT)	HALF-LIFE (YEAR)	SPECIFIC POWER (WATTS PER GRAM)
Tritium	beta	19	12.3	0.33
Carbon-14	beta	156	5,730	0.0013
Nickel-63	beta	67	100	0.0058
Promethium-147	beta	225	2.6	0.41
Polonium-210	alpha	5,305	0.38	141
Plutonium-238	alpha	5,593	87.7	0.56

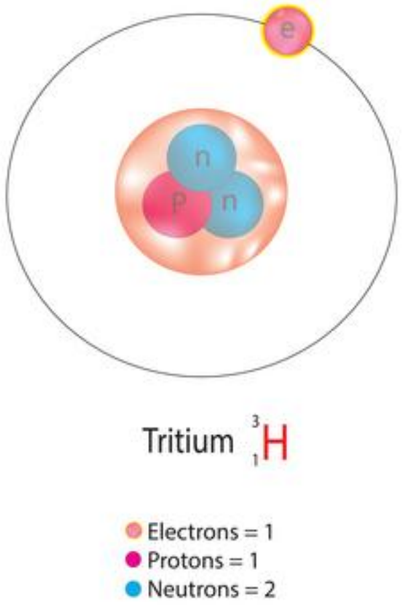
CREDIT/SOURCE: JAKE BLANCHARD

Radioisotopes emit particles with a spectrum of energies. The decay energy is a measure of the kinetic energy of emitted particles as the radioisotope decays. The specific power provided here is a measure of how much power an ideal, pure radioisotope source can generate per unit of mass at the beginning of its life.

https://spectrum.ieee.org/nuclear-battery-revival

Tritium

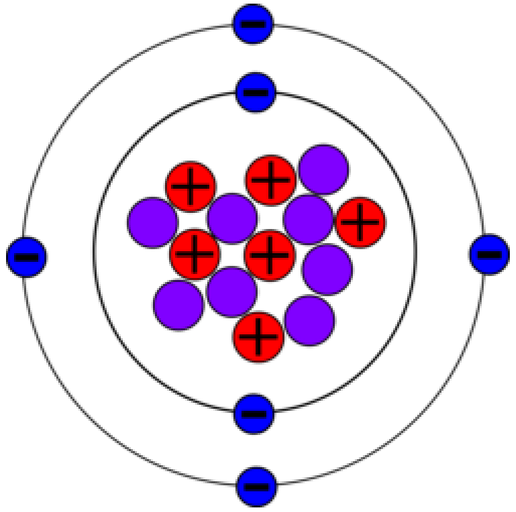
- Natural: Produced in the atmosphere in small amounts by cosmic-ray interactions with nitrogen, oxygen and other light nuclei.
- Reactor/by-product sources:
  - Neutron capture on deuterium in heavy-water reactors (e.g., CANDU, D(n,γ)T), leading to tritium accumulation in the moderator/coolant heavy water that is periodically stripped and recovered.



$$^{14}_{7}\mathrm{N} + ^{1}_{0}n \rightarrow ^{12}_{6}\mathrm{C} + ^{3}_{1}\mathrm{H}.$$

Carbon-14

- Natural (dominant): Cosmogenic production in the upper atmosphere when secondary (thermal) neutrons from cosmic rays are captured by atmospheric nitrogen: 14N(n,p)14C14N(*n*,*p*)14C.
- Anthropogenic: Extra C-14 was added to the global inventory by open-air nuclear weapons tests (mid-20th century), which produced large neutron fluxes in the atmosphere.



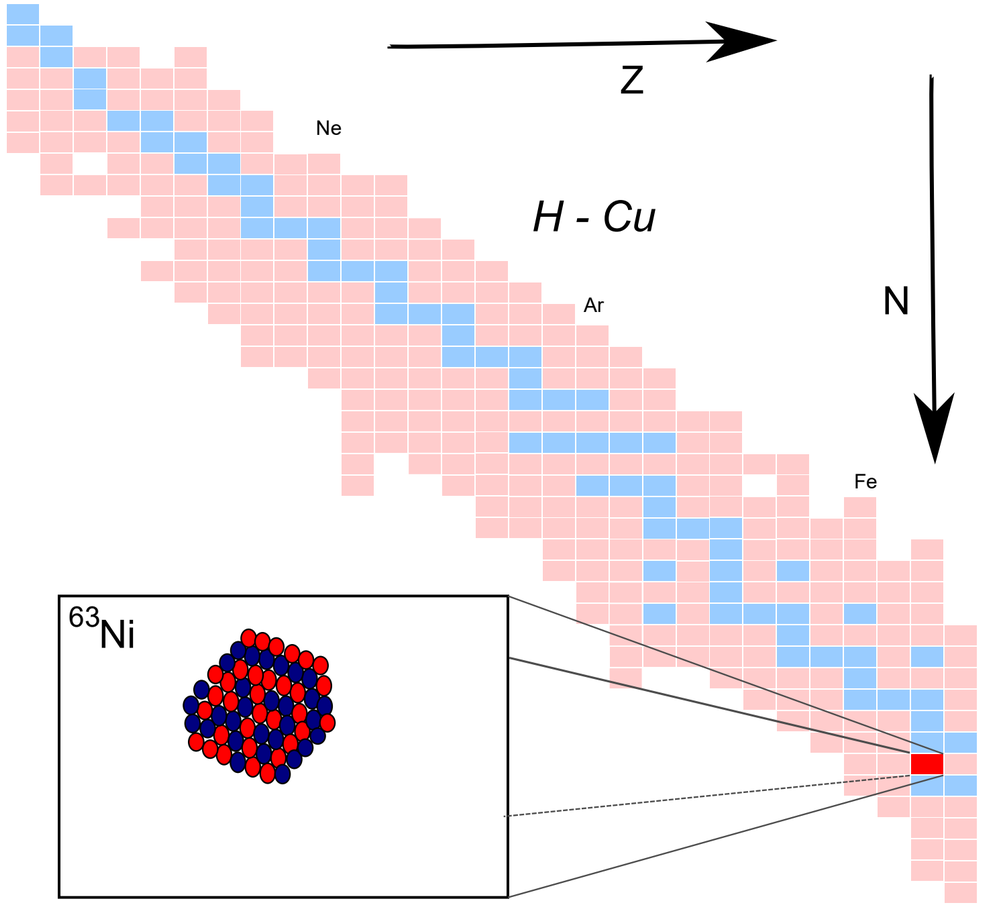
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The nuclear decay equation is: $\ce{^{14}_{6}C -> ^{14}_{7}N + ^{0}_{-1}e + \bar{\nu}_e}$

A neutron in the carbon-14 nucleus converts into a proton, emitting an electron (beta particle) and an electron antineutrino, producing stable nitrogen-14.

Nickel-63

- Industrial production: Mainly by neutron irradiation of enriched 62Ni62Ni in a reactor via 62Ni(n,γ)63Ni62Ni(*n*,*γ*)63Ni.
- Alternative route: Fast-neutron reactions on copper targets,
  e.g. 63Cu(n,p)63Ni63Cu(*n*,*p*)63Ni, using high-flux fast reactors (e.g., BN-type) with copper or Ni-enriched targets.



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At the nuclide level:

$$^{63}_{28}\mathrm{Ni} \rightarrow {}^{63}_{29}\mathrm{Cu} + \beta^{-} + \bar{\nu}_{e}.$$

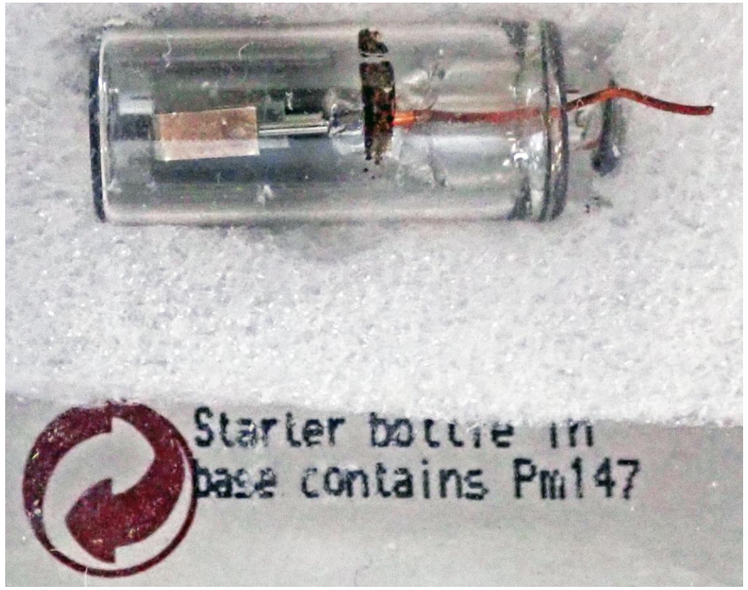
A neutron in the Ni-63 nucleus converts to a proton, emitting an electron and an electron antineutrino, producing Cu-63.

Daughter nuclide: stable Cu-63.

Decay energy *Q*: about 67 keV, with maximum beta energy ≈66-67 keV and average ≈17 keV.

Promethium-147

- Reactor/fission product:
  - Formed as one of the fission products of 235U235U or 239Pu239Pu in reactor fuel; it is chemically separated from spent fuel solutions.
  - Historically accumulated at reprocessing sites (e.g., Hanford, ORNL inventories) as a separated fission-product nuclide.
- Minor routes: Neutron activation of suitable precursors is possible but less commonly used industrially than straight fission-product recovery.



"Promethium (Element - 61) 2" by James St. John is licensed under CC BY 2.0.

Promethium-147 beta decays by beta minus emission to stable samarium-147.

The nuclear decay reaction can be written as:

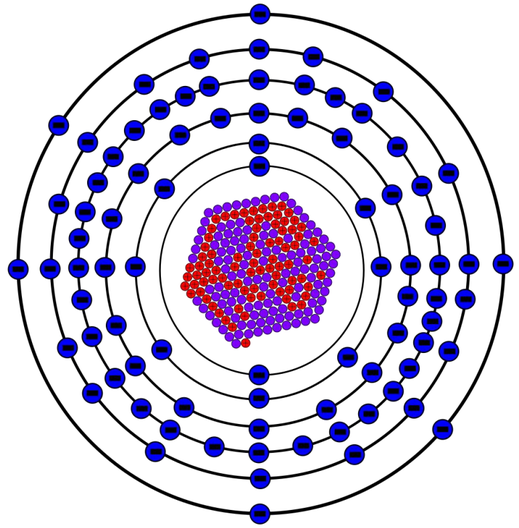
$$^{147}_{61}\mathrm{Pm} \rightarrow {}^{147}_{62}\mathrm{Sm} + \beta^{-} + \bar{\nu}_e$$

This decay has a half-life of about 2.6 years and the beta particles have a maximum energy of roughly 0.224 MeV.

Polonium

Polonium (practically Po-210)

- Industrial production: Typically by alpha-particle irradiation of bismuth-209 targets (e.g., Bi-209 bombarded with ~30–40 MeV α-beams), producing 210At210At which beta-decays to 210Po210Po; the Po is then chemically separated from the Bi matrix.
- Reactor route: Neutron irradiation of Bi-209 in reactors to form Bi-210 which decays via Pb-210 to Po-210, again followed by radiochemical separation; functionally similar in that Bi-209 is the starting material.



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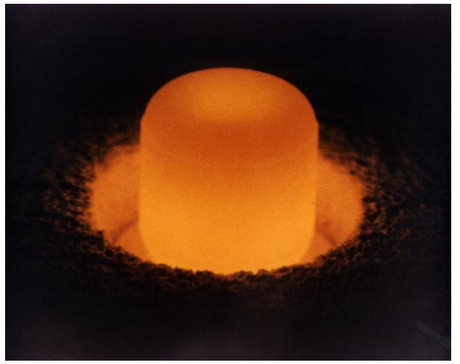
For any alpha-decaying polonium isotope, the nuclear reaction can be written in the form:

$^{A}_{84}\mathrm{Po} \rightarrow {}^{A-4}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$, where A is the mass number.

Polonium always has atomic number 84, so losing an alpha particle (2 protons, 2 neutrons) turns it into lead with atomic number 82.

The mass number decreases by 4 because the emitted alpha particle carries away 4 nucleons.

Plutonium-238



Department of Energy, Public domain, via Wikimedia Commons

- Reactor target production:
  - Produced by neutron irradiation of neptunium-237 (usually as NpO_2 dispersed in aluminum) via 237Np(n,γ)238Np→238Pu237Np(*n*,*γ*)238Np→238Pu after beta decay.
  - The Np-237 itself is recovered as a by-product from irradiated uranium (natural or enriched) during reprocessing, then converted (e.g., to Np oxalate, calcined to NpO_2) and fabricated into targets.
- Legacy stock: Some Pu-238 also historically came from power-reactor fuel campaigns and special production reactors, but modern U.S. production is essentially via the Np-237 target pathway.
- For the dominant alpha decay mode, the nuclear reaction is:
- 94238Pu→92234U+24He94238Pu→92234U+24He
- The 24He24He term is an alpha particle (a helium nucleus).
- This decay has a half-life of about 87.7 years for Pu-238.
- Full decay chain context
- The immediate daughter, uranium-234, continues to decay through the so-called radium series, eventually ending at stable lead-206.
- In addition to alpha decay, Pu-238 has extremely small branching modes such as spontaneous fission and rare cluster emissions, but these are negligible compared with the main alpha decay path.

Who Invented the Nuclear Battery?

- Henry Moseley showed proof of concept in 1913. His nuclear battery consisted of a glass sphere silvered on the inside with a radium emitter mounted at the center on an isolated electrode. Electrons resulting from the beta decay of radium caused a potential difference between the silver film and the central electrode. However, the idle voltage of the device was way too high -- tens of kilovolts -- and the current was too low for practical applications.
- Moseley created the world's first atomic battery, or beta-cell while working in the laboratory of Ernest Rutherford. Moseley's career was cut short when, August 1914, World War I broke out, and Moseley enlisted in the British Army's Royal Engineers. Moseley was serving as a technical communications officer at the Battle of Gallipoli when on August 10, 1915, he was shot in the head by a sniper. Moseley was only 27-years-old when he died, and he is buried on Turkey's Gallipoli Peninsula.

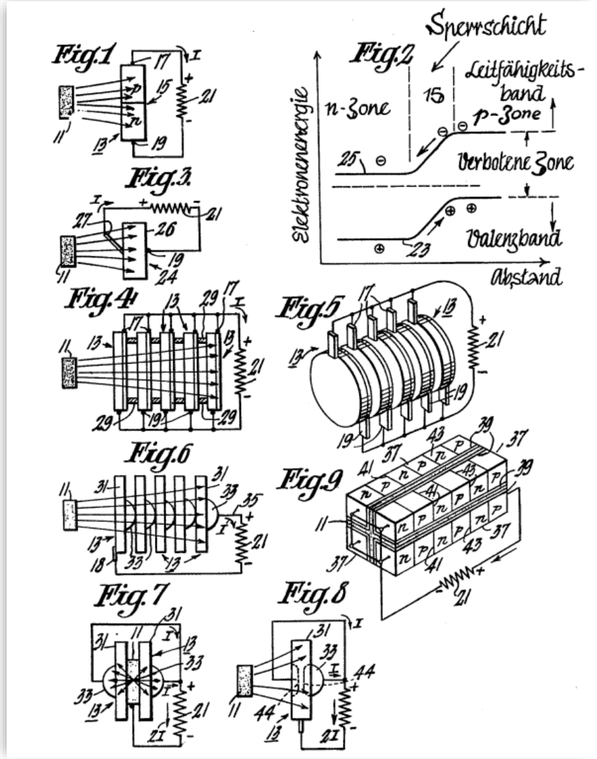


https://commons.wikimedia.org/wiki/File:Henry_Moseley.jpg

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Beta Decay Conversion Into Electricity—Non Thermal

- In 1953, Paul Rappaport proposed the use of semiconducting materials to convert the energy of beta decay into electricity. Beta particles -- electrons and positrons -- emitted by a radioactive source ionize atoms of a semiconductor, creating uncompensated charge carriers. In the presence of a static field of a p-n structure, the charges flow in one direction, resulting in an electric current. Batteries powered by beta decay came to be known as betavoltaics. The chief advantage of betavoltaic cells over galvanic cells is their longevity: Radioactive isotopes used in nuclear batteries have half-lives ranging from tens to hundreds of years, so their power output remains nearly constant for a very long time. Unfortunately, the power density of betavoltaic cells is significantly lower than that of their galvanic counterparts. Despite this, betavoltaics were used in the '70s to power some cardiac pacemakers, before being phased out by cheaper lithium-ion batteries, even though the latter have shorter lifetimes.
- DE1036413B issued in 1958, owned by RCA then GE Aerospace. Paul Rappaport
- See also, US2588254, issued in 1952, owned by Purdue.



Rappaport and Purdue Patents

US2588254, filed in 1952: Purdue

- We claim as our invention: 1. A device comprising a unitary body of germanium having a plurality of alternating regions of N-type and P-type characteristics and means connecting said regions in series aiding relationship.

DE1036413, filed in 1954: Paul Rappaport RCA

- 1. Primary voltage source in which the energy of nuclear radiation emanating from a radioactive material is directly converted into electrical energy by means of a semiconductor body containing a depletion layer, characterized in that the radioactive material (11) is arranged in the space between several rod-shaped semiconductor bodies (37) containing alternating p- and η-zones, and that every second depletion layer between these zones is electrically bridged.
  Referenced publications:
  German patent specification no. 842 694;

US2913510: Birden and Jordan-Early Thermogenerator

- 1. A radioactive cell comprising an evacuated outer envelope, a thermally-conducting capsule containing radioactive material characterized by emission of radiation selected from the group consisting of alpha particles and beta rays disposed therewithin, and a thermopile having two groups of alternate junctions and provided with a pair of output terminals forming the cell output, one group of junctions being in direct thermal contact with said capsule and electrically insulated therefrom and the other group being in thermal contact with said envelope whereby a temperature difference is maintained-across said thermopile. Issued 11/17/1959.

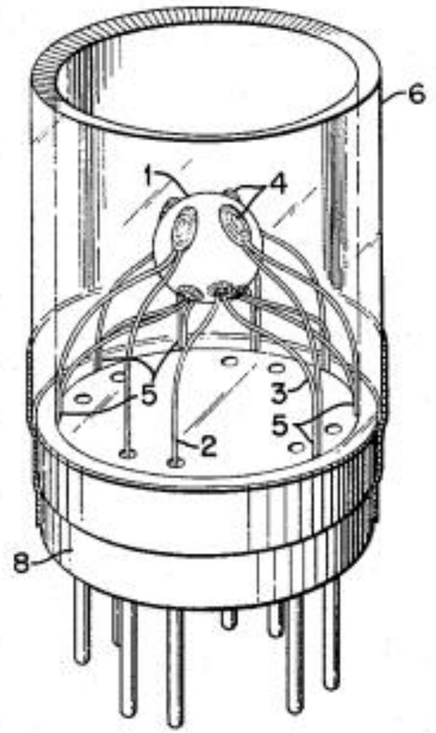
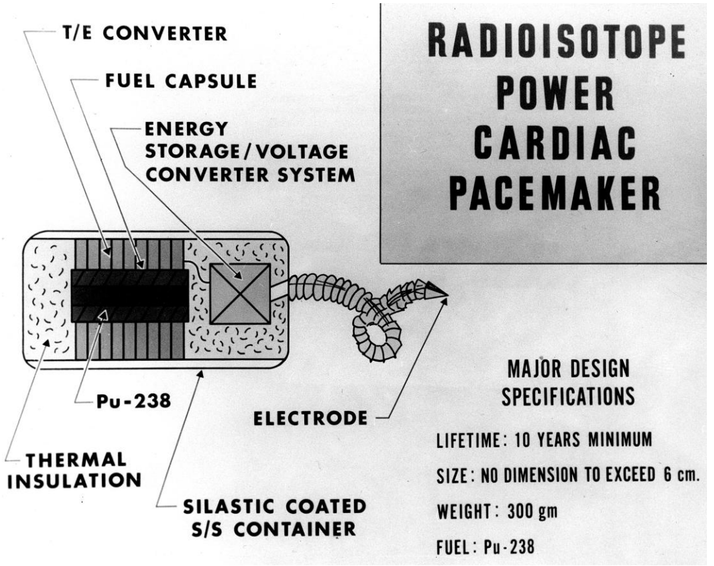


Fig. 1.

Uses of Nuclear Batteries—Early Days

- In the 1970s, doctors in Paris implanted the first nuclear-powered pacemaker, and over the next five years, at least 1,400 additional people received the devices, mostly in France and the United States. Encased in titanium, the batteries for these devices contained a radioactive isotope—typically about a tenth of a gram of plutonium-238—and could operate for decades without maintenance. The invention provided relief to a population of people who previously needed surgery every few years to change out their pacemaker's chemical battery.



ENERGY.GOV, Public domain, via Wikimedia Commons

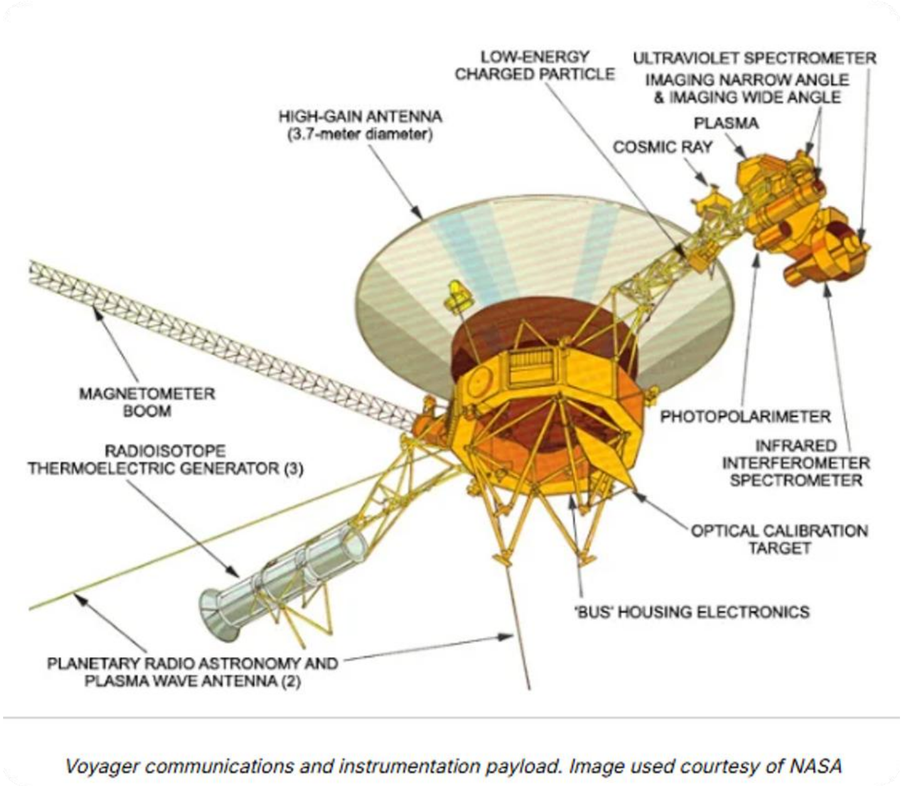
Uses of Nuclear Batteries—Early Days—Problems

- As time went on, the whereabouts of radioactive pacemakers became increasingly difficult to track. In the United States, the devices were supposed to be returned to the U.S. Department of Energy for plutonium recovery. But often, that didn't happen. Doctors changed jobs, manufacturers went out of business, patients died, and families forgot about their loved one's pacemaker. Too often, the radioactive material landed in crematoriums and coffins.
- Uncomfortable with the situation, regulators worldwide stopped use of the devices. The last known nuclear-powered pacemaker was implanted in 1988. After that, aside from a few specialty uses, such as deep-space probes and Siberian lighthouses, development and deployment of nuclear batteries effectively came to a halt.

Nuclear Batteries in Space

- One of the most compelling applications past and present is in uncrewed spacecraft for long-distance missions, which require decades of reliable power. Solar power works for missions close to the sun, but by the time a spacecraft gets to Jupiter, the available solar irradiance drops below 4 percent of that on Earth.
- That leaves nuclear fission and radioisotope power as the only viable options for deep-space missions. Fission is ideal for larger power needs in space, like NASA's proposed 100-kilowatt lunar nuclear reactor. But for lower, onboard power needs, nuclear batteries offer simpler designs and lower mass. The current radioisotope workhorse in space is the radioisotope thermoelectric generator, or RTG, which produces a few hundred watts.
- By the late 1950s and early 1960s, U.S. programs under the SNAP (Systems for Nuclear Auxiliary Power) umbrella developed RTGs for military and space applications, emphasizing reliability, long life, and containment in case of launch or reentry accidents. Early RTGs carried relatively small radioisotope inventories and were originally designed to burn up on reentry, though later designs were changed to fully contain the plutonium fuel in all credible accident scenarios.

Nuclear Batteries in Remote Areas



Voyager communications and instrumentation payload. Image used courtesy of NASA

• NASA's two Voyager missions, launched in 1977, each carry three RTGs that weigh about 38 kilograms, including 4.5 kg of plutonium-238. They're cylindrical and about the size of an office wastebasket. They initially produced 157 watts of electric power, but that drops over time as the plutonium-238 decays. A 157-W Voyager-based RTG that launched in 1977 will produce about 88 W today.

• Another good use for nuclear batteries is to supply power in remote locations on Earth. Beginning in the 1970s, for example, the Soviet Union deployed over 1,000 RTGs in northwestern Russia to power its uncrewed lighthouses, radio beacons, and weather stations. Most of these batteries ran on strontium-90, and each weighed about 2,000 kg. The United States has deployed hundreds of similar systems for remote power both on land and on the ocean floor, particularly for remote monitoring sites in the Arctic.

Nuclear Batteries in Warfare

- One new use where the benefits may outweigh the risks and costs is providing longer-lived power to soldiers—something the U.S. military has explored. Soldiers' missions often take them to remote or unstable locations where electricity may be unavailable, preventing them from charging their equipment. This forces soldiers to carry batteries, the weight and life of which limit their missions. Small nuclear batteries would provide a lightweight alternative—potentially 1/100 the weight—due to their higher energy density relative to that of chemical batteries. But they would need to be encased to shield soldiers from the radiation, and designed to withstand harsh conditions, which would add weight.
- Another potential new use for nuclear batteries is to power autonomous sensors or robots that communicate, move, or fly. One compelling use would be insect-size flying microdrones for civilian and military purposes. But collecting them at the end of their flights might be difficult and would also leave tiny bits of radioactive material littering the landscape.

Why Haven't Nuclear Batteries Been Widely Commercialized?

Safety and Radiation Risks

- The primary safety issue involves the radioactive materials used, such as plutonium-238 or strontium-90, which can pose health risks through radiation exposure if mishandled, damaged, or accidentally released during events like spacecraft re-entry. Environmental contamination from improper disposal or leaks is a major concern, potentially affecting soil, water, and ecosystems over long periods. Strict regulations and protective casings mitigate these risks, but public perception of nuclear technology often hinders acceptance.

Production and Cost Barriers

- Manufacturing nuclear batteries requires specialized facilities and materials, driving up costs significantly compared to conventional batteries. The process involves complex handling of radioactive isotopes, which demands rigorous safety protocols and limits scalability for mass production. Additionally, sourcing suitable isotopes can be challenging due to supply constraints and contamination issues with byproducts like other caesium isotopes in spent fuel.

Performance Limitations

- These batteries suffer from low power density and conversion efficiency, typically outputting only microwatts to milliwatts, making them unsuitable for high-power demands like consumer electronics or vehicles. Over time, radioactive decay leads to gradual power depletion, and the devices cannot be turned off, potentially causing unnecessary heat in applications. Technological hurdles, such as improving beta particle conversion without radioactive damage to components, further restrict their efficiency.

Disposal and Regulatory Challenges

- Spent nuclear batteries generate radioactive waste that requires secure, long-term disposal to prevent proliferation risks or theft for malicious use. Limited data on environmental impacts complicates regulatory approvals and environmental impact assessments. While innovations like diamond-based designs aim to address some issues, scalability and cost remain barriers for broader commercial viability.

Cost Comparison

Battery Type	Typical Cost per kWh (2025)	Power Output Range	Application Example
Lithium-ion	$85–$151	Watts to kilowatts	EVs, electronics, storage
Nuclear Battery	$300-$500+ for microwatts	Nanowatts to microwatts	Medical implants, clocks

How are Current Nuclear Batteries Better than Those of the 1970s, 80s?

- Modern designs, such as betavoltaic batteries, now use a broader range of radioisotopes and incorporate semiconductor materials that dramatically increase energy conversion efficiency—some prototypes achieve over 8% efficiency, compared to less than 1% in earlier models. This means less radioactive material is needed for the same output, reducing cost and potential risk.
- Recent nuclear batteries use advanced semiconductors, such as titanium dioxide and silicon carbide, and are sensitized with dyes or treated with citric acid to enhance electron collection and energy conversion. These improvements allow for much higher energy densities, sometimes ten times that of lithium-ion batteries, and longer lifespans, with some designs promising power for decades or even millennia.
- Modern nuclear batteries are designed to be much safer, with shielding that effectively blocks harmful radiation and materials that minimize leakage. Miniaturization has also advanced, enabling applications in medical implants, remote sensors, and space exploration where size and reliability are critical.
- Modern betavoltaic cells offer extremely high energy density but very low power density, typically in the microwatt to nanowatt range per device, even though they can deliver that power for decades. Commercial products such as tritium-based NanoTritium™ cells and similar devices are explicitly positioned as “long-life micro-power sources” for sensors, medical implants, aerospace electronics, and other ultra-low-power loads.

Beijing Betavolt



Image: Betavolt

Beijing Betavolt New Energy Tech Co.

- Beijing Betavolt is a private Chinese startup.
- Beijing Betavolt last year announced plans to commercially launch a 1-Watt battery in 2025. It may not have obtained a license and funding to do so. (from IEEE, **"The Unlikely Revival of Nuclear Batteries" 25 Aug. 2025)**
- Assuming Beijing Betavolt's device has a conversion efficiency of about 5 percent, the battery would have to hold about 20 curies, or 740 billion becquerels (0.4 grams), of nickel-63. This is well above the typical amount of nickel-63 available on the market, which is normally in the millicurie range.
- CN116598038 claims priority from RU2021137985
- CN119207858 claims priority from RU2023119639-RU2807315C1

CN116598038

- 1. A method for manufacturing a nuclear battery, characterized in that the method comprises:

  Multiple converters are fabricated on a diamond substrate using a specific process.

  Obtain the open-circuit voltage and short-circuit current of each of the plurality of converters;

  The plurality of converters are grouped to obtain at least two groups, each group including at least two converters connected in parallel; converters in the same group are mounted in parallel on a substrate isolated from the substrates of other groups; converters in multiple groups are mounted in a housing, and a β radiation source is mounted in the housing; multiple groups are connected in series.

  Specifically, the ratio of the difference between the maximum and minimum open-circuit voltages of the converters within each group to the minimum open-circuit voltage of the converters within the group is less than the target ratio. The number of converters in each group is determined based on the fact that, after the converters in each group are connected in parallel, the ratio of the difference in short-circuit current of each group to the minimum short-circuit current of multiple groups is less than the target ratio.

RU2907315C1-Priority

(54) **BETA-VOLTAIC CURRENT SOURCE AND METHOD OF ITS MANUFACTURE**

(57) Abstract:

FIELD: beta-voltaic current source.

SUBSTANCE: invention relates to a beta-voltaic current source (BVCS) and a method for its manufacture. BVCS contains a beta radiation source 1, a beta radiation converter 2 and an energy storage device 3. The source (1) of beta radiation is placed on a converter (2) of beta radiation having a substrate made of a single crystal of diamond. The energy storage device (3) is made in the form of a supercapacitor, in which a non-woven material made of long carbon nanotubes is used as an electrode material, and a concentrated solution of sulphuric acid is used as an electrolyte. The method includes forming a beta radiation converter (2) and placing a beta radiation source (1) on top of it, forming an energy storage device (3) in the form of a supercapacitor, in which a non-woven material made of long carbon nanotubes is used as an electrode material. A concentrated solution of sulphuric acid is used as an electrolyte, and a source (1) of beta radiation and an energy storage device (3) are combined to form a BVCS.

EFFECT: more compact dimensions of the BVCS with an increase in the output current of the BVCS in an extended operating temperature range.

10 cl, 2 dwg

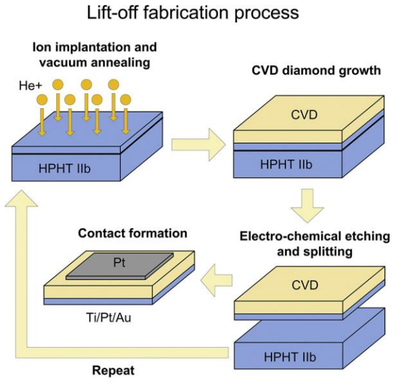
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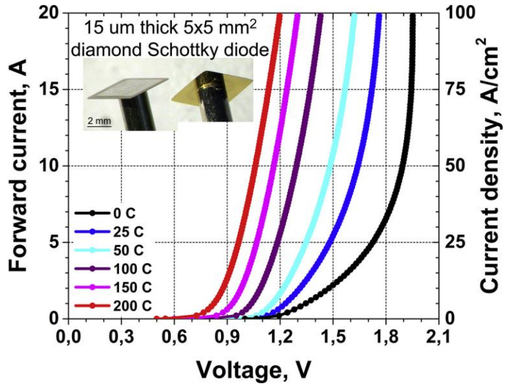
Inventors for CN116598038 and CN119207858-Beijing Betavolt

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GOLOVANOV Anton
BLANK Vladimir
BUGA Sergei
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Nuclear Diamond Battery from Russia

- A research team led by Vladimir Blank, the director of TISNCM (Technological Institute for Superhard and Novel Carbon Materials) and chair of nanostructure physics and chemistry at MIPT (Moscow Inst. Of Physics and Tech), came up with a way of increasing the power density of a nuclear battery almost tenfold. The physicists developed and manufactured a betavoltaic battery using nickel-63 as the source of radiation and Schottky barrier-based diamond diodes for energy conversion. The prototype battery achieved an output power of about 1 microwatt, while the power density per cubic centimeter was 10 microwatts, which is enough for a modern artificial pacemaker. Nickel-63 has a half-life of 100 years, so the battery packs about 3,300 milliwatt-hours of power per 1 gram -- 10 times more than electrochemical cells.
- The nuclear battery prototype consisted of 200 diamond converters interlaid with nickel-63 and stable nickel foil layers. The amount of power generated by the converter depends on the thickness of the nickel foil and the converter itself, because both affect how many beta particles are absorbed. Currently available prototypes of nuclear batteries are poorly optimized, since they have excessive volume. If the beta radiation source is too thick, the electrons it emits cannot escape it. This effect is known as self-absorption. However, as the source is made thinner, the number of atoms undergoing beta decay per unit time is proportionally reduced. Similar reasoning applies to the thickness of the converter.
- See RU174126U1





V.S. Bormashov, S.A. Terentiev, S.G. Buga, S.A. Tarelkin, A.P. Volkov, D.V. Teteruk, N.V. Kornilov, M.S. Kuznetsov, V.D. Blank,
Thin large area vertical Schottky barrier diamond diodes with low on-resistance made by ion-beam assisted lift-off technique,
Diamond and Related Materials,
Volume 75, 2017, Pages 78-84, ISSN 0925-9635,
https://doi.org/10.1016/j.diamond.2017.02.006.
(https://www.sciencedirect.com/science/article/pii/S0925963516306422)

What are Schottky Barrier-Based Diamond Diodes?

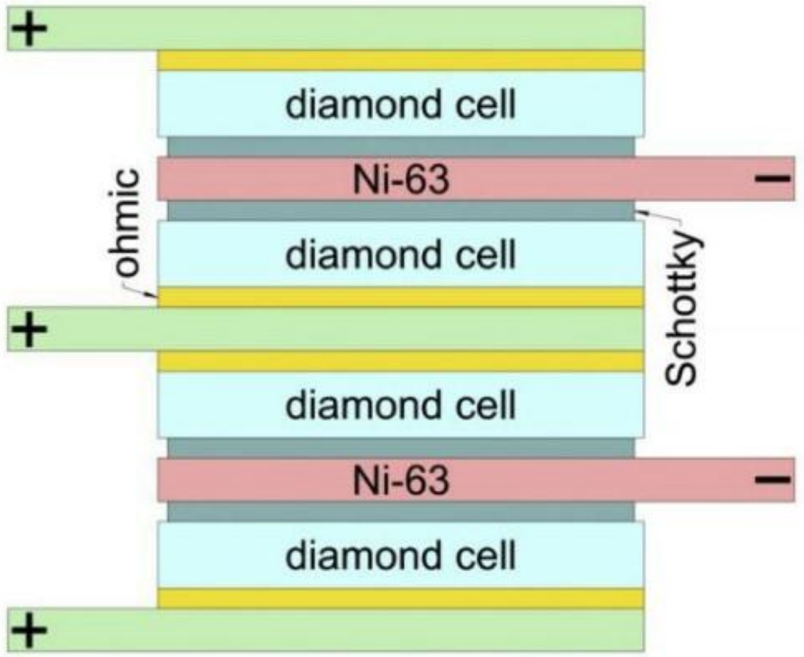
- Schottky barrier-based diamond diodes are rectifying devices in which the active semiconductor is diamond and the junction is formed between a metal and the diamond (rather than a p–n junction), creating a Schottky barrier that controls current flow.

Beijing Betavolt Invention

- Beijing Betavolt nuclear batteries generate current through the semiconductor transition of beta particles (electrons) emitted by the radioactive source nickel-63. In order to do this, Betavolt's team of scientists developed a unique single crystal diamond semiconductor with a thickness of only 10 microns.
- CN116598038A (China): "Nuclear battery and manufacturing method thereof." Assignee: Beijing Betavolt New Energy Technology Co., Ltd. It discloses forming multiple diamond semiconductor converters on a substrate, testing and grouping them by open-circuit voltage/short-circuit current, paralleling within groups and series-connecting groups inside a housing with a beta source (e.g., Ni-63, Pm-147, Sr-90) to improve efficiency and manage variability; it includes process details for diamond layers and contacts and states the target grouping tolerance (≤20%). Status: pending. Priority claimed to RU2021137985 (Dec 21, 2021).

From Article Published in 2018

The devices is made of stacks of isotope of nickel-63 sandwiched between a pa
of special semiconducting diodes called a Schottky barrier.



(V. Bormashov et al./Diamond and Related Materials)

V.S. Bormashov, S.Yu. Troschiev, S.A. Tarelkin, A.P. Volkov, D.V. Teteruk, A.V. Golovanov, M.S. Kuznetsov, N.V. Kornilov, S.A. Terentiev, V.D. Blank,
High power density nuclear battery prototype based on diamond Schottky diodes,
Diamond and Related Materials,
Volume 84, 2018, Pages 41-47, ISSN 0925-9635,
https://doi.org/10.1016/j.diamond.2018.03.006.
(https://www.sciencedirect.com/science/article/pii/S0925963517307495)

Beijing Betavolt

- The BV100 nuclear battery from Beijing Betavolt costs about $300 to $500 per unit, which is much higher than conventional batteries like lithium-ion or coin cells. For comparison, a standard lithium coin cell battery costs about $1.50 and lasts a few years, needing replacement every 1-3 years. Although BV100's initial price is higher, it offers 50 years of operation without recharging or replacement, which conventional batteries cannot match.
- In terms of energy density, the BV100 has over 10 times the energy density of typical lithium batteries, making it much more efficient in long-term energy storage despite the high upfront cost. Conventional batteries typically need frequent maintenance and replacements, adding to their lifetime cost. Thus, while the BV100 is more expensive initially, it could become cost-effective over time in applications requiring uninterrupted, maintenance-free power for decades.
- The coin-sized BV100 outputs 100 microwatts at 3 volts using nickel-63 decay and diamond semiconductors, targeting low-power uses like sensors, medical devices, and drones. It promises 50-year lifespan without charging, extreme temperature tolerance (-60°C to 120°C), and safe operation with no external radiation. A 1-watt version is planned, potentially stackable for higher power.

RU174126, Priority 12/27/2016

- Diamond Diode with Schottkey Barrier
- Tech Inst. of Superhard and New Carbon Materials
- 1. A diamond diode with a Schottky barrier, comprising a heavily boron-doped single-crystal diamond substrate of the p+ type, in contact with a lightly boron-doped homoepitaxial single-crystal diamond layer of the p^- type, a protective dielectric layer located on the surface of the lightly doped layer, a cathode in the form of an electrode with a metal contact forming a Schottky barrier, located partially on the surface of the lightly doped layer and partially on the surface of the protective dielectric layer, and an anode in the form of an ohmic contact placed on the heavily doped diamond substrate, characterized in that between the lightly doped single-crystal layer and the Schottky contact, functional zones are made of n-type diamond, characterized by a volume concentration of free charge carriers of at least 10^{17} cm^{-3} at room temperature, wherein the functional zones of n-type single-crystal diamond are made with a total area not exceeding 50% of the area of the Schottky contact.
- Tech Inst. Working on this tech since the early 1990s

RU170474: Radioisotope Sources: 12/27/2016 — Exp 2026

- 1. A direct current radioisotope source comprising a housing made of two metal parts which are positive and negative electrical poles and an insulating material, semiconductor diode structures, a radioactive isotope, cathodes and anodes, characterized in that a stack of semiconductor diode structures is placed in the housing, which are made of a layer of a heavily boron-doped synthetic diamond substrate and a high-purity or lightly boron-doped diamond film, a cathode and an anode are created on opposite sides of each of the diode structures, and layers of conductive foil are placed between the diode structures, wherein the cathodes are electrically connected to each other through a foil layer, and the anodes are also electrically connected to each other through a foil layer, wherein a portion of each foil layer is made to extend beyond the geometric limits of the stack of diode structures, wherein the layers of foil made of radioactive material and located between the cathodes are made to partially extend to one side of the stack and form an electrical contact with the negative pole of the source, and the layers of foil located between the anodes are made to extend to the other side of the stack and form an electrical contact with the positive pole of the source.
- 2. Radioisotope constant current source according to claim 1, characterized in that the anode of the semiconductor diode structure is in the form of an ohmic contact by a heavily doped substrate, and the cathode is in the form of Schottky contact with the opposite side of the structure.
- 3. Radioisotope constant current source according to claim 1 and 2, characterized in that the thickness of the semiconductor diode structure is made of from 1 to 3, the mean free path of the decay products of radioactive material used in the synthetic diamond, and the thickness of the foil is made of radioactive material of from 0.5 to 2 run lengths of degradation products in foil material, wherein the foil is made of one or more isotopes selected from the group of nickel-63, tritium, promethium-147, strontium-90, americium-241, plutonium-238, plutonium-239.

RU2668229: Method for Manufacturing Semiconductor Converter

- 1. A method for manufacturing a semiconductor converter of ionizing radiation energy into electrical energy, including manufacturing an epitaxial layer on a semiconductor substrate and forming positive and negative contacts, characterized in that the substrate is made of type IIb diamond, a sacrificial layer and a residual layer are formed on one side of the diamond substrate by implanting ions with an energy of at least 100 keV, followed by annealing the substrate in a vacuum or inert gas atmosphere at a temperature of 700 to 2000°C, then an epitaxial layer of type IIb diamond with a thickness of 5 to 50 μm is synthesized on the residual layer, the synthesized diamond layer is removed from the ends of the substrate, then the sacrificial layer is removed by electrochemical etching in a strong oxidizer, the epitaxial layer of diamond with the residual layer is separated from the main part of the substrate, a positive contact of the converter is formed on the residual layer, then the diamond epitaxial layer is exposed to ionizing radiation with a wavelength of no more than 200 nm and a power of no less than 50 μW/cm^2 in an oxygen atmosphere at a pressure of 10-50 kPa for no less than 5 minutes, or the diamond epitaxial layer is heated to a temperature of 600-700°C in an oxygen atmosphere for no less than 5 minutes, or the diamond epitaxial layer is exposed to oxygen plasma at a pressure of 0.5-20 Torr at a power density of 10-2000 mW/cm^2 for no less than 20 seconds, and a negative contact of the converter is formed on the diamond epitaxial layer.
- Expires 2037

RU2640788: Method for Obtaining Doped Diamond Monocrystal: Exp 2036

- A method for producing alloyed diamond, including the effect of high pressure and temperature on a reaction system of carbon in the form of graphite and phosphorus, characterized in that nitrogen is additionally introduced into the reaction system in the following ratio of components, wt.%: carbon 95.0-97.0; phosphorus 3.0-5.0; adsorbed nitrogen 0.001&0.0005, wherein a blank in the form of a washer is prepared from graphite powders with an admixture of nitrogen and phosphorus and placed on a blank in the form of a washer made of a solvent metal alloy made of iron, aluminum and carbon with the following content of components, wt.%: iron 92.5-95.0; aluminum 0.5-2.5; carbon 4.0-5.0, wherein a cesium chloride substrate is placed under the washer made of the metal-solvent alloy, into which a seed diamond single crystal is preliminarily pressed, oriented with its (100) face parallel to the plane of the metal-solvent washer, and the temperature in the diamond growth zone is set at 100-250-C higher than the melting temperature of the metal-solvent alloy and is held at this temperature for 50 to 150 hours, wherein the diamond is obtained in the pressure range of 5.5-6.0 GPa with a temperature difference between the seed crystal and the carbon-nitrogen-phosphorus source of 20-50pC. A method for producing alloyed diamond, including the effect of high pressure and temperature on a reaction system of carbon in the form of graphite and phosphorus, characterized in that nitrogen is additionally introduced into the reaction system in the following ratio of components, wt.%: carbon 95.0-97.0; phosphorus 3.0-5.0; adsorbed nitrogen 0.001&0.0005, wherein a blank in the form of a washer is prepared from graphite powders with an admixture of nitrogen and phosphorus and placed on a blank in the form of a washer made of a solvent metal alloy made of iron, aluminum and carbon with the following content of components, wt.%: iron 92.5-95.0; aluminum 0.5-2.5; carbon 4.0-5.0, wherein a cesium chloride substrate is placed under the washer made of the metal-solvent alloy, into which a seed diamond single crystal is preliminarily pressed, oriented with its (100) face parallel to the plane of the metal-solvent washer, and the temperature in the diamond growth zone is set at 100-250-C higher than the melting temperature of the metal-solvent alloy and is held at this temperature for 50 to 150 hours, wherein the diamond is obtained in the pressure range of 5.5-6.0 GPa with a temperature difference between the seed crystal and the carbon-nitrogen-phosphorus source of 20-50pC.
- Cited in CN117026356 and CN116180237 (Univ. Sichuan)

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High power density nuclear battery prototype based on diamond Schottky diodes

V.S. Bormashov [a c], S.Yu. Troschiev [a], S.A. Tarelkin [a], A.P. Volkov [a], D.V. Teteruk [a], A.V. Golovanov [a], M.S. Kuznetsov [a], N.V. Kornilov [a], S.A. Terentiev [a], V.D. Blank [a b c]

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Betavolt: 4th Generation Diamond Semicond

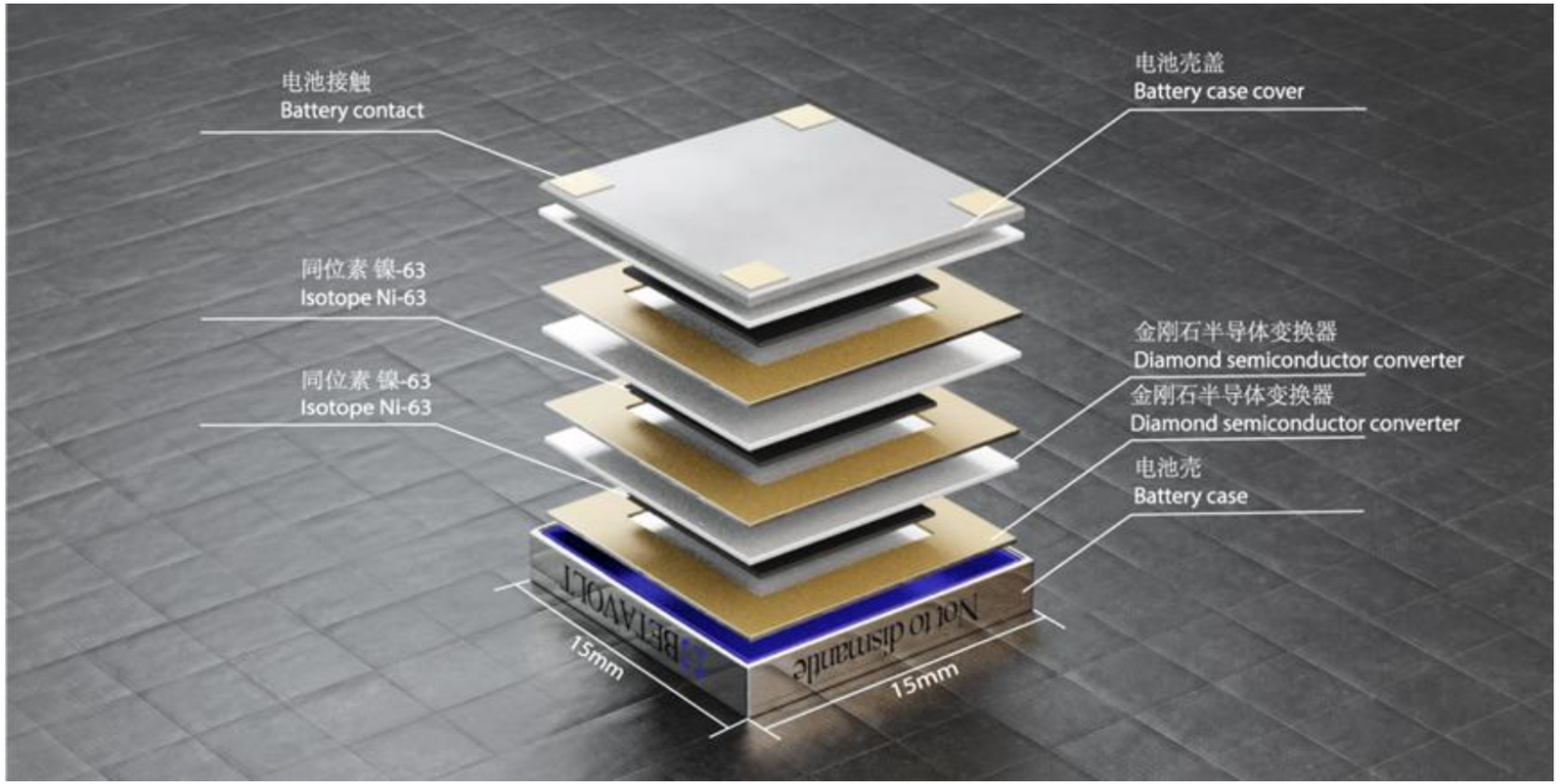


Image: Betavolt

University of Bristol aka Arkenlight

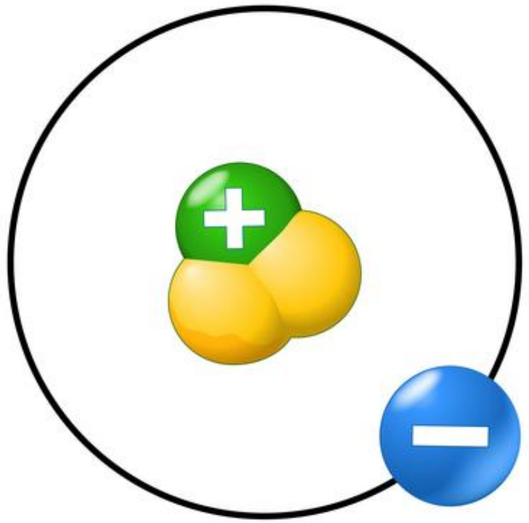
- In 2016 a team of physicists and chemists from the University of Bristol made a ‘diamond battery’ that used Carbon-14 in the form of diamond-like carbon as beta radiation source. Later prototypes found nickel-63 to be a better source with diamond non-electrolytes/semiconductors for energy conversion.
- The Bristol group extracted carbon-14 isotopes from irradiated graphite from former nuclear power plants. Tom Scott and his colleagues incorporated this long-lived radioisotope into lab-grown diamond to generate current. In 2020, the Bristol researchers founded Arkenlight to develop such a battery and unveiled the first ever carbon-14 diamond and diode devices in September 2025.
- ‘They’ve been turning the irradiated graphite into diamond film, which itself is a wide-band gap semiconductor,’ says Rushton. ‘You’ve got diamond made from a beta emitter, which irradiates itself and creates electricity. ’ Since carbon-14 has a half-life of 5730 years, the batteries could provide intermittent power for thousands of years.
- It’s these extended lifetimes of nuclear batteries that make them particularly well-suited for applications like space exploration, and long-term monitoring of infrastructure or challenging environments. ‘Such applications could include deep-sea exploration, space missions or remote monitoring stations,’ says Wang.
- Tom Scott and Neil Fox



https://www.arkenlight.co.uk/news

Arkenlight Battery Products

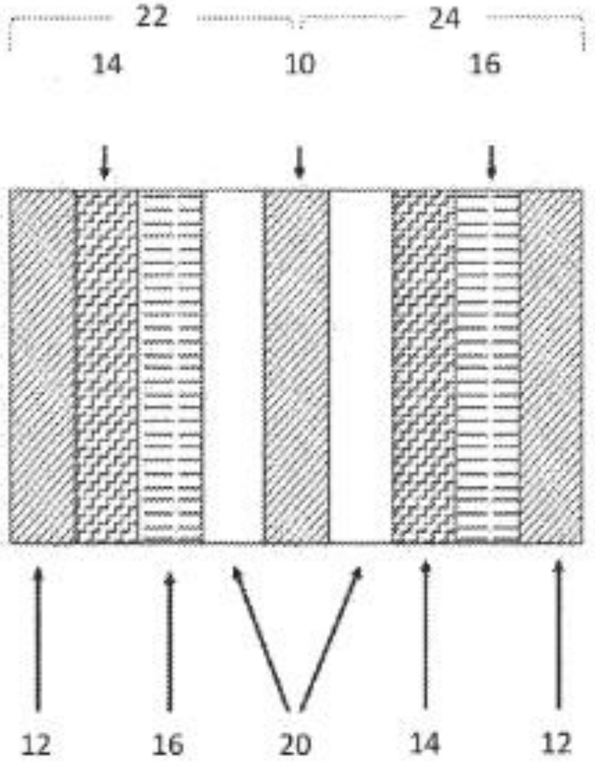
- Arkenlight has sold a type of battery, but not the diamond-based nuclear battery that has received the most attention. The company has been selling a product called a "betalight voltaic," which is a tritium-based battery used for sensor pods in the nuclear industry. This product is at a high technology readiness level (TRL 9) and has been available in the marketplace for some time, providing up to 35 microwatts of power for low-power applications. Arkenlight charges approximately £1,000 (~$1,200 USD) for its tritium battery.
- However, Arkenlight's more advanced diamond-based nuclear batteries—using carbon-14 or tritium embedded in synthetic diamond—are still in the prototype or pilot-scale production stage and have not yet been sold commercially as of late 2025. These batteries are being developed for ultra-long-life, maintenance-free power for sensors, IoT devices, and space applications, but are not yet integrated into major procurement programs or widely available for purchase.



Tritium

Arkenlight—Univ. Of Bristol Neil Fox US11302456-EP, CA, JP, GB

- A team of physicists and chemists from the University of Bristol have grown a man-made diamond that, when placed in a radioactive field, is able to generate a small electrical current.
- 1. An electrical power source comprising a semiconductor, the semiconductor comprising a diamond material and a radioactive source embedded within the diamond material, wherein the radioactive source comprises a beta-emitting radioisotope and atoms of the radioisotope are substitutionally or interstitially integrated into the diamond material,
- wherein the diamond material comprises a plurality of regions in the form of layers within a continuous crystal lattice of the diamond material, and
- wherein at least one layer of the diamond material comprises the radioactive source and at least one layer of the diamond material does not comprise the radioactive source.



City Labs Commercial Products

- The flagship offering is the P100 Series NanoTritium™ battery, which is a tritium-based betavoltaic battery designed for low-power, long-life applications such as sensors, microelectronics, and medical devices. This battery is currently available for commercial purchase, with prices starting around $5,250 per unit, and is being used in fields like aerospace, defense, medical implants, and industrial monitoring. Pricing for different voltage models in past references ranged from around $3,500 to $4,500, but the most current base pricing is listed at $5,250 per battery.

City Labs

- City Labs focuses wholly on tritium, a radioisotope of hydrogen that emits beta particles. These betavoltaic devices act similarly to photovoltaics. However, instead of photons hitting a solar material, beta particles bombard a semiconductor and knock out electrons, creating electron–hole pairs. A charge difference builds up between the semiconductor’s positive side with an excess of holes (p-type layer) and its negative side with an excess of electrons (n-type layer).

Customers of City Labs Nuclear Batteries

- Lockheed Martin and Northrop Grumman for aerospace and defense applications, such as durable power sources for equipment in extreme environments and secure crypto key retention systems.
- United States Air Force Research Laboratory and NASA for research and development projects, including powering satellites, probes, and advanced sensors.
- Welltec® for down-hole drilling technology, where the batteries are used to monitor wells in harsh conditions.
- Purdue University and NSWC Crane for collaborative research on improving battery performance for defense and aerospace.
- Medical device developers for applications such as pacemakers and other implants requiring long-lasting, maintenance-free power.
- Industrial and surveillance technology companies for sensors, RFID tags, and other devices needing reliable, long-life power in remote or extreme environments.

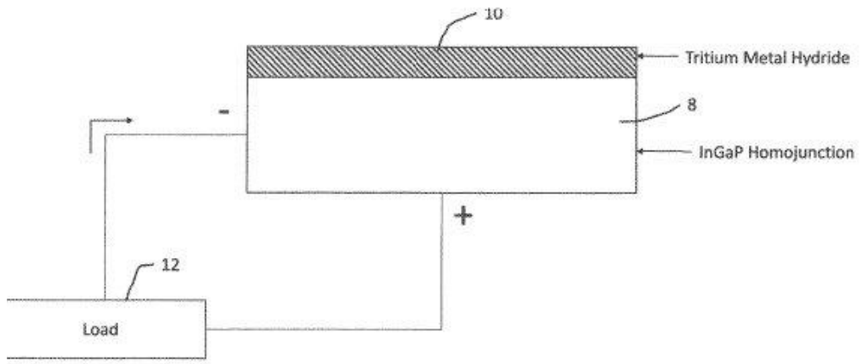
City Labs Patents-8 US Pats + Applns

US9711250: Increase surface area to increase efficiency by absorbing more beta particles

1. A betavoltaic power source comprising

- a source of beta particles;
- a substrate with shaped features defined therein;
- a InGaP betavoltaic junction disposed between the source of beta particles and the substrate, and also having shaped features therein responsive to the shaped features in the substrate, the InGaP betavoltaic junction device for collecting the beta particles and for generating electron hole pairs responsive thereto; and

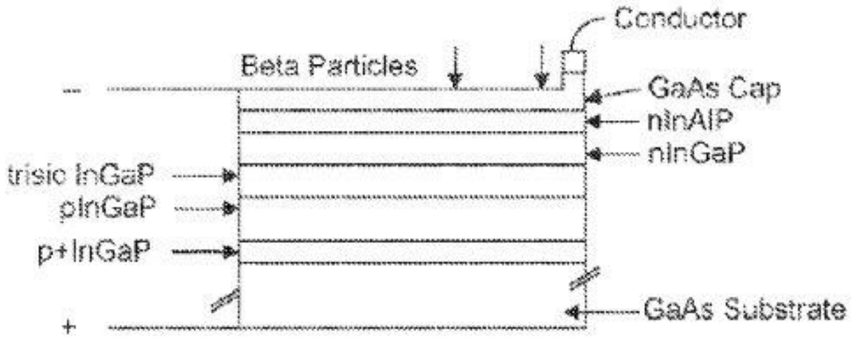
  wherein the substrate comprises a GaAs substrate having an orientation of (100) and surfaces of the shaped features having an orientation of (100), (010), or (001).



City Labs: US9887018; Expires 20291.

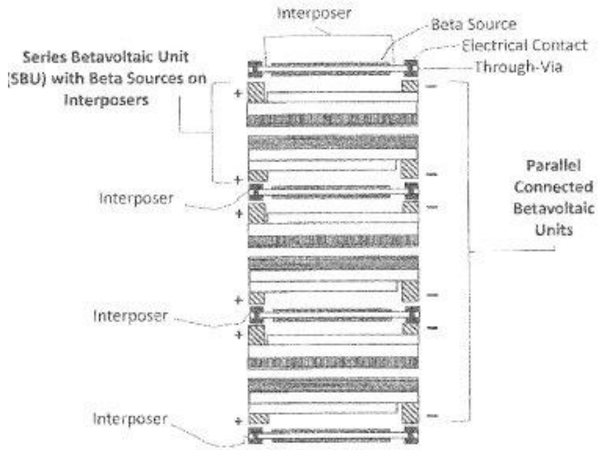
1. A device for producing electricity, comprising:

- a doped substrate defining a contact surface and a top surface;
- a first terminal in contact with the contact surface;
- an indium gallium phosphide semiconductor material comprising a plurality of indium gallium phosphide material layers disposed in contact with the top surface, each layer of the plurality of indium gallium phosphide layers having a predetermined dopant concentration and doped with either n-type dopants or p-type dopants;
- a beta particle source proximate an exposed surface of the semiconductor material, the beta particle source for emitting beta particles that penetrate into the exposed surface;
- a second terminal on the exposed surface of the semiconductor material;
- the semiconductor material for producing current between the first and second terminals responsive to the beta particles penetrating into the semiconductor material; and
- a back surface field reflector layer comprising one of InAlP, InAlGaP and ZnSe.



City Labs Patents

- **US12170154: US Only—Expires 2037**
- A device for producing electricity. The device includes a substrate having spaced apart first and second surfaces and doped a first dopant type, first semiconductor material layers disposed atop the first substrate surface and doped the first dopant type, and second semiconductor material layers disposed atop the first semiconductor material layers and doped a second dopant type. A first contact is in electrical contact with the second substrate surface or in electrical contact with one of the first semiconductor material layers. A beta particle source emits beta particles that penetrate into the semiconductor material layers; the beta particle source is proximate the uppermost layer of the second plurality of semiconductor material layers. A second contact is in electrical contact with one of the second plurality of semiconductor material layers. In one embodiment, bi-polar contacts (the first and second contacts) are co-located on each major face of the device.



Infinity Power



https://www.prnewswire.com/news-releases/strongest-nuclear-battery-is-revealed-by-us-company-302169533.html

- No commercial nuclear battery at this time for Infinity Power—Still in prototype stage
- Infinity Power will use nickel-63 in its coin-size battery, but may need less of it because of the novel electrochemical conversion process it has developed. The company says its conversion efficiency exceeds 60 percent—about six times as efficient as the best radioisotope power generators.
- In Infinity's design, the isotope is dissolved or suspended in a proprietary liquid electrolyte. The decay of the radioisotope produces high-energy beta particles that ionize the electrolyte, creating a potential difference between the anode and cathode immersed in the solution and driving electron flow through an external circuit to produce electricity.

Infinity Power

Instead of using thermoelectric couples or a semiconductor junction, Infinity Power uses a specially designed electrochemical system in which the radiation drives redox reactions that separate charge and generate a usable electrical current.

Ohio State University

- Ohio State announces battery cell research center in partnership with Honda, Schaeffler | WOSU Public Media
- Ohio State University is actively working on developing a nuclear battery that converts nuclear waste, specifically gamma radiation from isotopes like cesium-137 and cobalt-60, into electricity. This research involves a novel approach using scintillator crystals that emit light when exposed to radiation, combined with solar cells to convert that light into usable electrical power. The team has successfully created a prototype small enough to power microelectronics, and this work is seen as a promising pathway to utilize radioactive waste for sustainable energy production.
- Scientists design novel battery that runs on atomic waste

Ohio State

- Using a combination of scintillator crystals, high-density materials that emit light when they absorb radiation, and solar cells, the team, led by researchers from The Ohio State University, demonstrated that ambient gamma radiation could be harvested to produce a strong enough electric output to power microelectronics, like microchips.
- To test this battery, which is a prototype about 4 cubic centimeters small, researchers used two different radioactive sources, cesium-137, one of the most significant fission products that comes from spent nuclear fuel, and cobalt-60, a nuclear activation product. The battery was tested at Ohio State's Nuclear Reactor Laboratory. The NRL supports student and faculty research, student education, and service to industry – it does not produce electrical power.

Ohio State

- Their results showed that when cesium-137 was used, the battery generated 288 nanowatts. Yet with the much stronger isotope cobalt-60, the battery produced 1.5 microwatts of power, about enough to switch on a tiny sensor.
- Although most power outputs for homes and electronics are measured in kilowatts, this suggests that with the right power source, such devices could be scaled up to target applications at or beyond the watts level, said Raymond Cao, lead author of the study and a professor in mechanical and aerospace engineering at Ohio State.
- The study was recently published in the journal *Optical Materials: X.*

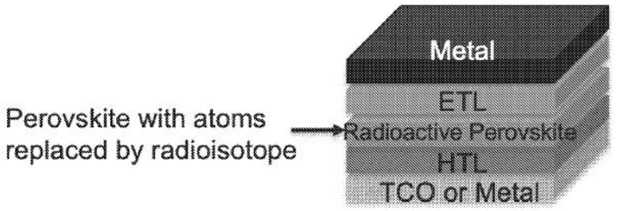


https://engineering.osu.edu/people/cao.152

US12213327

1. A charge or electricity generating device comprising:

- a first electrode;
- an electron transport layer;
- a perovskite layer;
- a hole transport layer; and
- a second electrode;
- wherein the electron transport layer is disposed between the first electrode and the perovskite layer such that the electron transport layer is in physical contact with the first electrode and the perovskite layer;
- wherein the perovskite layer is disposed between the electron transport layer and the hole transport layer such that the perovskite layer is in physical contact with the electron transport layer and the hole transport layer;
- wherein the hole transport layer is disposed between the second electrode and the perovskite layer such that the hole transport layer is in physical contact with the perovskite layer and the second electrode;
- wherein the perovskite layer comprises a perovskite having a crystal lattice comprising a plurality of atoms, wherein at least a portion of the plurality of atoms within the crystal lattice of the perovskite comprise a radioactive isotope having a half-life of 100 days or more, wherein each radioactive isotope replaces one atom that is a non-radioactive counterpart of the radioactive isotope, such that the perovskite intrinsically comprises one or more radioactive isotopes in its crystal lattice.



US12213327

Figure 3

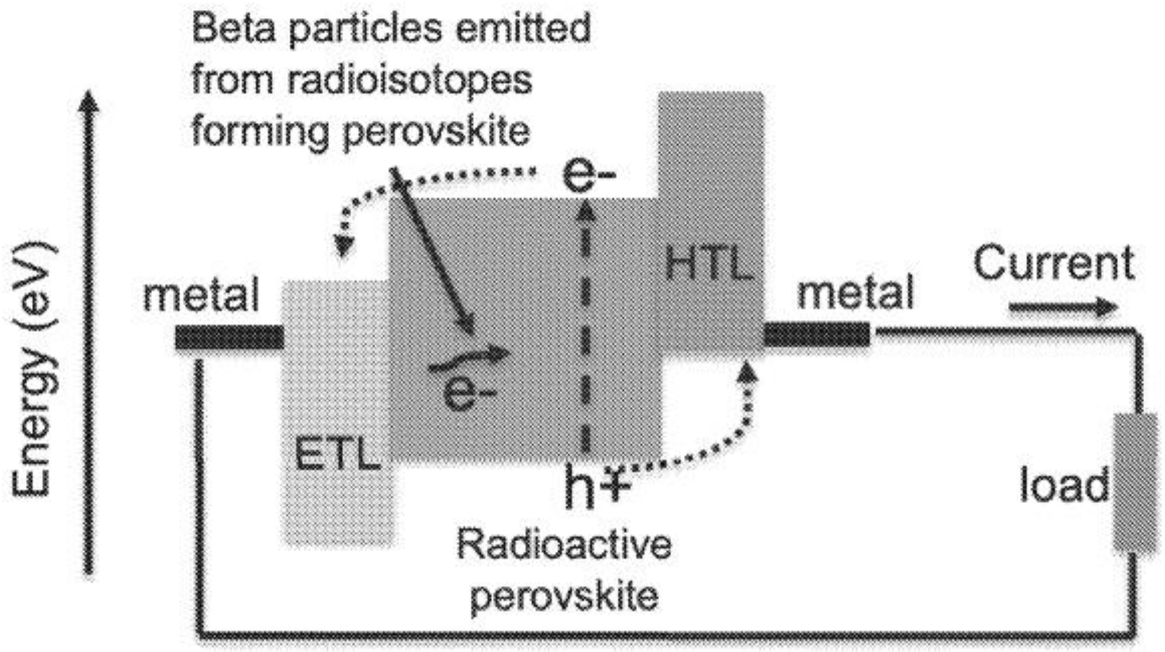


Figure 4

Daegu Gteongbuk Inst. Of Sci and Tech

- Daegu Gyeongbuk Institute of Science and Technology (DGIST) is actively developing nuclear battery technology, specifically betavoltaic batteries using radiocarbon (carbon-14), but there is no direct evidence in recent reports of formal collaboration with other institutions or companies on this specific project. The research is led by Professor Su-Il In and his team, and the work is funded by the National Research Foundation of Korea and DGIST's own research programs. While other groups, such as the University of Bristol in England, are also working on similar nuclear battery technologies, there is no indication of a joint project or partnership between DGIST and these external groups as of late 2025. The DGIST team is focused on improving the semiconductor and energy conversion efficiency of their radiocarbon-based batteries, with potential applications in medical implants, remote sensors, and space exploration
- A safe nuclear battery that could last a lifetime - American Chemical Society

UK Atomic Energy Authority

- Partnering with the University of Bristol.
- EP4578030—Tritium Extraction

Soochow University

- Soochow University is actively working on nuclear battery technology, particularly focusing on the use of americium as a radioactive source. The university's research team, led by Professor Shuao Wang, has developed a novel micro-nuclear battery that converts alpha radiation from americium into electricity with unprecedented efficiency—reportedly 8,000 times more efficient than previous designs.

Collaboration Details

- Soochow University is collaborating with several other Chinese research institutions on this project, specifically targeting the development and optimization of nuclear batteries using americium, a radioactive element derived from nuclear reactor waste. While there is no explicit mention of international partnerships in the most recent reports, the research is part of a broader effort within China to advance nuclear battery technology for applications such as medical devices, sensors, and space exploration.

Current Status and Future Goals

- The Soochow-led team is working to further improve the efficiency and safety of their nuclear battery design, with ongoing experiments to determine optimal concentrations and configurations for safe use. The battery is still in the research and development phase, with the goal of making it practical for real-world applications, though it currently produces much less power than conventional batteries.
- In summary, Soochow University is collaborating with other Chinese research institutions on nuclear battery development, focusing on americium-based designs, and is making significant progress in efficiency and safety.
- High-Performance Radioluminescent Nuclear Battery Based on Ultrabright $Cs_3Cu_2I_5$:Tl Single Crystal Scintillator | IEEE Journals & Magazine | IEEE Xplore

Alpha Decay Batteries—Soochow Chow U

- Alphas-decay batteries
- Nuclear batteries can be based on a range of different radioisotopes and each of these brings different advantages and challenges. ‘The alpha-decay radioisotopes possess a higher decay energy,’ notes Yaxing Wang at Soochow University in Suzhou, China. He was part of a team that recently reported a dramatic boost in the efficiency of converting americium-243 radioisotope decay into usable electrical power.
- A standard design for micronuclear batteries based on alpha decay involves two key layers: a radiation source, and a scintillator made of a radioluminescent material that releases photons when it is bombarded by alpha particles. These photons then drive a photovoltaic cell to produce an electric current. But in Wang’s new setup, the radioisotope is incorporated alongside a terbium-based transducer unit within a single crystalline material.
- ‘The decay energy of α-particles from the radioisotope can be very efficiently deposited on the neighbouring high-impedance transducer unit at distances on the Ångström scale, minimising the unwanted energy loss,’ Wang explains.
- As a result, the new design is able to convert alpha-decay energy into light 8000 times more efficiently than a setup based on separate americium and terbium layers. Overall, Wang’s radiophotovoltaic battery produces twice as much power per decay event than the previous record-holder, a battery based on the alpha decay of plutonium-238 that was developed 16 years ago.

CN116768719

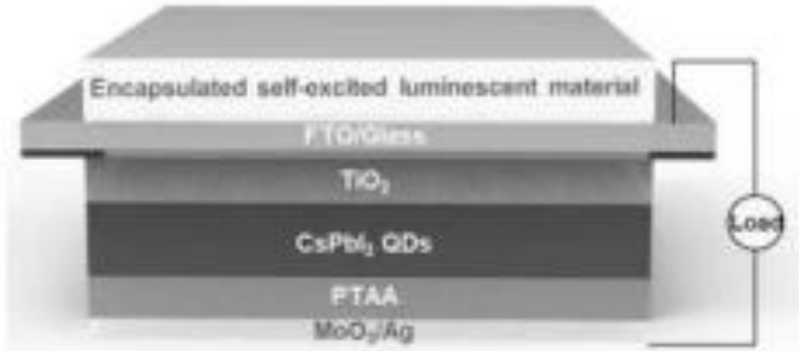
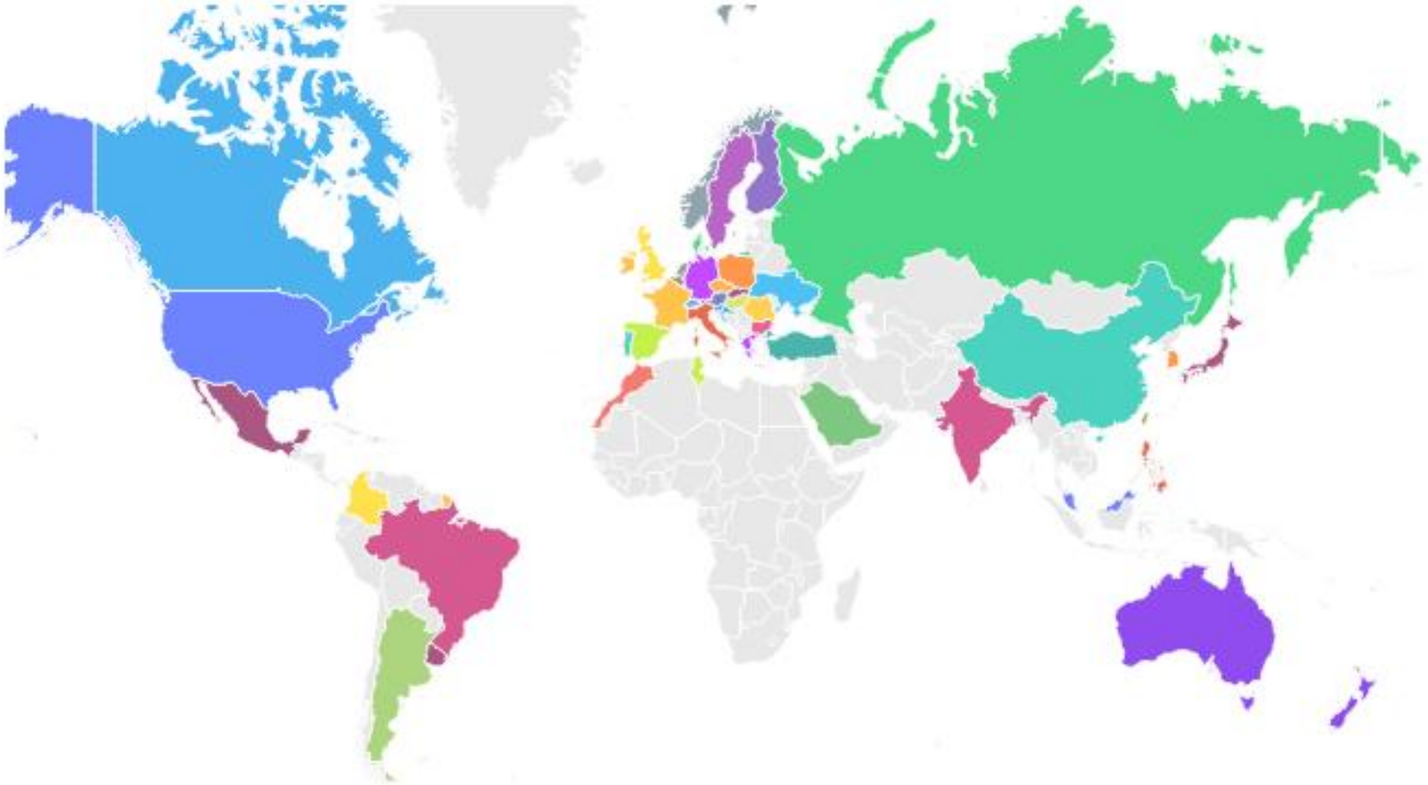


图5

Top countries/regions

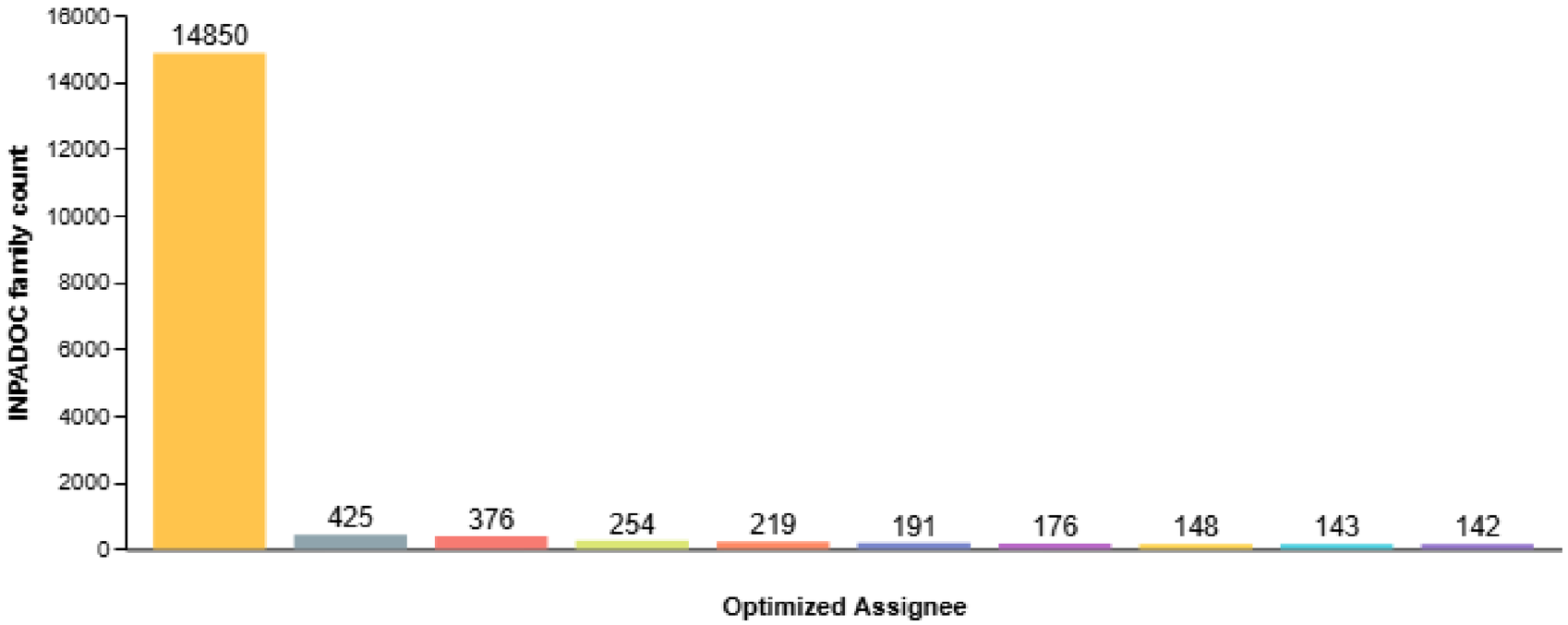
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- 1. China, Mainland(9921)
- 2. EP(394)
- 3. Japan(2094)
- 4. Korea, Republic of(1169)
- 5. Other(566)
- 6. Russian Federation(121)
- 7. Taiwan(216)
- 8. United Kingdom(136)
- 9. United States(1274)
- 10. WO(495)

Top Optimized Assignees

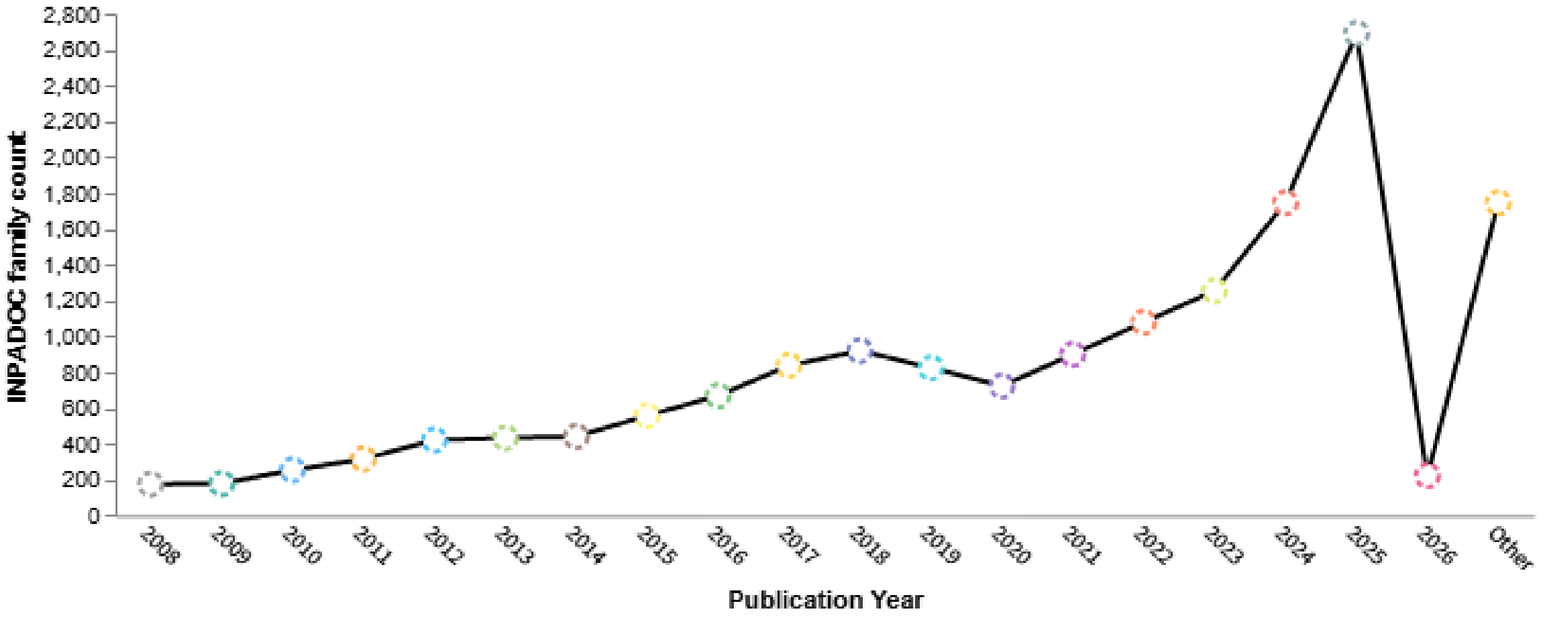
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- 1. Other(14850)
- 2. CHINESE ACADEMY OF SCIENCE(425)
- 3. STATE GRID CORP OF CHINA(376)
- 4. CHINA NUCLEAR POWER DESIGN INST(254)
- 5. CHINA GEN NUCLEAR POWER CORP(219)
- 6. LG CHEM LTD.(191)
- 7. TOSHIBA CORP(176)
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- 10. SAMSUNG SDI CO LTD(142)

Patent publishing trends

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1. 2008(176)
2. 2009(178)
3. 2010(254)
4. 2011(315)
5. 2012(422)
6. 2013(433)
7. 2014(441)
8. 2015(557)
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12. 2019(824)
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14. 2021(899)
15. 2022(1079)
16. 2023(1254)
17. 2024(1745)
18. 2025(2691)
19. 2026(223)
20. Other(1745)

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