Nanotechnology
and
Energy Harvesting from Radioisotopes

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Summary

What are nuclear batteries, anyway?

There have been more than 50 years of development efforts to harvest electrical energy from radioactive isotopes. This talk will provide the basic concepts that must be considered when building a so-called nuclear battery. Some developments of the last century will be mentioned.

There has been a resurgence of interest in the first decade of the 21st century. Over $50 million in mostly government funds has been spent. However, the goal of commercializing a suitable technology has yet to be achieved.

It appears that carefully applying nanotechnology to maximize the energy obtained from direct conversion devices will lead to the first commercially successful micro-power sources. Some of the issues that must be resolved to achieve this accomplishment will be discussed.

The ultimate goal of obtaining a non-trivial fraction of the nation's electrical power needs from radioactive waste lies some decades in the future.

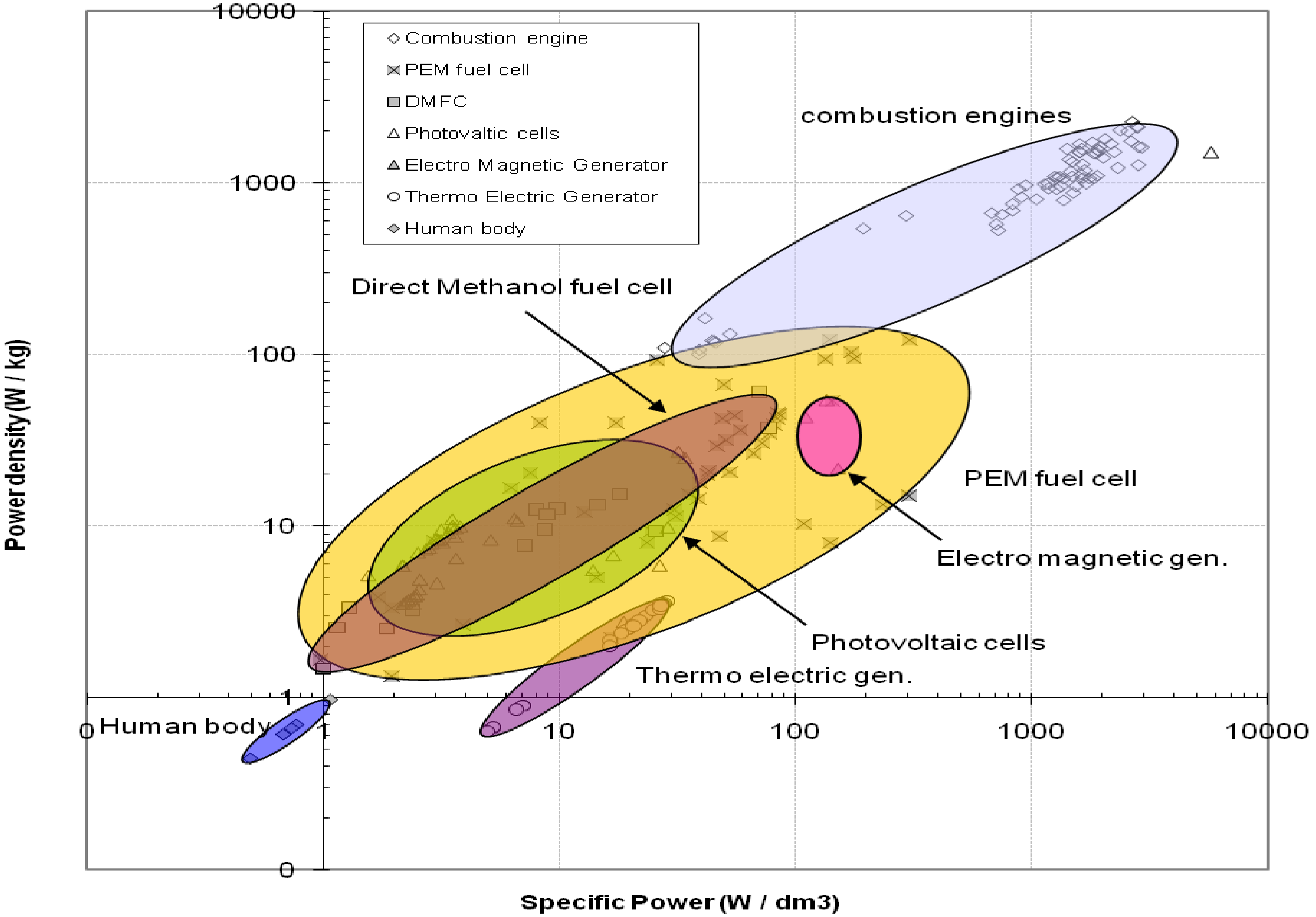
Acknowledgement: Discussions with and materials from Professor James P. Blanchard of the University of Wisconsin at Madison

Outline

What is …

- Energy Harvesting
- Basic Nuclear Concepts
- Current Micro-/Nano-Technology Developments
- Potential Nanotechnology Solutions
- Future Outlook

Energy Harvesting Technologies



What is a Nuclear Battery?

- *Convert energy of radioactive decay into electricity*
- Options:
  - Direct charge collection
  - Indirect (convert to light for photovoltaic)
  - **Betavoltaic**
  - Thermoelectric
  - Thermionic
  - Thermophotovoltaic

Radioisotope Types

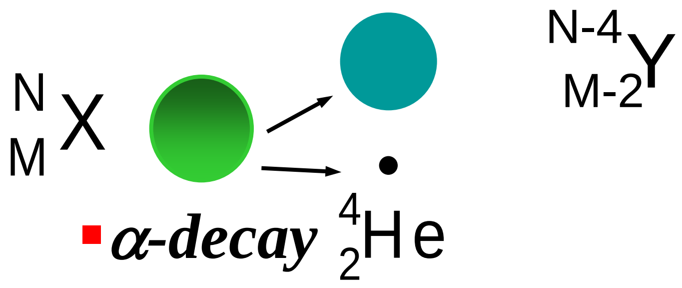
- Alpha emitters –
  - release energetic He nuclei – (4-6 MeV/particle)
- Beta emitters –
  - emit electrons or positrons (and neutrinos) –
  - (10s–100s keV with characteristic energy spectra)
- Gamma emitters –
  - Nucleus emits very energetic photons (electromagnetic ‘rays’ – highly penetrating)

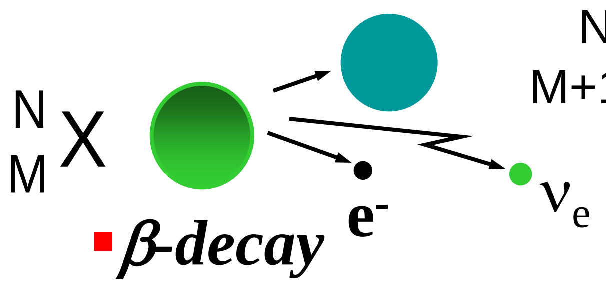
Note: X-rays are photons emitted by very excited atoms.

Isotope Selection

- Type of radiation
  - Alpha (α)
  - Beta (β)
- Half-Life
  - Long - Long battery life (238-Pu: 0.6 W/g, $T_{½}$=86 yr)
  - Short - Higher power density (210-Po: 137 W/g, $T_{½}$= 4 mos)
- **<u>Cost</u>**
- Design for particle range, displacement damage
- Avoid gamma rays. Reduce Brehmstrahlung (<u>safety</u>)
- Watch out for (α, n) reactions

Radioisotopes and Decay





Isotope	Average energy	Half life	Specific activity	Specific Power	Power Density
	(KeV)	(year)	(Ci/g)	(W/g)	(W/cc)
63-Ni	17	100	57	0.0067	0.056
3-H	5.7	12	9700	0.33	0.000083
90-Sr/ 90-Y	200/930	29/2 d	140	0.98	2.5
210-Po	5300	0.38	4500	140	1300
238-Pu	5500	88	17	0.56	11
244-Cm	5810	18	81	2.8	38

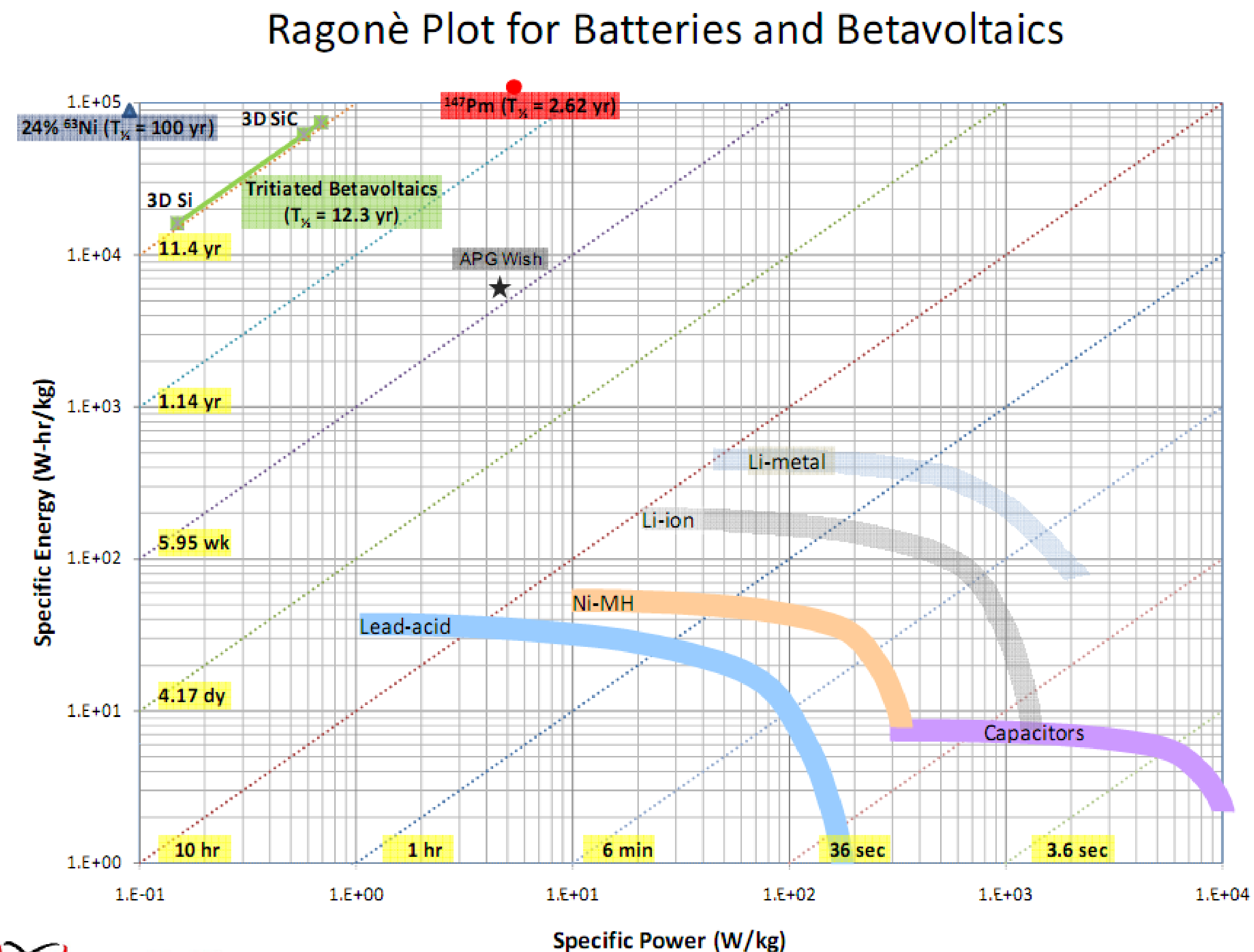
Key Take Away: Average range for α and β particles is 1-10 μm.

Power Source Comparison

- Consider 1 mg for power source

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

Power versus Energy Comparison



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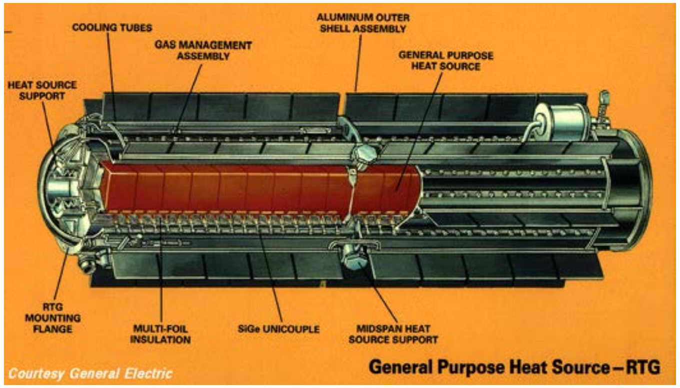
Battery & Capacitor Data from http://berc.lbl.gov/venkat/Ragone-construction.pps

RTG for Heating and Power

Radioisotope Thermoelectric Generator

- Used in many NASA missions
- Use ceramic loaded with Pu-238 for heating
- Thermoelectric power generation
- 

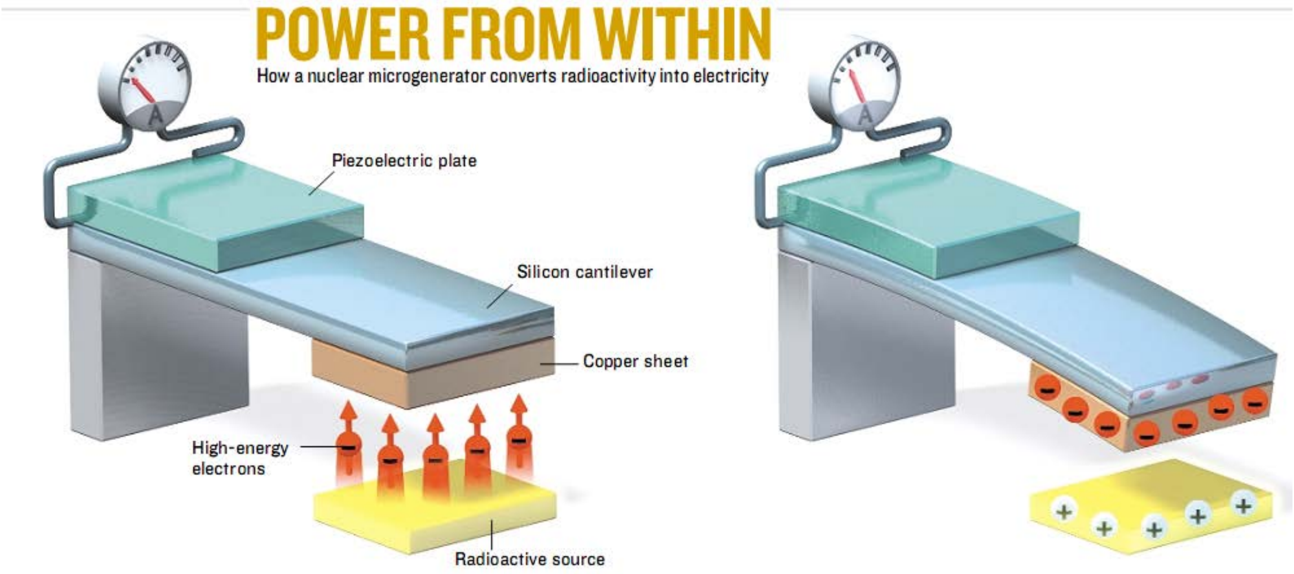
- Fuel: 2.7 kg. 133 kCi
- Power: 276 W
- Power (11 years): 216 W
- Total Weight: 56 kg
- Lifetime: over 20 years
- Dimensions: D=42 cm, L=114 cm

Pacemakers (circa 1970)

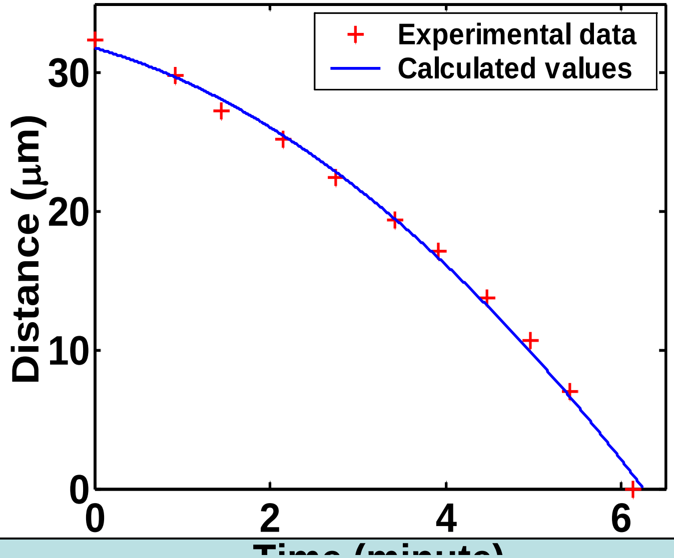
- 3 Ci Pu-238
- ~3 ounces, ~3 inches
- <mW power levels
- 100 mrem/y to patient
- Since supplanted by Li batteries (~7 year life)
- Regulators nervous about tracking Pu
- Thermoelectric (some betacell concepts)

- http://www.naspe.org/library/electricity_and_the_heart/

Self reciprocating cantilever

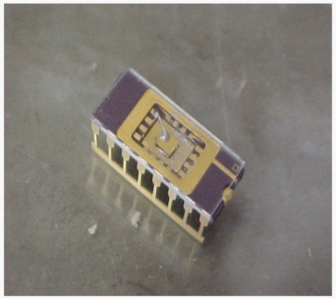


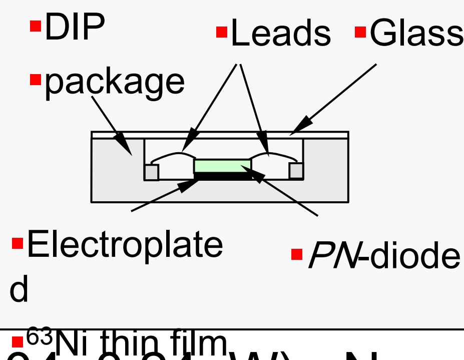
- Initial gap (d_0): 33 μm
- Period: 6 min. 8 sec.
- Residual charges: 2.3×10^{-11}C
- Peak force (kd_0): 10.1 μN
- Assumed Collection efficiency (α): 10%

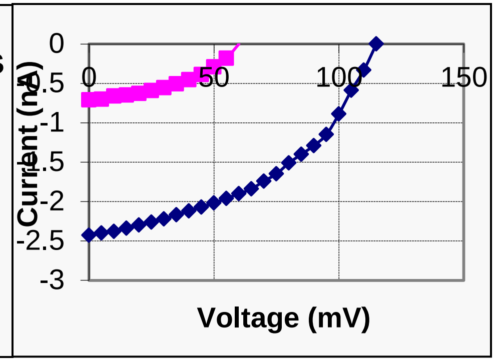


Betavoltaic Prototypes

- First type: planar Si *pn*-diode with electroplated ^{63}Ni



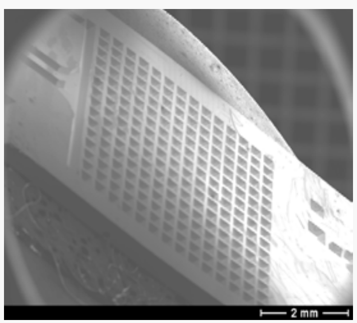


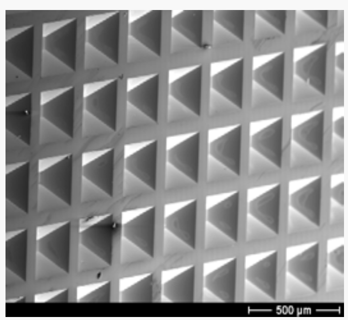


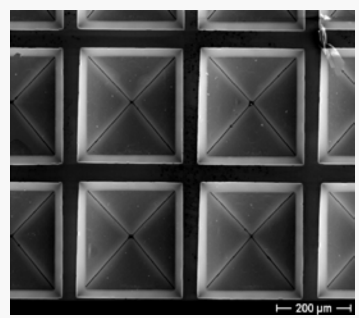
	0.25mCi	1mCi
I_p	0.71nA	2.41nA
V_o	64mW	115mV
P_{max}	0.04nW	0.24nW

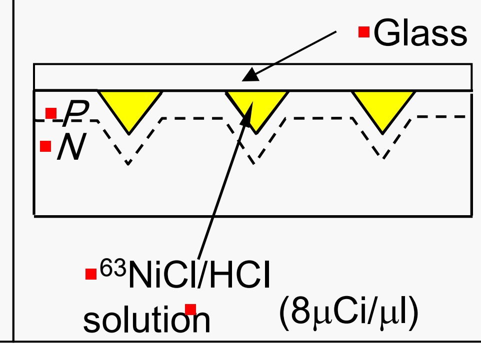
Nanopower(0.04~0.24nW) - No performance degradation after 1 year

- Second type: inverted pyramid array Si *pn*-diode







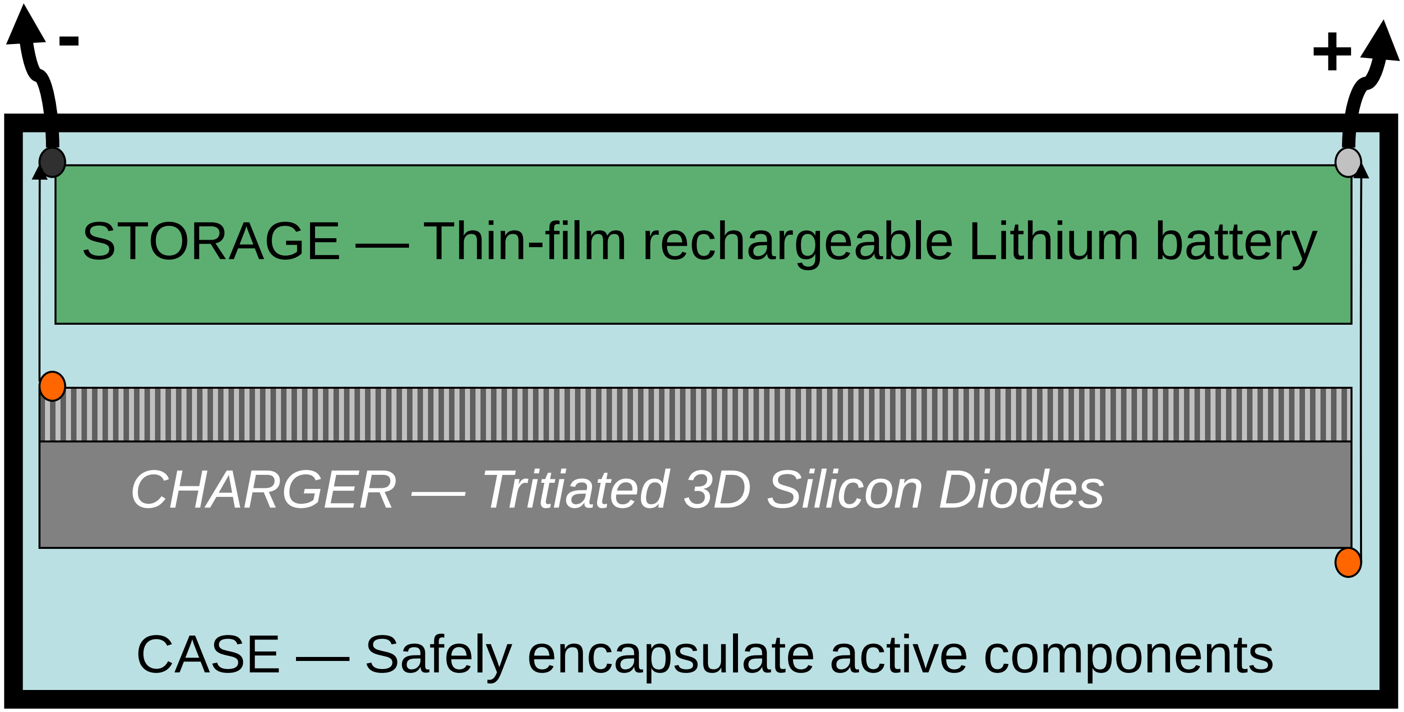


- Area magnification: 1.85 / - 0.32nW (128mV/2.86nA)

Efficiency:0.03~0.1%

~10 times > micromachined RTG

Continuous *Charger* Technology



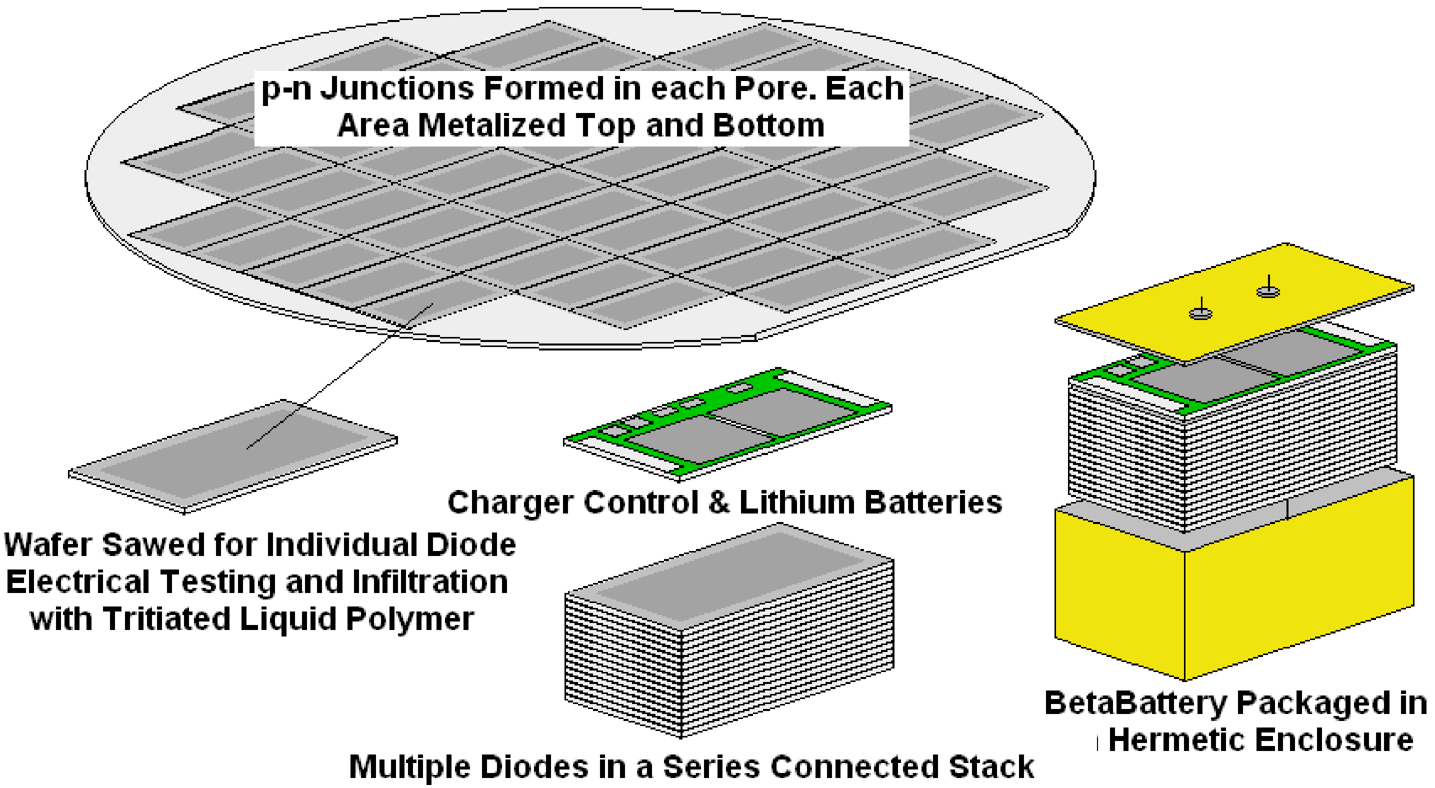
The BetaBattery™ – A Long-Life, Self-Recharging Battery

The Solution

Self-Recharging BetaBattery™

- Ultra long-life battery pack with built-in charger
  - Low power applications (<10V, <100μA, <1000 μW)
  - Flexible duty cycle (e.g., 4 mA for 1 sec. every 3 min.)
- Enabling platform technology
  - Perform extremely high value tasks
  - Importance great compared to power cost
- Proven and proprietary IP
  - Own basic patents
  - Developed through SBIR grants from NSF
  - Sponsored university research was licensed

Prototype BetaBattery Fabrication



BetaBattery Fabrication Steps

Assembly Procedure

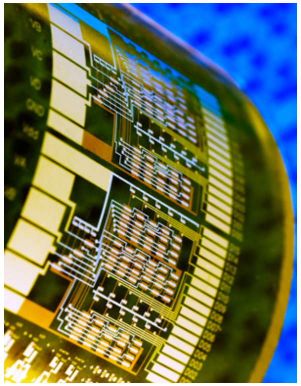
BetaBatt™

Maximizing Efficiency

- Cost
  - Radioisotopes are very expensive
  - Want to maximize energy conversion
- Geometry
  - Locate decaying nuclei adjacent to converter
  - 3D configuration
  - Minimize volume of inactive materials
  - Converter dimensions commensurate with range
- Flexible source manipulation capability

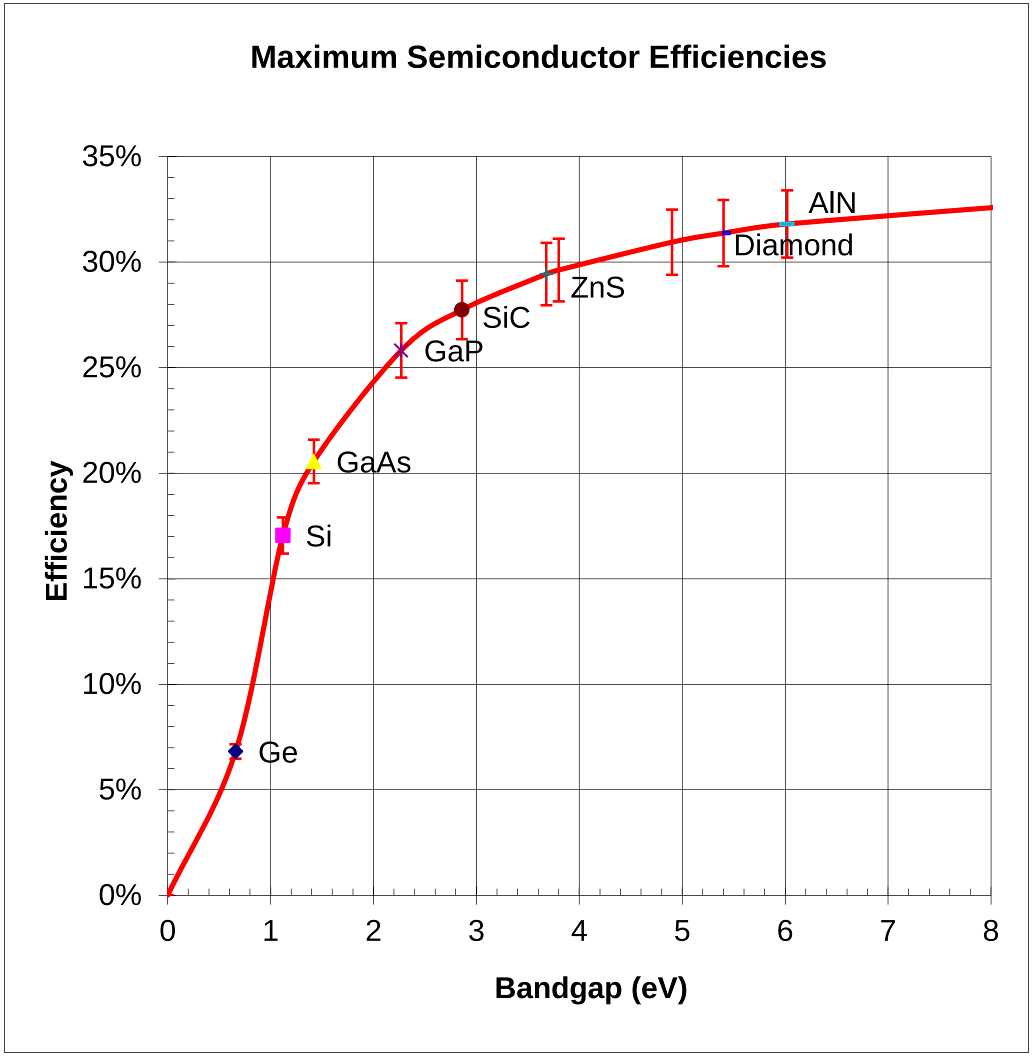
Thin, Flexible Semiconductors

- For low energy beta emitters, source layers must be thin (sub-micron)
- Range of particles in semiconductor is also a few microns at most
- Hence, thin semiconductors are an advantage
- Multi-layer devices can offer good power density with good efficiency



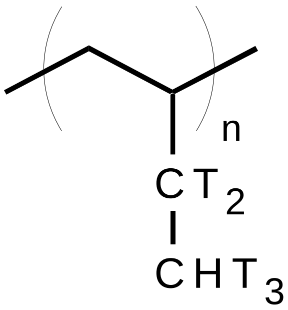
Wide Bandgap Semiconductors

- Silicon carbide, etc.
  - Wider bandgap will produce greater conversion efficiencies
  - Simulations indicate as much as 25% possible



Tritiated Energy Source

Tritiated Butyl Rubber Molecule



- Synthesis procedure can be ‘tuned’
  - Polymer can be solid or liquid
  - Liquid can be solidified by ‘cross-linking’
- Enables flexible device geometry
  - Maximize delivery of energy to converter
  - ‘Harvest’ most tritium decay energy
- Microfluidic infiltration into converter

Nanotechnology Potential

- Converter
  - Nano particle diodes, carbon nanotube diodes
  - Nano printing techniques for device fabrication
  - Self assembly using micro- or nano-fluidics
- Graphene (or other 2D film)
  - Usage as electrode
- Energy Source
  - Continuous production in film format
- Substrate Development
  - Film transfer and release

Device Fabrication

- Manufacturing Issues
  - Macro-scale devices from nano-scale components
  - Cost-effective means of energy source preparation
  - Efficient methods of integrating energy source and converter device and film assembly procedures

- Radioactive Materials Handling
  - Minimize waste generated
  - Minimize manipulation of radioactive materials
  - Maximize safety for personnel, users and public

Potential Markets

Government & Military	Anti-Tamper and Security, Sensors and Detectors, Health Monitoring of “Smart” Electronics, Covert Operations and Intelligence
Human Health	Cardiac Rhythm Management (Pacemakers) Micro stimulators and Drug delivery, etc.
Subsea	Valves and Actuators Sensors and Controls Telemetry
Subsurface	Real-Time Measurements 4D Seismic
Outer Space	Space Vehicles, Satellites
Micro-Electronics	Microelectronic Mechanical Systems (MEMS) **Self-Powered Electronic Circuitry**
Communications/Sensors	RFID Tags Implanted Microcircuits

Bottom Line

- Market Applications
  - Justify cost and risk of using radioisotope fuels
  - Advantage is very long life
- Power Delivery
  - Prototypes now: 10s – 100s nanoWatts/device
  - Production ‘soon’: 200 – 2000 microWatts/cm^3
- Nanotechnology will play a role
- Success
  - Requires significant research and engineering development supported by adequate funding

Fukushima Daiichi

Close the Nuclear Fuel Cycle

Support Japan's Recovery