Nuclear Pacemakers

Introduction

Back in the early 1970s cardiac pacemakers were powered by mercury-zinc batteries. These batteries would run the simple circuitry of these early pacemakers for a maximum of 3 years. Most often however, the mercury cells would fail in barely 20 months, which forced patients to undergo frequent surgeries to perform device replacements.

Nuclear batteries were introduced in the pacing industry around 1973 to prolong the longevity of the implanted device. Several pacemaker manufacturers of the time introduced nuclear models to their product lines. These devices offered young patients the possibility of having a single pacemaker implant last their whole life. However, by the mid-1970s, nuclear pacemakers were displaced by devices powered by lithium cells. The lithium-powered units had a calculated longevity of approximately 10 years, and physicians decided that it was much better for patients to be updated once a decade to units incorporating new technologies [Parsonnet et al., 1979] rather than carry a large, old-technology pacemaker all their life.

The implant of nuclear-powered pacemakers stopped in the mid-1980s [Parsonnet et al., 1990]. Lithium-powered batteries are now the norm, and just a handful of patients remain implanted with nuclear pacemakers.

Pacemakers powered by a Radioisotope Thermoelectric Generator

In the late 1960s Medtronic – today the largest manufacturer of implantable medical devices in the world - teamed up with Alcatel, a French company, to design a nuclear-powered pacemaker. The first human implant of the device took place in Paris in 1970.

The nuclear battery (Figure 1) in the Medtronic device used a tiny 2.5 Ci slug of metallic Plutonium 238 (Pu-238). The radiation produced by the Pu-238 bombarded the walls of its container, producing heat that a thermopile then converted to an electrical current. A thermopile is a stack of thermocouples, which are devices that convert thermal energy directly into electrical energy using Seebeck effect. As shown in Figure 2, a thermocouple is made of two kinds of metal (or semiconductors) connected to each other in a closed loop. If the two junctions are at different temperatures, an electric current will flow in the loop.

Figure 1 – The nuclear battery developed by Alcatel for Medtronic used a tiny slug of metallic Plutonium 238. The heat produced by the decay of the Pu-238 was converted to electricity by a thermopile.

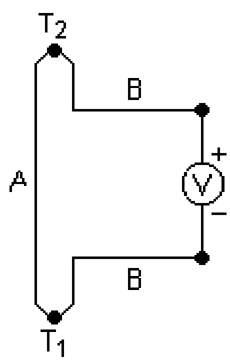

Figure 2 – In a thermocouple, a voltage - the thermoelectric EMF - is created in the presence of a temperature difference between two different metals or semiconductors. In the isotopic thermoelectric generator, many thermocouples are arranged in series/parallel to form a thermopile which produces useful power levels. One of the junctions of each thermocouple (e.g. T1) is exposed to the heat generated by the decay of the Pu-238, the other junction (e.g. T2) is at body temperature.

Plutonium-238 decays with a half-life of approximately 85 years. As such, the radioisotope thermal generator (RTG) using this material will lose a factor of 0.81% of its capacity per year. Although the thermocouples used to convert thermal energy into electrical energy degrade as well, the electrical output of the complete assembly degrades by only 11% in 10 years. The pacemaker shown in Figure 3 still works well 35 years after it was manufactured.

Figure 3 - This Medtronic nuclear pacemaker still “ticks” 35 years after it was manufactured.

A similar isotopic thermoelectric generator was developed in the US by Numec Corporation under a contract from the US Atomic Energy Commission and sold for $3,200 (back in 1974). The thermopile of Figure 4 consisted of doped bismuth telluride pairs that were placed in a parallel/series arrangement to generate some 300 µW of power to run the pacemaker shown in Figure 5.

Figure 4 – Thermopiles used in the ARCO Medical pacemaker. The resistance is about 14kΩ ohms. ~80 pairs of cupron-tophel thermocouples (isolated with glass tape) in series generate about ~1-2 volts. Six of these tapes are wound together (series/parallel) to make a thermopile. The core of the thermopile is heated with plutonium 238 in a series of capsules. This thermopile was sealed in a vacuum. Photographs courtesy of Paul Spehr who worked at ARCO before it was acquired by Intermedics.

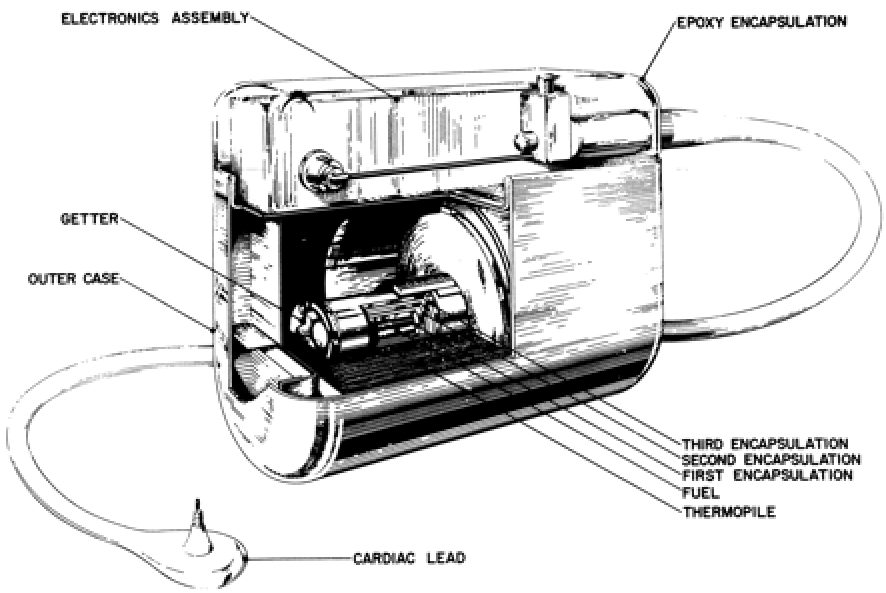

Figure 5 - This diagram shows the basic construction of the Pu-238 battery developed by Numec Corporation for the ARCO Medical pacemaker.

One of the main problems of these isotopic generators is the extremely high toxicity of plutonium. Just 1µg in the blood stream could be fatal. Indeed, plutonium is among the sixth most toxic material ever discovered. It spontaneously bursts into flame upon contact with air, and then burns to give off a fine, highly-radioactive dust.

The various shields designed to prevent accidental escape of the plutonium fuel were responsible for most of the battery's volume and weight. Multiple encapsulation layers were designed to protect the core against incineration, airplane accidents and direct gunshot wounds.

Radiation was not a major concern. 1 mR/hr could be measured 2 cm away from the capsule. Most of the pacemakers included some additional shielding, so wearing a plutonium-powered pacemaker delivered a dose of approximately 100 mrem per year to the patient. To put this in perspective, a healthy U.S. adult receives an average of 360 mrem every year from natural and medical sources, where between 26 and 96 mrem come from solar radiation, and about 40 mrem come from natural radioactivity in our food. A single transatlantic flight contributes about 2 mrem. Parsonnet et al. reported that the frequency of malignancy in his 155 nuclear-pacemaker patients was similar to that of the population at large and primary tumor sites were randomly distributed.

In fact, the radiation from plutonium-based pacemakers was so low that it was deemed harmless even for a pregnant woman. A pacemaker implanted in the abdomen was calculated to deliver a dose of 57 mrem during the full term, which is approximately 20 times less than the maximum allowable dose (1,125 mrem).

Pacemakers Powered by a Beta-Voltaic Cell

At more or less the same time that implantable-grade plutonium cells made their appearance, McDonnell-Douglas Astronautics developed a different kind of nuclear cell for pacemakers. The Betacel 400 had promethium-147 sandwiched between semiconductor wafers (Figure 6). Promethium-147 is a soft β emitter with no γ lines. It has a half life of 2.6 years. As the radioactive promethium isotope decays, it emits β-particles (electrons). Internally, and as shown in Figure 7, the impact of the β-particles on a p-n junction causes a forward bias in the semiconductor similar to what happens in a photovoltaic cell (a solar cell). Electrons scatter out of their normal orbits in the semiconductor and into the circuit creating a useable electric current. The Betacel 400 had an open-circuit voltage of 4.7V and a short circuit current of 115µA. The maximum power output was 370µW. A pacemaker of the time (the current consumption of which could be modeled by a 200kΩ resistor) was expected to last for 10 years when powered by this nuclear battery.

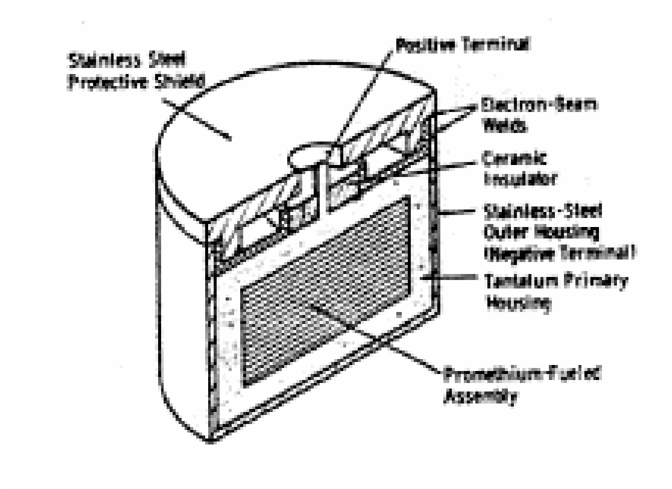

Figure 6 – Construction of a Betacel betavoltaic generator. β radiation from promethium-147 causes a voltage difference across a semiconductor p-n junction

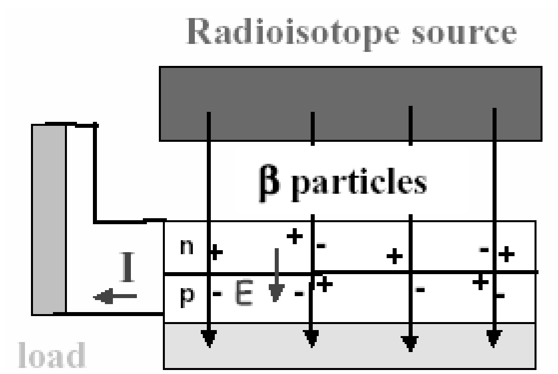

Figure 7 - The impact of the β-particles on a p-n junction causes a forward bias in a semiconductor similar to what happens in a photovoltaic cell.

A Betacel-powered nuclear pacemaker was implanted by Dr. Orestes Fiandra[1] in Uruguay. The device, shown in Figure 8, was constructed by Dr. Fiandra's factory in South America. This pacemaker stimulated the heart at a constant rate of 68 ppm.

[1] The first successful long-term human implant of a pacemaker was achieved in Uruguay on February 2, 1960 by Dr. Orestes Fiandra and Dr. Roberto Rubio. The pacemaker was manufactured by Elmqvist and was implanted in Uruguay in a 34-year-old patient with AV block. In 1969, Dr. Fiandra started manufacturing pacemakers at the "Centro de Construccion de Cardioestimuladores del Uruguay" (CCC for short).

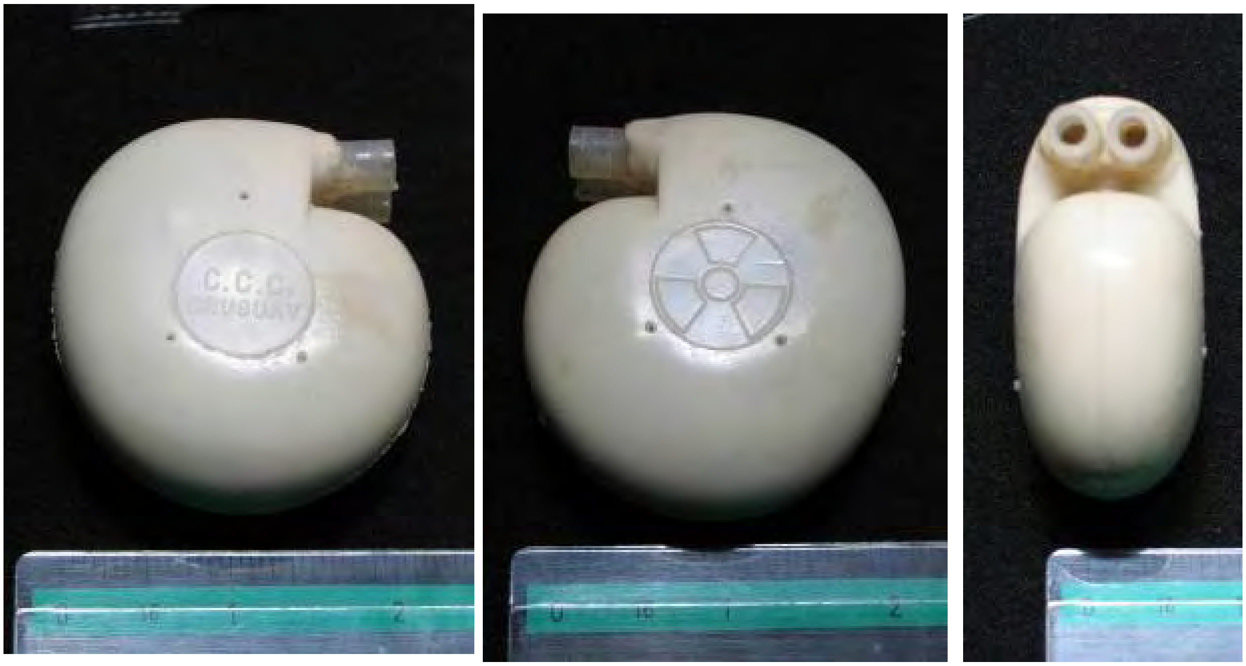

Figure 8 – This nuclear-powered pacemaker was constructed by CCC del Uruguay and implanted in 1974. The power source was a McDonnell-Douglas Betacel 400 betavoltaic cell.

Figure 9 – No radiation above normal background could be detected from this CCC Betacel-powered nuclear pacemaker 30 years after it was manufactured.

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