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Research Article

# Comparison of NANOR®-type LANR Components to $^{238}$Pu as a Heat Source for Space Flight

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**Abstract**

Plutonium-238 creates heat by its natural radioactive decay to alpha particles and generates electricity using thermoelectric generators (0.57 W/g, but ∼25 mW/g when shielding and supports are considered). The technology has been proven to work on more than two dozen US space vehicles. Yet, two problems exist: (1) NASA has currently only ∼1 kg of isotope exceeding the specifications requisite for space power delivery and (2) the safety of $^{238}$Pu. There is a need to consider alternative LANR systems. As a heat producing source, the Series 6 NANOR®-type components deliver up to 150 mW of excess power, and so less than a dozen of them could replace 1 g of $^{238}$Pu in the power density metric. If present limitation of higher temperatures can be achieved, then the most efficient and safe deep space energy production systems in the future may include preloaded LANR components.
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*Keywords:* Electricity production, NANOR®-type component, Plutonium, Safety, Space exploration, Space power delivery, Thermoelectricity

## 1. Space Exploration: Big Changes are Coming

NASA will now permit some future spacecrafts to use $^{238}$Pu to heat a thermoelectric generator for electrical power, and "keep spacecraft elements warm" – which is a reversal from its previous position (Fig. 1) [1,2]. This recurrent technology will rapidly advance planetary science missions such as those planned to the far side of the moon (given its two-week lunar night [3–6]).

However, given the other dire issue associated with of $^{238}$Pu, one must consider if there are other alternatives. Is it really the best or the safest? To facilitate the analysis, after reviewing both energy production sources, $^{238}$Pu and lattice assisted nuclear reactions (LANR) [7–16] in general, and the NANOR®-type LANR component, in particular, Section 4.3 [15,16], several metrics will be used and addressed, including power density, energy density, maximum temperature achieved, temperature differential achieved, lifetime, and safety.

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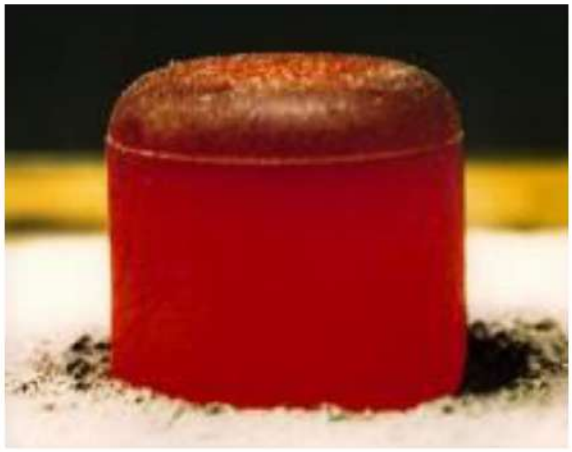

**Figure 1.** A spontaneously warm pellet of pure $^{238}$Pu. In the picture, the metallic pellet is red hot after its insulation (to contain the heat) was removed. As with LANR, this so-called "free energy" is actually from nuclear de-excitations.

## 2. Background

### 2.1. Plutonium is an unusual element

There are 15 different plutonium isotopes, all radioactive, emitting alphas (helium nuclei) and gamma radiation (high energy penetrating ionizing radiation) as they decay. All Pu isotopes are fissionable and two are fissile (capable of supporting a chain reaction by sustaining fission from neutrons of any energy). Each fission yields ∼200+ MeV (82 TJ/kg). Plutonium-244 is the most stable isotope with the longest half-life, 82 million years, and the isotope which is usually cited in tables. It existed on Earth in trace amounts since before the atomic age only in uranium deposits, such as at Oklo, Africa. It is not found elsewhere in the Earth's crust. Things changed in the atomic age, and today many tons of plutonium drift through the Earth's biosphere because of atmospheric weapons testing which continued through the 1960s. Some of the most relevant plutonium isotopes in the atomic age are listed in Table 1.

Pure metallic plutonium has six crystalline structures, the most known for any element. The alpha phase is brittle and hard like cast iron, and ignites rapidly as it is oxidized in air to form $PuO_2$, which is the commercial ceramic form. The other metallic phases are each different, some only workable as alloys.

**Table 1.** Plutonium isotopes.

| | |
|---|---|
| $^{238}$Pu | Half-life 87.5 years, alpha decay to $^{234}$U, releasing 5.6 MeV |
| $^{239}$Pu | Fissile (half-life 24,000 years, alpha decay to $^{234}$U) |
| $^{240}$Pu | Fertile (half-life 6,560 years, alpha decay to $^{236}$U) |
| $^{241}$Pu | Fissile (half-life 14.4 years, beta decay to $^{241}$Am) |
| $^{242}$Pu | Half-life 374,000 years, alpha decay to $^{238}$U |
| $^{244}$Pu | Which is usually cited, and alpha decays to $^{240}$U |

### 2.2. $^{238}$Pu Synthesis and production

There are two different grades of plutonium: reactor-grade and weapons-grade. They differ slightly isotopically. Both are a potential proliferation risk. Reactor-grade plutonium comes from commercial nuclear reactors. It is obtained from spent nuclear fuel, and contains many isotopes of plutonium generated after the fuel has been irradiated ("burned"') for several $(3+)$ years.

This plutonium is important for these commercial reactors because although $^{238}$Pu makes up only one or two percent of spent fuel, it still creates a significant fraction of the reactor heat. This is because of its short half-life.

The first problem is that commercial reactor-grade plutonium is not useful for producing $^{238}$Pu for RTGs because of the tremendous difficultly in isotopic separation of pure $^{238}$Pu. Therefore, today $^{238}$Pu is obtained from uranium which is fast-irradiated during a brief 2–3 months interval within a weapons-grade plutonium production reactor.

Plutonium-238 was first synthesized by Glenn Seaborg, in 1940, using $^{238}$U as a target for deuterons. In this pathway, $^{238}$Np is first formed which then decays to $^{238}$Pu. A second production pathway for $^{238}$Pu uses irradiation of $^{237}$Np, obtained from reactor fuels and target recovery projects. That irradiation forms $^{238}$Np first, which then decays to $^{238}$Pu. This pathway was undertaken at Savannah River. The third pathway is to have $^{238}$Pu produced as a byproduct of weapons-grade $^{239}$Pu production (Fig. 2). At the Savannah River weapons reactor before 1988, $^{238}$Pu (contaminated with $\sim$16% $^{239}$Pu) difficult-to-achieve production recovery efficiencies improved from 3 to 98% finally permitting space exploration in a plethora of space craft (Section 3.2).

Plutonium is now made in nuclear reactors and salvaged from dismantled nuclear weapons. The most common plutonium isotope formed in a typical nuclear reactor is fissile $^{239}$Pu, formed by neutron capture from $^{238}$U (followed by beta decay). When fissioned, it yields the same energy as the fission of $^{235}$U. It takes $\sim$10 kg of nearly pure $^{239}$Pu to make a weapon. This much material requires 30 MW-years of reactor time, special processing, and a three month burn of uranium.

### 2.3. End of $^{238}$Pu production in 1988 and current prevalence

The US stopped all $^{238}$Pu production at the Savannah River Site reactors in 1988. In June 2000, the US and Russia agreed to each dispose of 34 tons of weapons-grade plutonium by 2014. To make up the difference in availability and


**Figure 2.** Irradiated neptunium at the ORNL fuel core. The blue color is Cherenkov radiation which emanates from spent fuel before it is removed from the High Flux Isotope Reactor (HFIR).

that required, since 1992, the USA bought ∼16.5 kg $^{238}$Pu from Russia for American spacecraft, until production and sales ceased in 2009. The US neptunium inventory was transferred to Idaho National Laboratory (INL) in 2008. In October 2016, Russia suspended its Agreement upon "a (Russian) presidential decree" [17].

Today, the total world generation of new reactor-grade plutonium is ∼70 tons per year. It is extracted from 1300 tons of used, burned fuel, but as discussed above, it is contaminated and not useful for space and similar applications. In the US, $^{238}$Pu inventory includes NASA (civil space) and other national security applications. As of March 2015, a total of 35 kg (77 pounds) of $^{238}$Pu was available for civilian space uses. However, only 1 kg has had $^{239}$Pu and the other contaminants removed resulting in an isotopic distribution meeting NASA specifications requisite for space power delivery.

### 2.4. Future $^{238}$Pu plans for production

In February 2013, a small amount of $^{238}$Pu was produced by the Oak Ridge's High Flux Isotope Reactor, and by December 2015, Oak Ridge National Laboratory reported that its researchers had successfully produced 50 g (1.8 ounces). To recover from the paucity of useful $^{238}$Pu, the US production rate target is 0.4 kg now and 1.5 kg $^{238}$Pu per year by 2025 [18]. However, generating larger quantities is quite complicated and involves moving a lot of radioactive material around (Fig. 3).

In March 2017, Ontario Power Generation (OPG) and its Venture Arm, Canadian Nuclear Partners, announced plans to produce $^{238}$Pu as a second source for NASA [19]. The plan is to use PNNL's $^{237}$Np targets, shipped to CNL's Chalk River Laboratories in Ontario, and there to be assembled into reactor bundles, then to have them sent to OPG's Darlington High Flux Isotope Reactor, there to be irradiated for ∼72 days to generate $^{238}$Pu.

Final removal requires the bundles returned to CNL for disassembly and chemical processing. The DOE's alternate complicated pathway uses a plutonium pipeline involving waypoints of ORNL, INL and Los Alamos National Laboratory. There is also a public–private partnership led by a company called Technical Solutions Management (TSM).

## 3. The Use of Plutonium in Space

### 3.1. The use of plutonium in space as a heat source

Obviously, space exploration needs heat and electricity, but solar irradiant power is too weak and just not feasible at the solar system rim. Therefore radioisotopes are one logical alternative to be used to heat instrumentation and to produce electricity. There are many radioisotopes known, but only 22 are safe enough, plentiful enough, and produce enough heat for the useful purpose of heating a deep-space probe (US National Academy of Sciences, 2009). Plutonium is a major contender, and a third of the heat generated by most nuclear power plants comes from plutonium.

Plutonium-238 creates heat by its natural radioactive decay to alpha particles. They collide with the nearby materials heating them up through collisions. Each gram of $^{238}$Pu has 1/238 mol, and therefore $2.53 \times 10^{21}$ plutonium atoms. The activity (decay rate of this sample) is 634 GBq with a decay rate of 634 billion per second. Each emitted alpha starts with 5.59 MeV and delivers $8.96 \times 10^{-13}$ J by its deceleration in the surrounding material which creates *de novo* heat. As it does, therefore each gram of $^{238}$Pu spontaneously generates 0.568 W of thermal power ("excess" thermal power). This continues decreasing through the half-life of 87.7 years.

In summary, the specific decay thermal power of $^{238}$Pu is 0.57 W/g which enables its use as a heat source, and as an electricity source in Radioisotope Thermoelectric Generators (RTGs) [20,21]. However, in the real world, RTGs necessarily have other materials including shielding which yields a net useful specific power of about 25W/kg plutonium. This makes the real world, effective decay thermal power of $^{238}$Pu only ∼25 mW/g. As discussed below, that thermal power is less than most Series 6 NANOR®-type components' excess power outputs (Section 5).

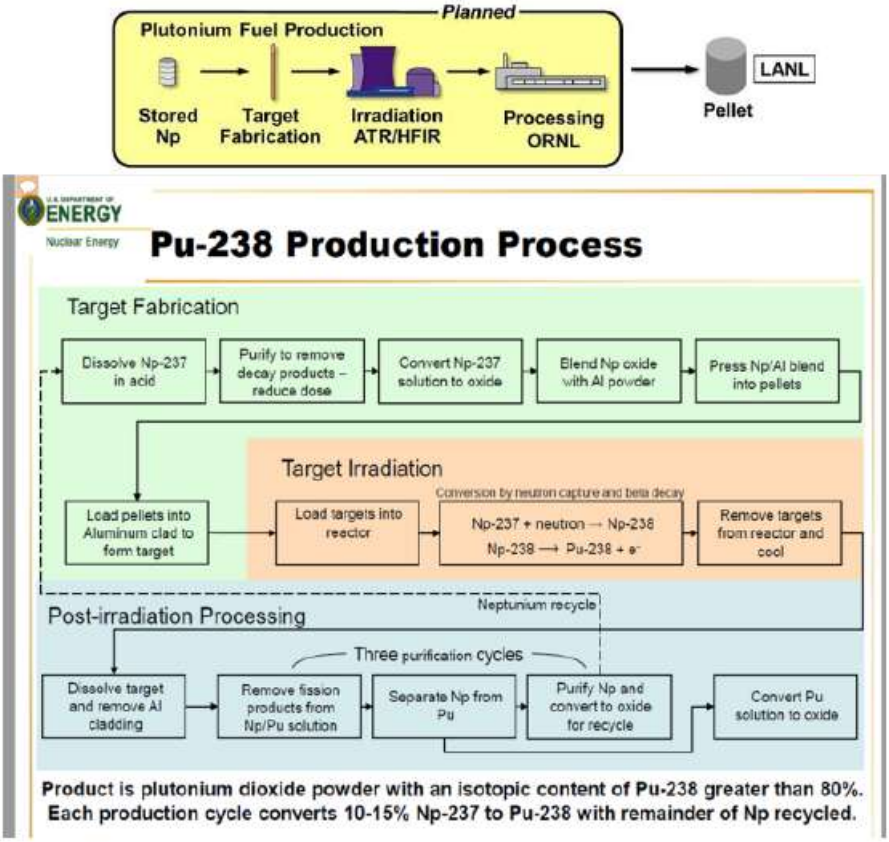


**Figure 3.** Complex pathway of Planned $^{238}$Pu Production. *Top*: overview bottom: DOE Process for the planned production of $^{238}$Pu.

### 3.2. $^{238}$Pu Heat production in space flight

Today, from Earth to the rim of the solar system, radioisotope thermoelectric generators (RTGs) are used to heat and provide electricity to spacecraft through many decades. Plutonium is the material of choice for heat and electrical power for space missions. More than two dozen US space vehicles, and many planetary and galactic probes, have depended on $^{238}$Pu heated RTGs.

These include the twin Voyager 1 and Voyager 2 probes still moving beyond the rim of the solar system, the Cassini Saturn orbiter, the Viking 1 and Viking 2 Mars landers, the Curiosity Mars rover, Pioneer 10 and 11, the SNAP-27 RTG on the moon for science experiments by the Apollo astronauts, and Transit Navy navigation satellites.

The Viking landers had 14 kg of $^{238}$Pu for 30 W output. NiCd batteries (28 V, 8 Ahr) were used to store the energy, and to enable higher power outputs when needed. The Cassini spacecraft carried three generators with 33 kg of plutonium oxide providing 870 W in orbit around Saturn. In the Pathfinder, Sojourner, and Polar Landers, the RTGs were used solely for heating, with electricity provided by solar cells.

The future will include New Horizons missions and the Mars Science Laboratory for long-term nuclear power generation.

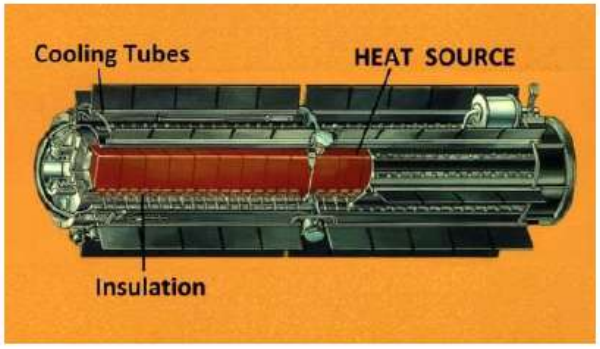


**Figure 4.** Actual RTG used in a US space probe (after GE GPHS-RTG).

### 3.3. $^{238}$Pu Heat production and RTGs

Plutonium-238 is therefore used as a heat source in RTGs. RTGs are reversed thermocouples, which convert the heat into its most important fungible product: electricity (Fig. 4). The first RTG used $^{210}$Po as the heat source. It was invented in 1954 by Ken Jordan and John Birden. On January 1, 1957, they entered into an Army Signal Corps contract (R-65-8- 998 11-SC-03-91) and began research using $^{210}$Po.

### 3.4. $^{238}$Pu in future NASA missions

The US 2019 Planetary science budget of $2.2 billion offers new opportunities. Within it, there is funding for NASA's current planned RTG, which is called the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). It will contain 4.8 kg of $^{238}$Pu as the ceramic oxide, with the radioisotope divided into eight 290 W RTG subunits. The total of 4.8 kg $^{238}$Pu oxide will produce 2 kW thermal power to generate 110 W electric power (2.7 kWh/day). The first MMRTGs are scheduled to go to Curiosity and the Mars 2020 rover. Another may go to Dragonfly, which is a finalist for a "New Frontiers" future mission to the moon.

## 4. Competing Heat-Production Systems

### 4.1. LANR systems and components

There are few choices because of plutonium has availability and experience, albeit the safety issues (*vide infra*). The other choices are conventional, unobtainable, and CF/LANR systems. Alkaline fuel cells were used in Apollo and on the Space Shuttle. But they are neither an efficient energy production or energy storage system. Conventional nuclear energy production systems are of two types, fission and fusion. In fission, fissile elements (e.g. plutonium or uranium) have their heavy nuclei divide. They have been discussed elsewhere and have issues of radioactivity (direct and induced), safety, and lack of energy source (e.g. photovoltaics) or being energy storage and not production. Therefore, there is a need/opportunity to consider CF/LANR systems.

### 4.2. Lattice assisted nuclear reaction (LANR) systems

Lattice assisted nuclear reactions (LANR, also known as cold fusion and LENR, low energy nuclear reactions) are an alternative to plutonium and other radionuclides for space travel [7–11]. LANR uses hydrogen-loaded alloys to

create heat and other products by enabling deuterium fusion to form an excited *de novo* helium nucleus at near room temperature [14]. Under difficult-to-achieve conditions, aqueous LANR systems produce several watts to fractions of a kilowatt of excess power. Nanomaterial LANR systems and specifically NANOR®-type portable components provide excess power in the milliwatt range. All of these systems are clean, without the harmful penetrating radiation emissions and radioactive waste that characterize other (hot) fusion sources [15,16]. The "excess heat" observed is derived from de-excitation of $^{4}$He* to its ground state via the lattice phonons with direct energy transfer to the lattice. LANR excess power density is more than 19,500 W/kg, with no radioactivity and zero carbon footprint (cf. Fig. 6) [12–16].

Conceptually, LANR systems are often described by their energy production in terms of the "microscopic" amounts of helium produced, as a reaction product [12]. In actual working aqueous LANR systems, the most significant other reaction product by mass is anodic-generated molecular oxygen [10], and it increases with time. This is very important for manned spacecraft because later, when the LANR activity decreases to a few percentage of the initial activity over time, for a 3 l system, this changes to $\sim$3.1 $\times$ $10^{13}$ J of heat, 732,000 l of molecular oxygen (needed for life and fuel cells) and only $\sim$1 l of *de novo* helium-4 per year.

Prof. George Miley (University of Illinois, USA) has been pivotal in suggesting and promoting cold fusion cells for use in outer space [7]. His devices are multi-layered thin films of palladium and nickel in a heavy water solution. Superconducting quantum interference devices (SQUID) have confirmed ultra-dense states of deuterons within palladium crystal defects after repeated loading by deuterons from the heavy water [22].

### 4.3. The NANOR®-type LANR component

Dr. Mitchell Swartz and associates have crafted both aqueous [12,13] and dry nanostructure [15,16] LANR components. Some have been constructed into preloaded, dry LANR devices capable of functioning as actual portable heaters. They have been shown in open demonstrations at MIT since 2012, and currently are fabricated to perform at the multiwatt level. For the lower power, nanostructured materials (Series 6 materials) the excess energy gain compared to driving input energy is up to 20–80 times input electrical power; with reasonable reproducibility and controllability. These would be very useful for space flight and distributed energy sources, especially because they are preloaded and driven by a DC electrical current. These devices deliver heat (or electricity) when wanted and not at a natural unchanging decay rate.

## 5. Analysis and Comparison by Metrics

With that background, this section continues with the important metrics to semiquantitatively determine whether, and if so –how, the NANOR®-type component might be important for space exploration, and how does it compare to $^{238}$Pu for that and other applications.

### 5.1. Metric 1 – Power density

As a heat producing source, the Series 6 NANOR®-type components delivered up to 150+ mW of excess power with circa 60–200 mg of active material was at the core (Fig. 5). As discussed above, each gram of $^{238}$Pu generates 0.568 W unshielded, and $\sim$25 mW shielded, thermal power per gram. Therefore, with respect to power density, the $^{238}$Pu– and NANOR®-type components are comparable in output power.

### 5.2. Metric 2 – Energy density

With respect to energy density, it is important to first consider lifetime, and then apply the power density. In this model, to the first order, the degradation of materials and thermoelectric converters (from gamma and alpha damage from the

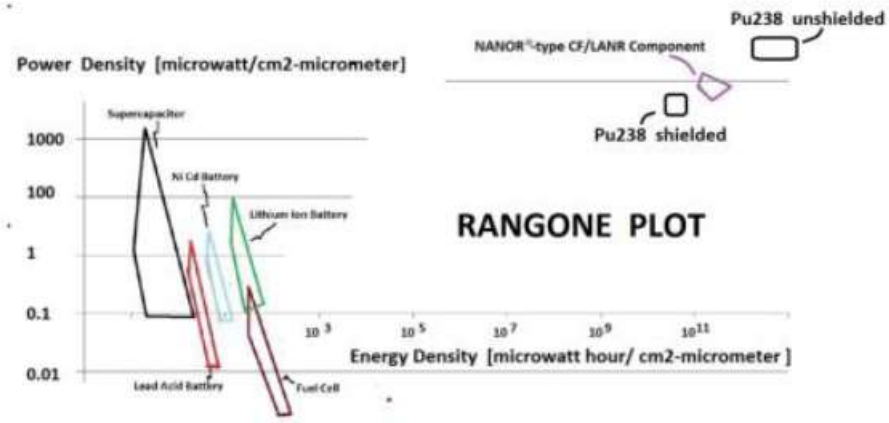


**Figure 5.** This graph is a Rangone-type plot of both the power density and the energy density of typical energy production and energy conversion devices/materials. These ranges from supercapacitor, to the lead acid battery, to the fuel cell, to the NANOR®-type cold fusion (lattice assisted nuclear reaction) component, to $^{238}$Pu. It can be seen that the latter two are one of the most efficient energy density devices known. Only the NANOR®-type component using LANR has zero carbon footprint.

$^{238}$Pu) will be ignored, but are an issue. It is also important to recognize that the analysis of the complete energy density available in the cold fusion systems is approximate. It is extremely unlikely that all of the deuterium could be used, so the numbers below, although derived on the quantity of deuterium in each of the components, are absolutely upper limits to what is available.

### 5.3. Metric 3 – Lifetime of energy production

Although the specific excess power is small, and the fact that the longevity of $^{238}$Pu clearly exceeds the lifetime of NANOR®-type technology at this time, a comparative analysis of the two for potential lifetime "excess" energy produced (and thus energy density) is still needed. The energy density of $^{238}$Pu is derived by the product of its half-life (87.5 years) and its (exponentially decreasing) power density. This is considerable, and as a result the Voyager spacecraft remain in communication after 41 years.

If we consider the dry preloaded NANOR®-type component, then with a typical Series 6 component delivering 150 mW excess power, the ∼300 micromoles of D in this unit could theoretically deliver approximately 100 MJ over 21 years. Although this is shorter than the $^{238}$Pu half-life, the aqueous LANR systems show that this can be greatly increased.

For example, if we consider the aqueous MOAC #3 nickel system [23,24], which is filled with 3000 ml of ordinary water. It can deliver circa 40 W excess power, and there is enough deuterium (55 mmol) to run for 13.3 years delivering 16.7 GJ excess energy. If we consider the future anticipated MOAC #4, with palladium cathode and very high impedance heavy water, and only the use of the lower limit of 40 W excess power (since there are approximately 300 mol of deuterium) this would make available 90.3 TJ over 71,600 years.

### 5.4. Metric 4 – Maximum temperature achieved

It is critically important to consider the peak temperature and temperature differential achieved. Both are relevant because, ultimately, it is the temperature differential that determines the thermoelectric conversion efficiency to make

electricity, the most fungible, therefore important, type of energy.

Plutonium in space using $PuO_2$ pellets achieves $\sim$1000°C peak local temperature. It is not clear if the NANOR® type components can achieve that at this time; mainly because so far the main metric in our experimental runs have been to maximize the incremental power gain factor, followed by reproducibility and the total power output achievable (in that order).

With respect to the maximum temperature, the LANR components, both aqueous and dry preloaded, have never been driven to the peak temperatures achievable for a number of reasons (safety unknown, protection of the reagents, etc.). However, the NANOR type component, a dry preloaded LANR material, is from a line of systems/materials that do have the possible characteristics heralding that the local temperature might, under suitable engineered conditions, be comparable to that achieved for $^{238}$Pu in this metric, too. First, successful aqueous PHUSOR type systems have achieved 155°C, outside of 50 ml aqueous surrounding; with the system electively clamped because of loss of heavy water [13]. Second, near infrared examinations of emissions from the core of the active material when excess heat was observed indicate a color temperature between $\sim$500 and 1000 K [25]. Third, coherent Raman anti-Stokes measurements have suggest that the effective temperature during excess heat, at core, is $\sim$1645 K ($\sim$1372°C) [26,27].

### 5.5. Metric 5 – Maximum temperature differential achieved ($\Delta T$)

The high temperature is needed to maximize the delta-$T$ ($\Delta T$) which determines the electrical conversion efficiency. This efficiency is a key important and limiting issue. Worse, the temperature differential in space is even more difficult to achieve. The reasons include that any additional mass for adds launch challenges and also because outer space being a vacuum necessarily makes it thermally insulating for conduction and convection. As a result, typical spacecraft cold junction temperatures are reported circa 300°C. This makes achieving a large magnitude $\Delta T$ as difficult to achieve in space as it is here on Earth.

The $\Delta T$ is the present limiting factor of many technologies including the important Advanced Stirling Engines that NASA has been developing for several decades requiring a $\Delta T$ of 500°C; which produce only 25% thermoelectric conversion efficiency and are so far unflown. Similarly, plutonium in space using $PuO_2$ pellets achieve only $\sim$7.5% thermoelectric conversion efficiency at their $\sim$1000°C the peak local temperature.

### 5.6. Non-$\Delta T$ systems

In this metric, it is important to consider the possibility of direct current conversion which does not requiring large $\Delta T$. Some NANOR-type components have been crafted to elicit direct current conversion which does not require large $\Delta T$. They use preloaded nanomaterials but only generate extremely low levels of electric power, directly [28]. Other suggestions range from MHD for de-excited alphas to electron capture directly.

### 5.7. Metric 6 – $^{238}$Pu - Safety issues

The metric of safety involving $^{238}$Pu is a very serious problem. It has the highest hazard number (#152) of all 256 known radionuclides [3]. Environmental issues, including potential contamination and human toxicity, limit the use [29]. The main threat to humans comes from its inhalation, especially when the particulate size is less than 10 $\mu$m. Additionally, as a consequence of the shorter half-life is that $^{238}$Pu is about 275 times more radioactive than $^{239}$Pu (i.e. 17.3 curies (640 GBq/g) compared to 0.063 curies (2.3 GBq)/g).

When $^{238}$Pu was made during WW2 and the cold war, the weapons component project's Special Metallurgical Building was nicknamed "Snake Mountain" because of the secondary environmental problems that developed [30]. As a result, work stopped there in 1968.

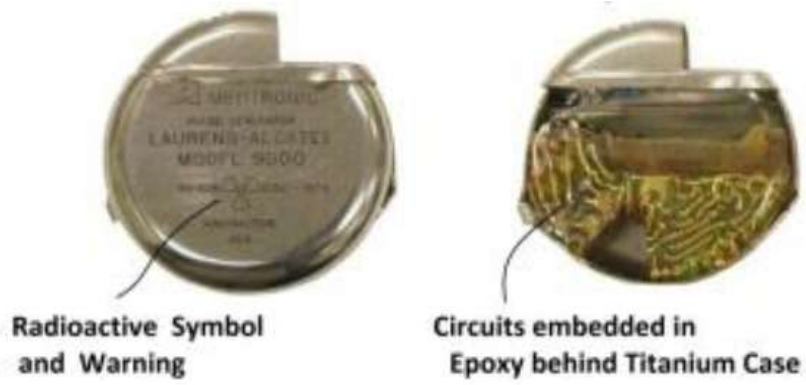


**Figure 6.** $^{238}$Pu Cardiac pacemaker showing identification used (2.75 in. diameter, plutonium removed).

Despite these issues, with engineering $^{238}$Pu has been used in several hundred cardiac pacemakers since 1966 (Fig. 6). Dose rates at the surface of the pacemaker was 15 mrem per hour, from gamma rays and neutrons. The patient's whole body exposure was circa 0.1 rem per year. This use stopped after recognition of post-cremation package leakage failures. Thus, $^{238}$Pu was judged to be just too dangerous for this biomedical application.

## 6. Conclusion

There are substantial heat and electricity requirements to fully explore space and other planets, including for colonization. Future missions are being planned as passengers continue to patiently and eagerly wait their turn to fly. Lattice assisted (or enabled) nuclear reactions (LANR) [7–16] may have significant advantages over present systems, since they provide ecologically clean energy and potential oxygen production sources. If the maximum core temperature can be raised sufficiently, or direct electrical conversion achieved at higher efficiency, then one of the most efficient and safe deep space energy production systems in the future may be preloaded LANR components.

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