Radioisotope Batteries

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April 2010

Introduction

- Radioisotope batteries provide reliable batteries with high energy density
- They are valuable when long life is needed and recharging or refueling is difficult
- Many of the conversion technologies can function in harsh environments
- They can be very useful as onboard MEMS power sources

Applications

- Long-lived cell phone batteries
- Self-powered sensors on automobiles
- Self-powered sensors in humans
- Sensors for tracking animals
- Building/bridge sensors
- MEMS
- Micro-robots
- Smart Dust Networks

Caveats

- Cost
- Safety/regulation
  - Shielding is generally simple
  - Concern is with breakage of packaging
  - Security is also an issue

Radioisotopes

- Alpha emitters – release energetic He nuclei – typically at 4-6 MeV per particle
- Beta emitters – emit electrons or positrons (and neutrinos or antineutrinos) – energy spectrum
- Gamma emitters – emit electromagnetic radiation – penetrating - undesirable

Isotope Selection

- Type of radiation
  - Alpha
  - Beta
- Half-Life
  - Long - Long battery life (238-Pu – 0.6 W/g, 86 yr half life)
  - Short - Higher power density (210-Po – 137 W/g, 3 month half-life)
- Avoid gammas in the decay chain (safety)
- Watch out for (alpha, n) reactions and Brehmstrahlung
- Watch particle range, displacement damage, and cost

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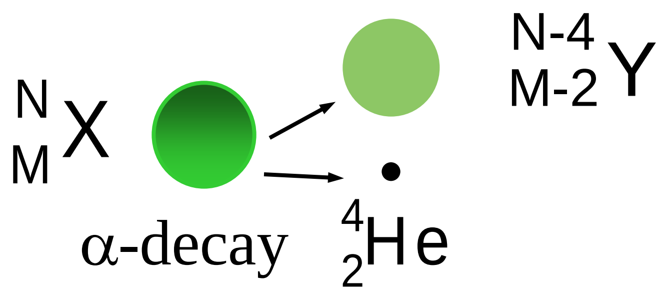
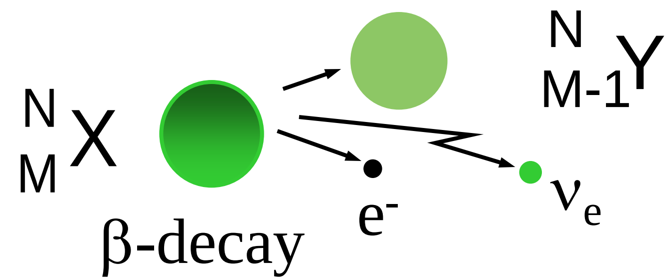
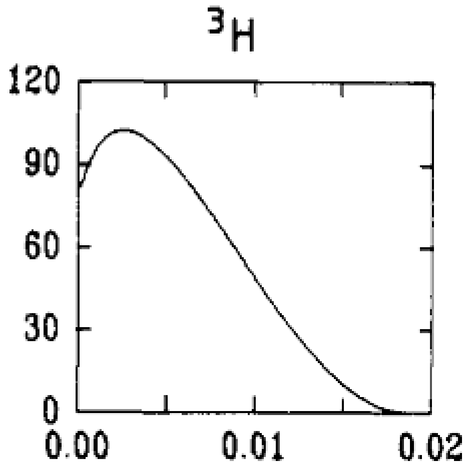
Radioisotopes and decay

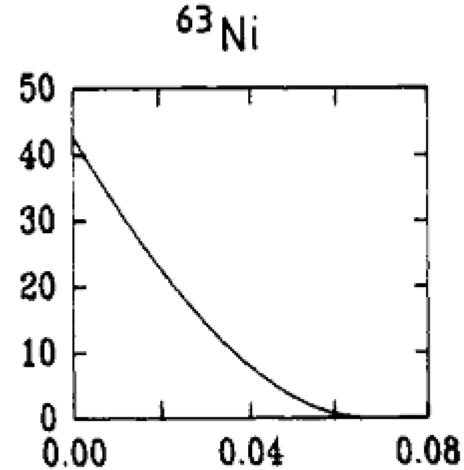


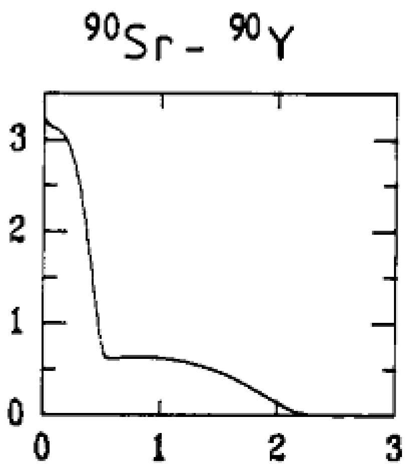


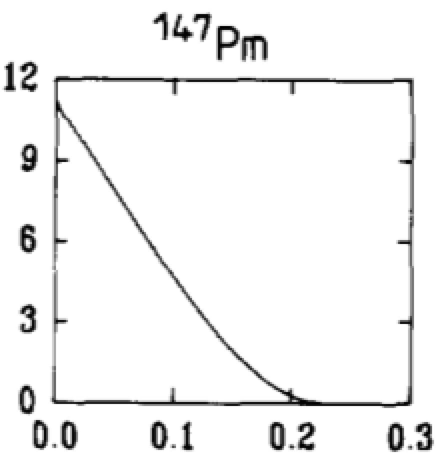
Isotope	Average energy	Half life	Specific activity	Specific Power	Power Density
	(KeV)	(year)	(Ci/g)	(W/g)	(W/cc)
63-Ni	17	100	57	0.0067	0.056
3-H	5.7	12	9700	0.33	-
90-Sr/ 90-Y	200/930	29/2 d	140	0.98	2.5
210-Po	5300	0.38	4500	140	1300
238-Pu	5500	88	17	0.56	11
244-Cm	5810	18	81	2.8	38

Beta Spectra (E in MeV)









What is a Nuclear Battery?

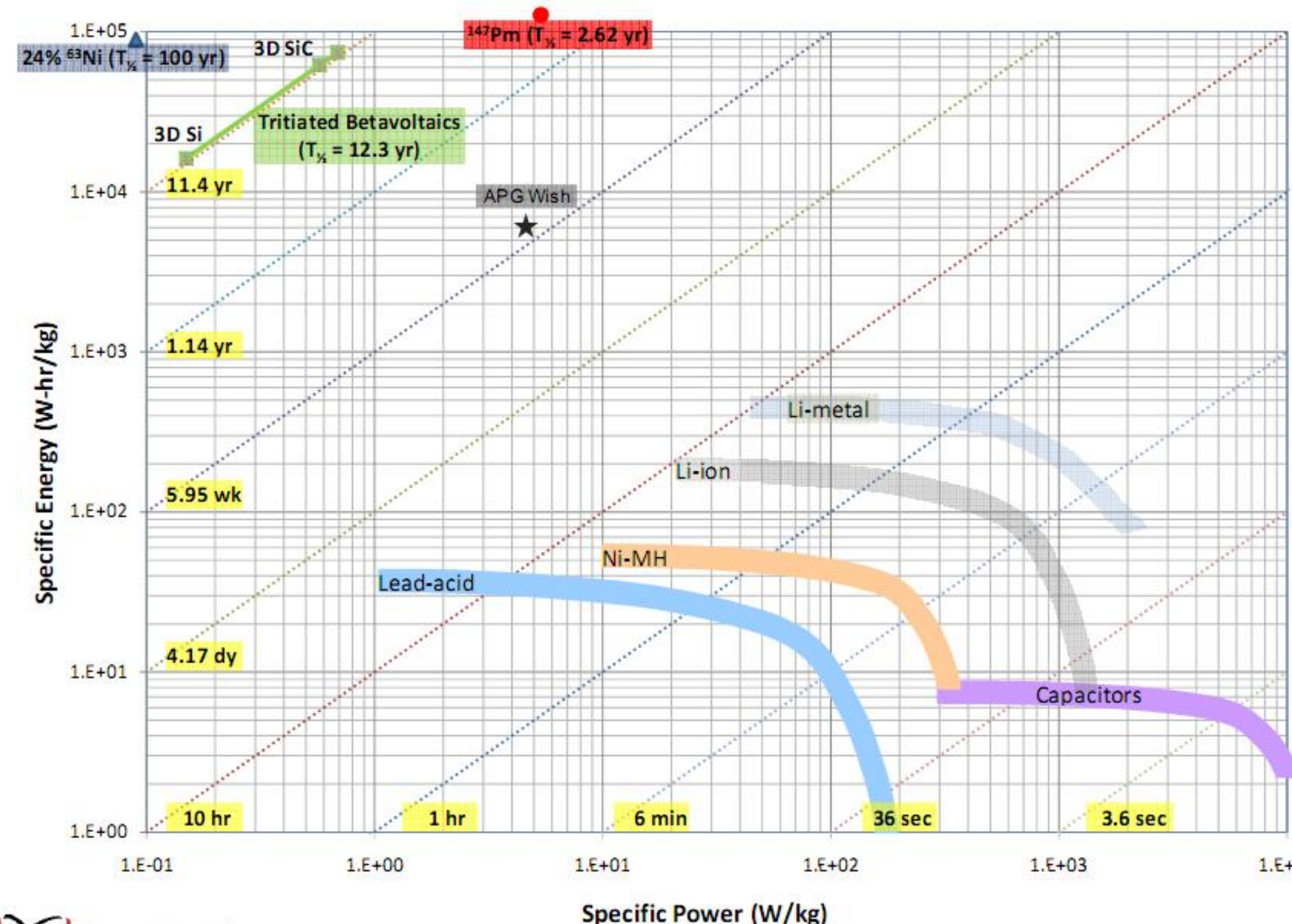
- Goal: convert energy from radioactive decay to electricity
- Options:
  - Direct charge collection
  - Indirect (scintillation)
  - Betavoltaic
  - Thermoelectric
  - Thermionic
  - thermophotovoltaic

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 years)	3000
3-H (5% - 4 years)	500

Ragonè Plot for Batteries and Betavoltaics



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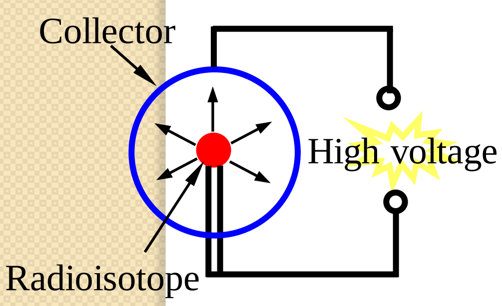
Battery & Capacitor Data from http://berc.lbl.gov/venkat/Ragone-construction.pps

Direct conversion nuclear battery

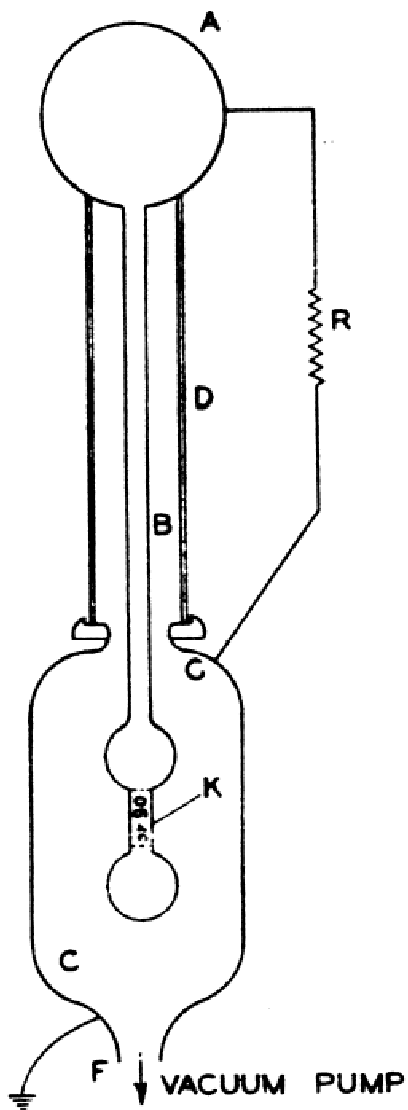


- Direct conversion nuclear battery: collecting charges emitted from radioisotopes with a capacitor to achieve high voltage output
  (J. H. Coleman, 1953)

$$V = \frac{Q}{C}$$

10-100 kV voltages can be created in vacuum

Static Accumulation

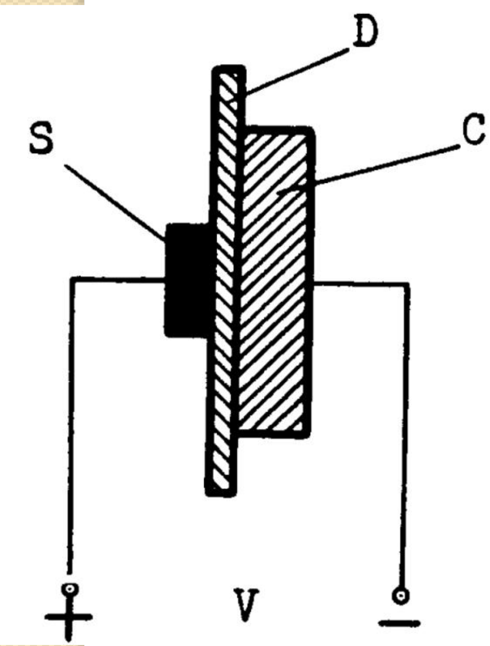


- Early 1950's
- Source at K
- D is electrical insulator
- Chamber is evacuated

- 0.25 Ci Sr-90
- 365 kV
- About 1 nA
- 0.2 mW

Linder, Rappaport, Loferski

Adding a Dielectric



•Early 1950's

•Source at S

•D is dielectric; C is collector

•Radiation penetrates dielectric

•No need for vacuum

•High voltage

•Prevents secondary electrons from getting back to source

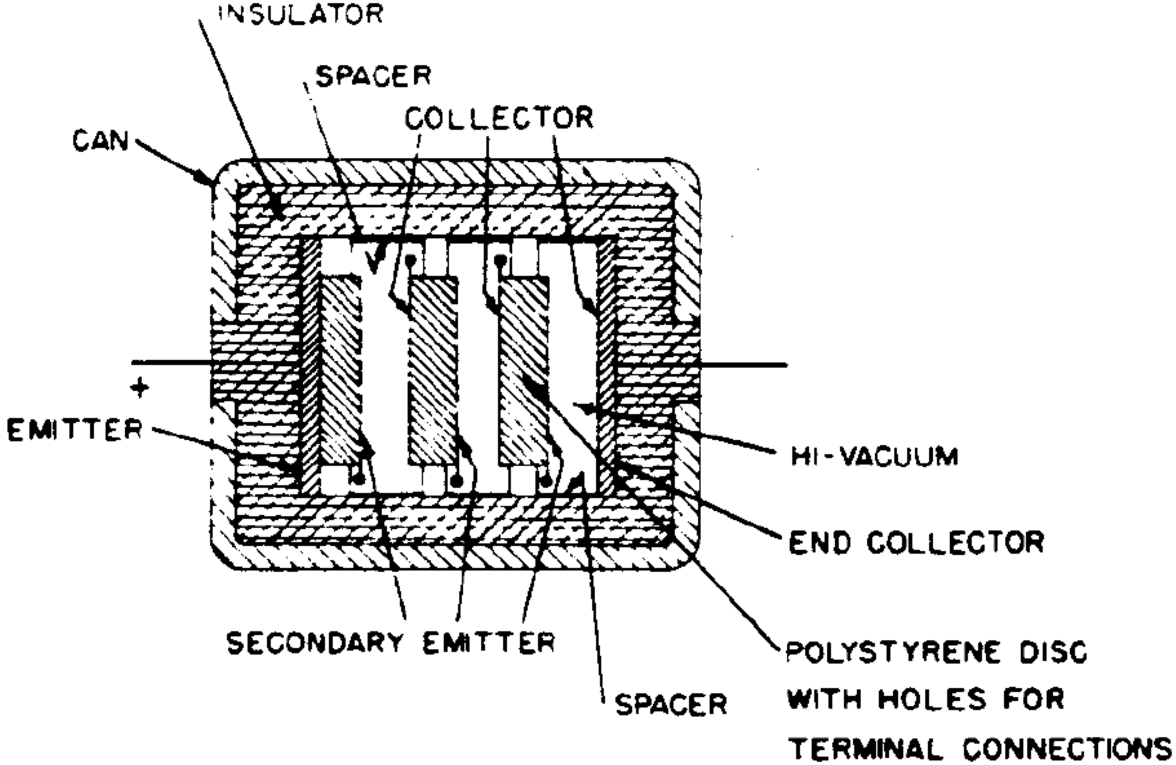
•50 mCi Sr-90

•polystyrene

•7 kV

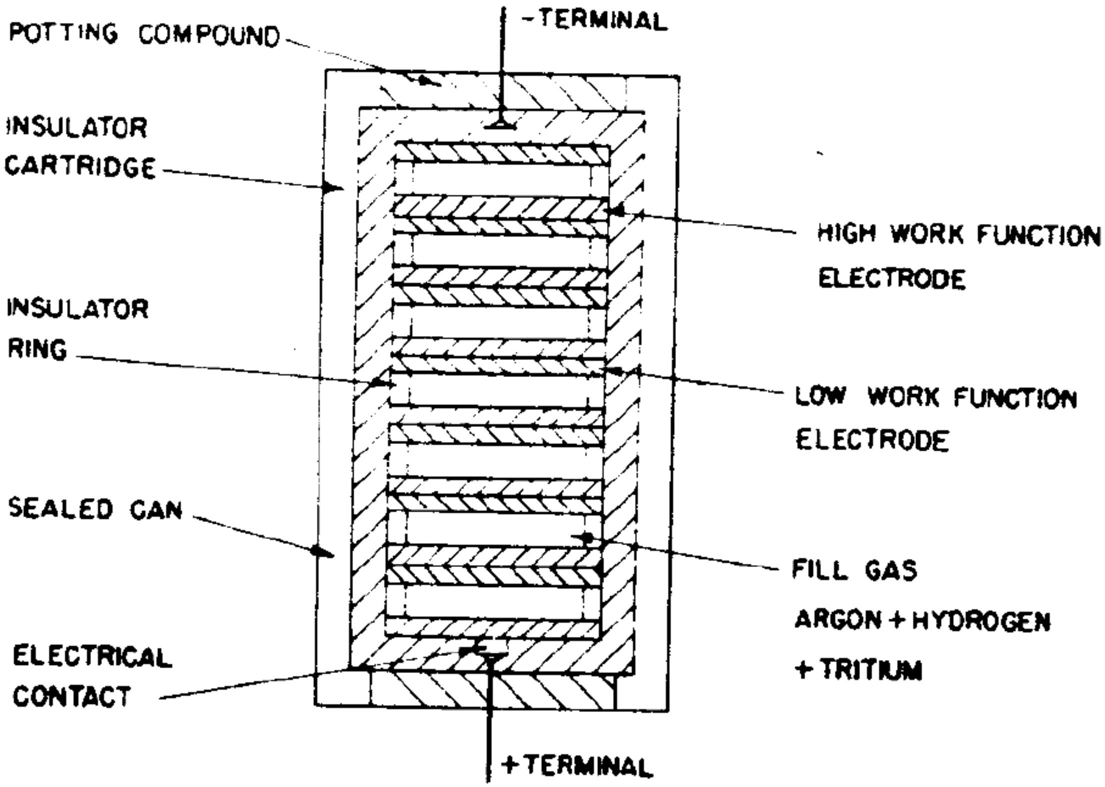
Keller et al

Secondary Collector



- Use beta source
- MgO used to maximize secondary's
- Collector is graphite coated Al
- 1e-5 mm Hg vacuum

Contact Potential



- Ionize gas between two plates
- Dissimilar plates will develop potential due to differing work functions
- Low efficiency (low absorption coefficient) and high ionization energy (30 eV)
- Operates at 1-2V

Pacemakers

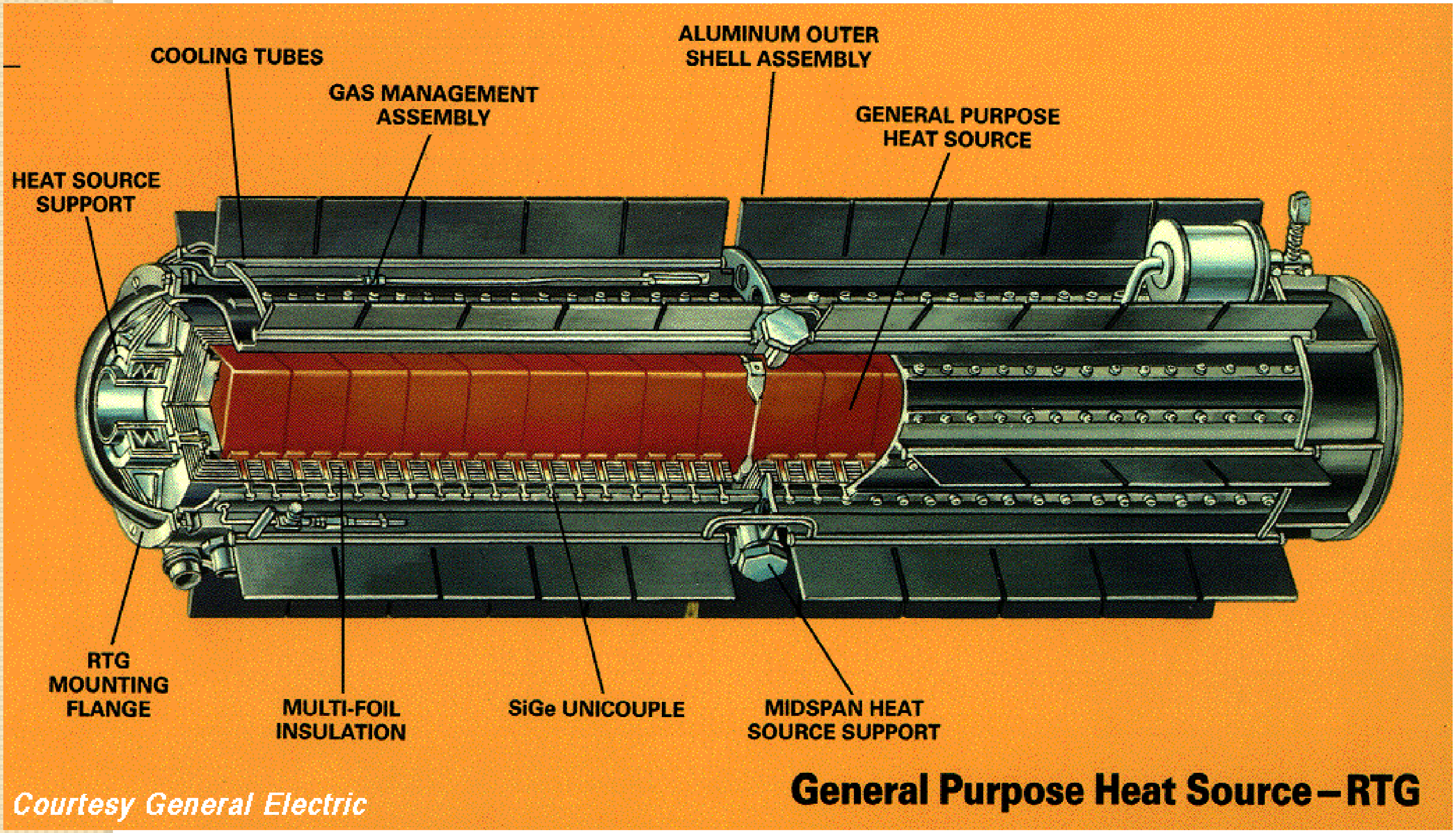
- 3 Ci Pu-238
- ~3 ounces, ~3 inches
- <mW power levels
- 100 mrem/y to patient
- Since supplanted by Li batteries (~10 yr life)
- Regulators nervous about tracking Pu
- Thermoelectric (some betacell concepts)

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

Radioisotope Thermoelectric Generators (RTGs)

- Used in many NASA missions
- Use radoisotope (usually ceramic Pu-238) to provide heat
- Electricity produced by thermoelectric
- No moving parts
- 41 have been flown by US

- 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

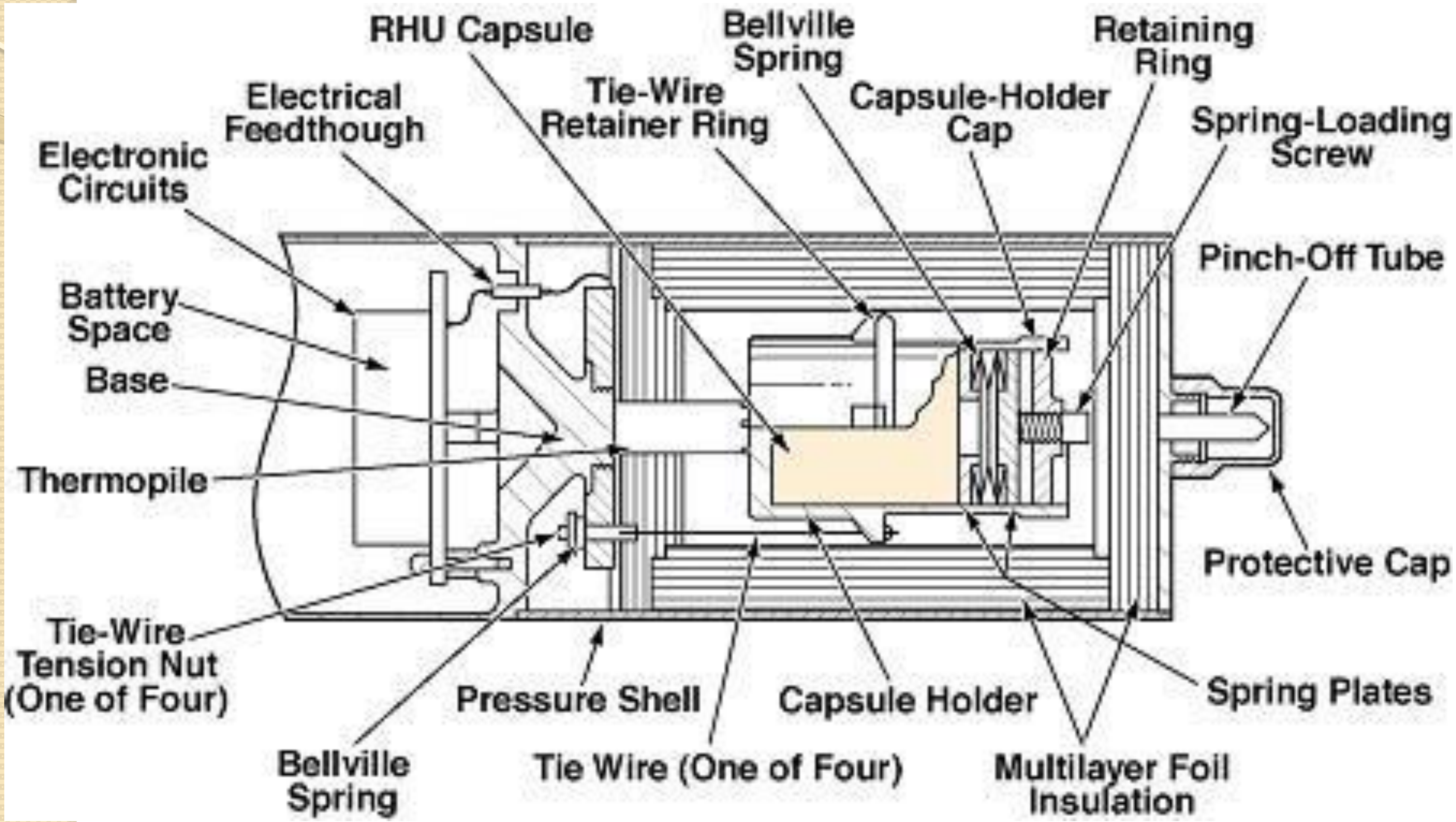

COOLING TUBES
GAS MANAGEMENT ASSEMBLY
ALUMINUM OUTER SHELL ASSEMBLY
GENERAL PURPOSE HEAT SOURCE
HEAT SOURCE SUPPORT
RTG MOUNTING FLANGE
MULTI-FOIL INSULATION
SiGe UNICOUPLE
MIDSPAN HEAT SOURCE SUPPORT
Courtesy General Electric
General Purpose Heat Source – RTG

Heating Units

- NASA's RHU
- 33 Ci
- Power is 1 W
- 1.4 oz.
- 1 cubic inch
- 2.7 g of Pu-238 (oxide form)
- Rugged, reliable

http://nuclear.gov/space/rhu-fact.html

A Compact Thermoelectric



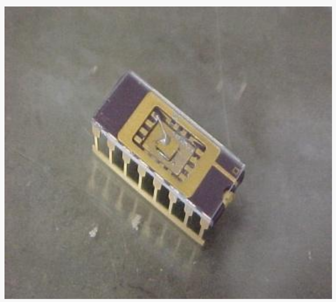
40 mW electric power

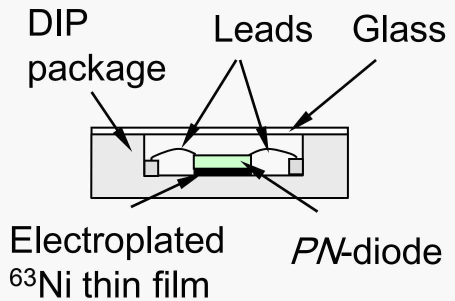
240 cm^3, 300 g total weight

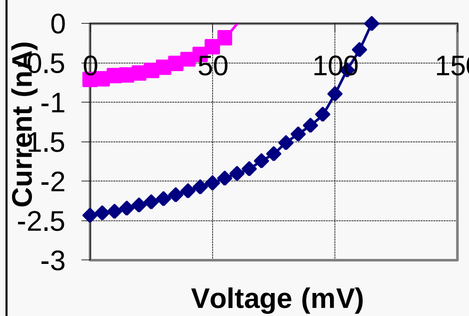
John H. Glenn Research Center, Cleveland, Ohio
Hi-Z Technology and JPL

Betavoltaic Microbattereis

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



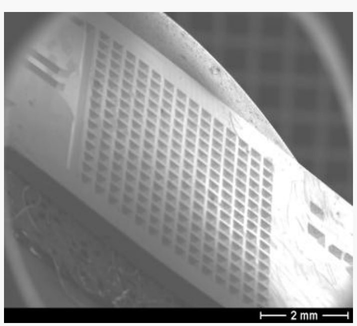


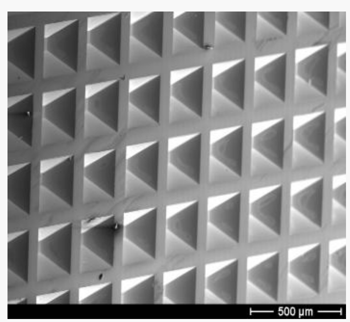


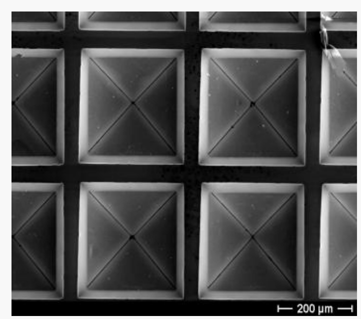
	0.25mCi	1mCi
I_p	0.71nA	2.41nA
V_{oc}	64mW	115mV
P_{max}	0.04nW	0.24nW

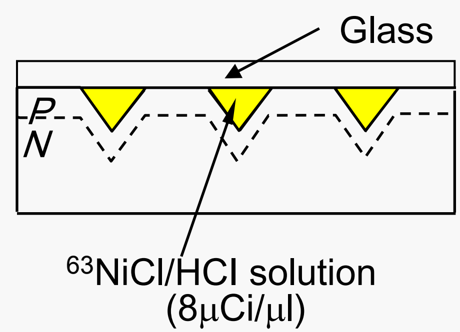
- Nanopower(0.04~0.24nW) obtained/ - No performance degradation after 1 year

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









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

- **Efficiency:0.03~0.1% → ~10 times > micromachined RTG**

Scaling of Power

- **Currently 1mCi of ^{63}Ni is used**
  - Source density of~0.0625 mCi/mm^2 leads to 2~8 nW/cm^2
- **10mCi~100mCi of ^{63}Ni is expected to be used**
  - Source density is ~1~2 mCi/mm^2
  - 100nW ~200 nW can be obtained
  - Gives 100~200 nW/cm^2
- **Energy conversion efficiency of 0.5~1% is expected to be achieved**
  - Theoretical conversion efficiency: 3~5%

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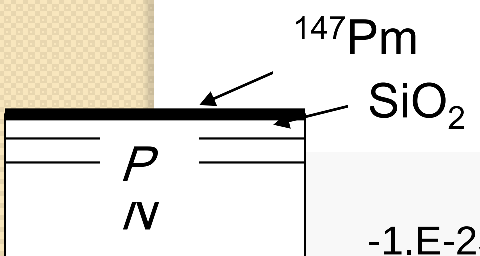
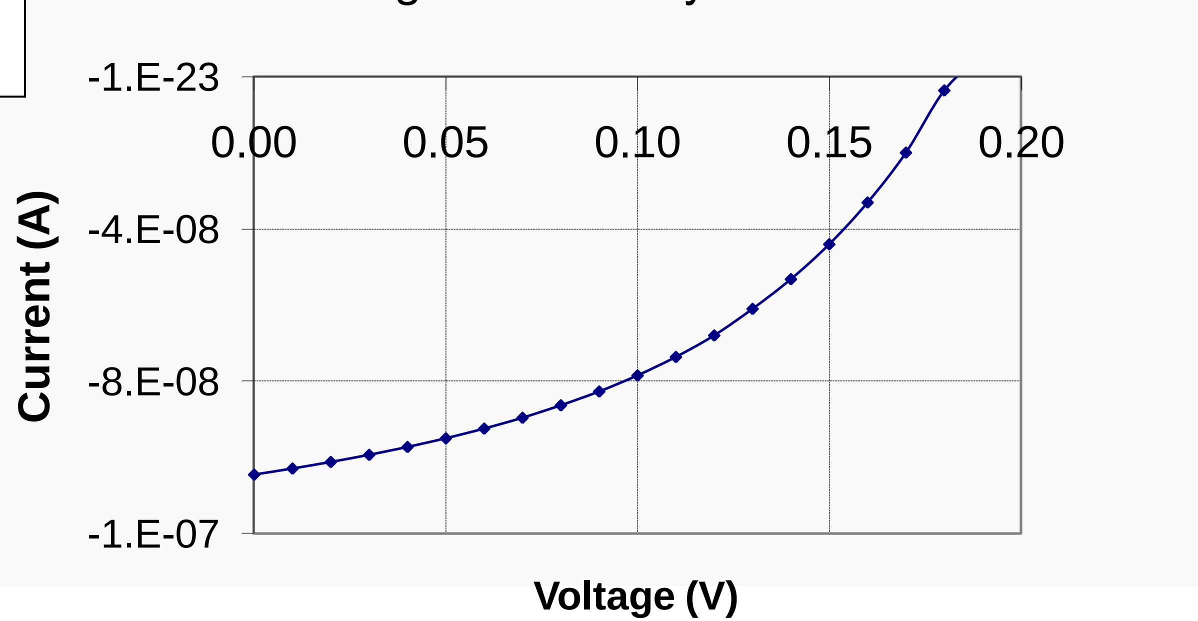
Using Radioisotope ^{147}Pm

- **Another way to raise power output : using high energy power source**
  - ^{147}Pm, with E_{avg}= 62 keV and E_{max}= 220 keV and half-life of 2.6 year is also a promising pure beta source for microbattery.

- **Preliminary Results**

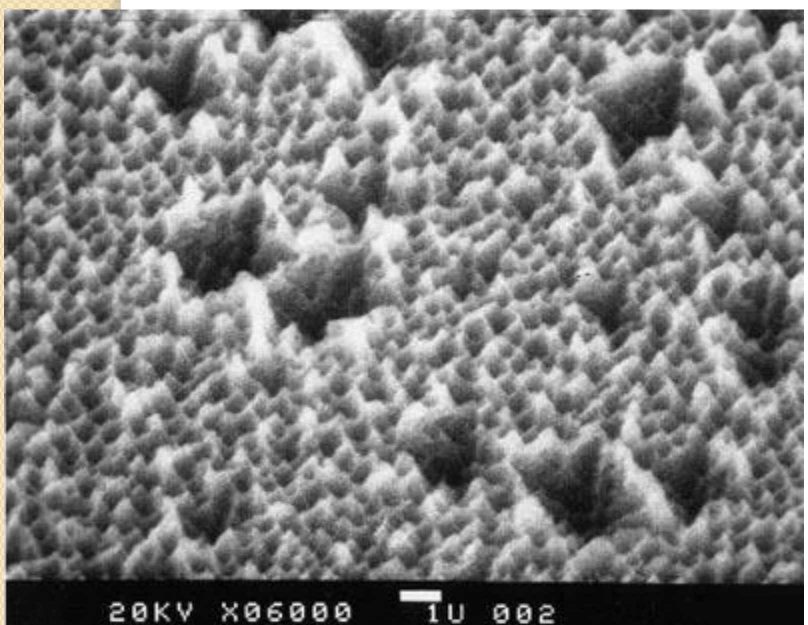
-1μm of SiO_2 is used as protection layer
- Device area : 2mm $\times$3mm
- 5mCi of ^{147}Pm is used
- test result : Is= 140nA, Voc=183mV, Pmax = 16.8nW
- Conversion efficiency: 0.62%
- long-term stability is under test

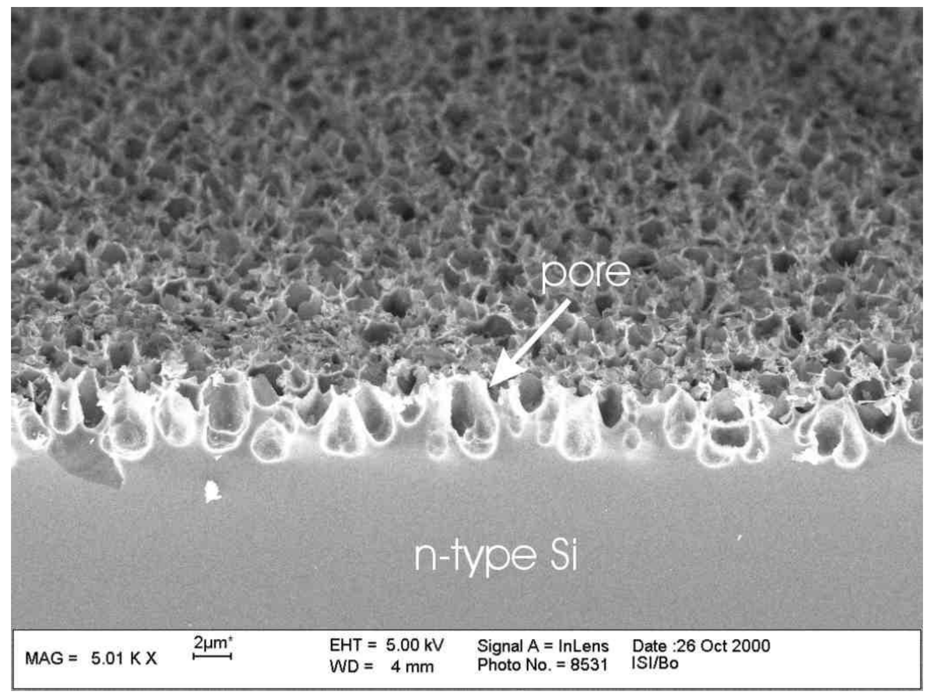




Porous Silicon

- Try to maximize area exposed to source

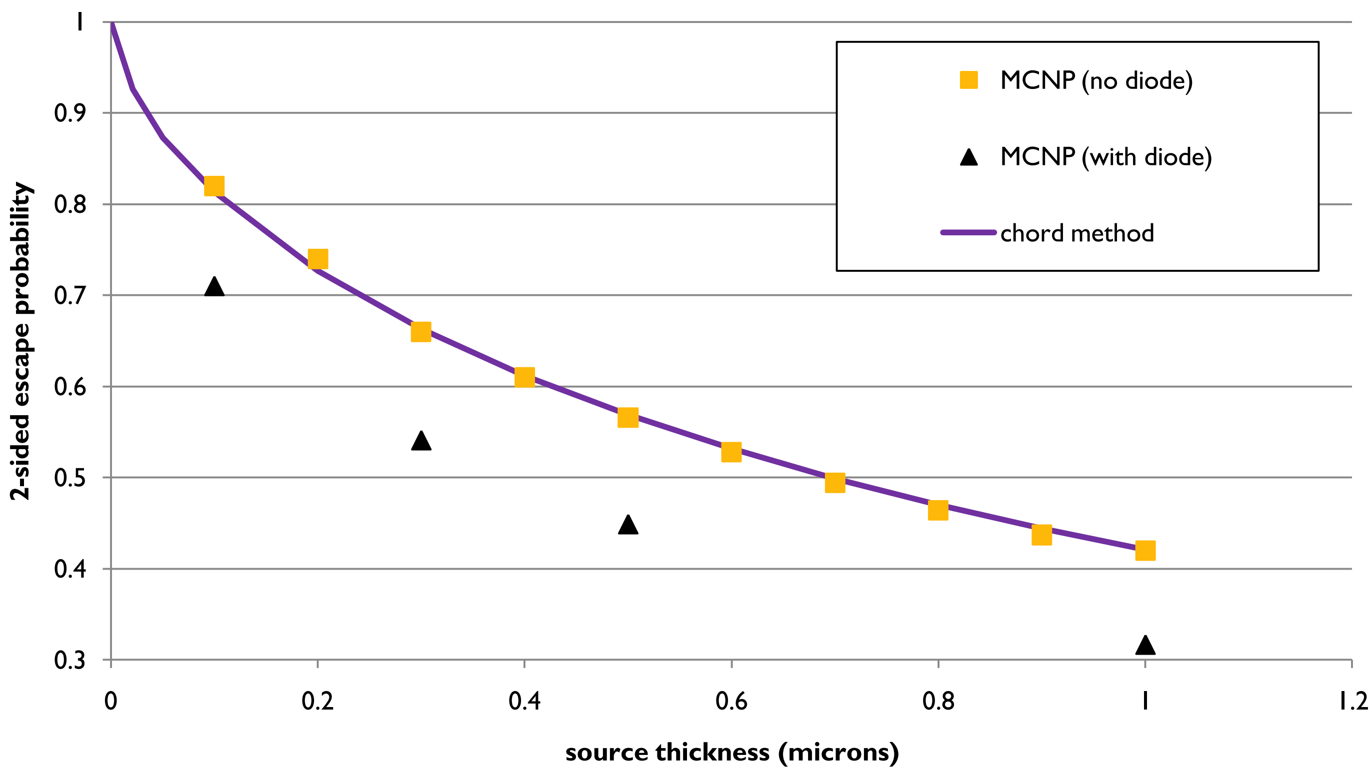


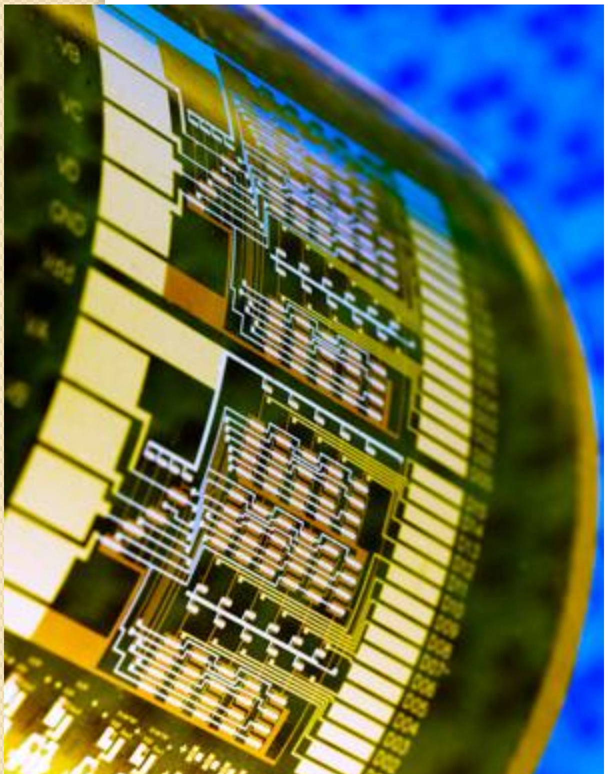


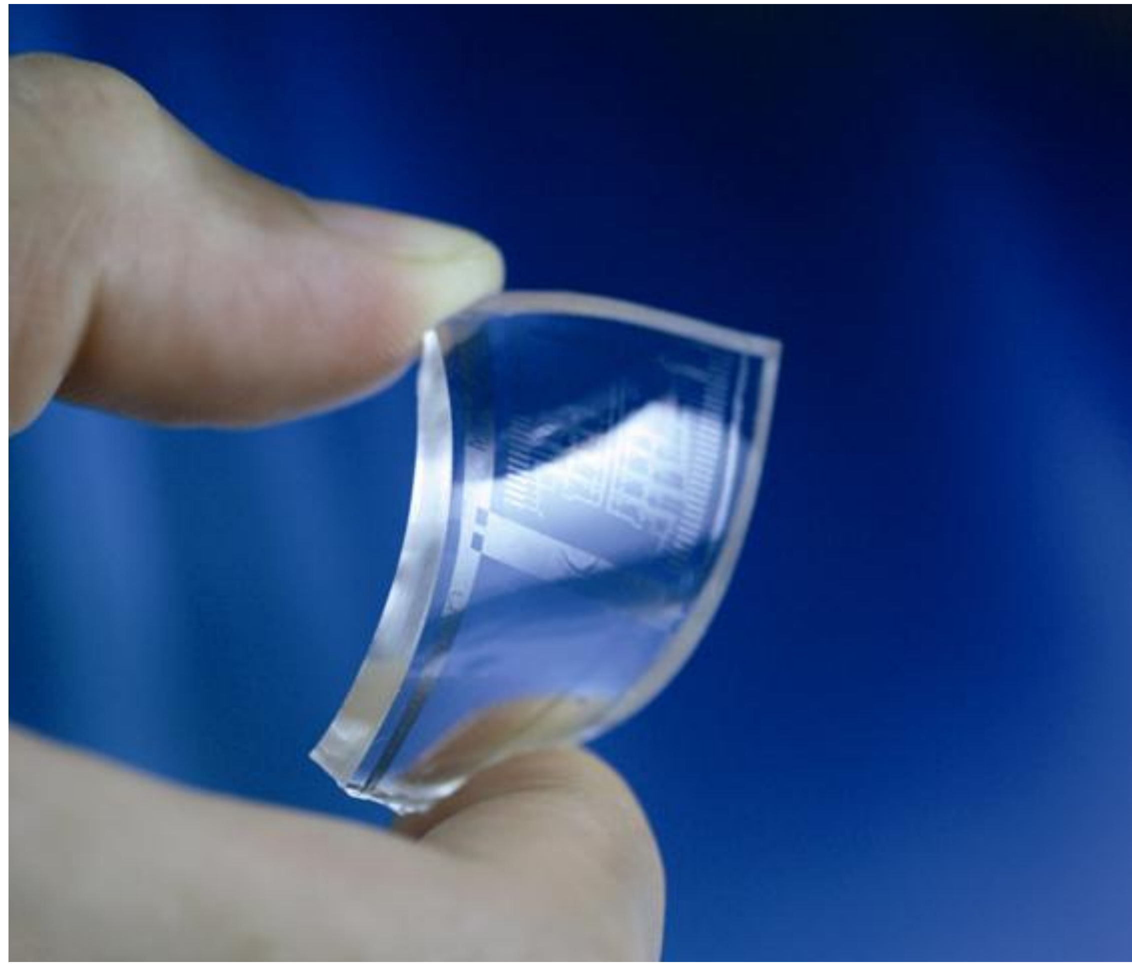
Thin, Flexible Semiconductors

- 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

Self-Absorption – Ni-63 and Si



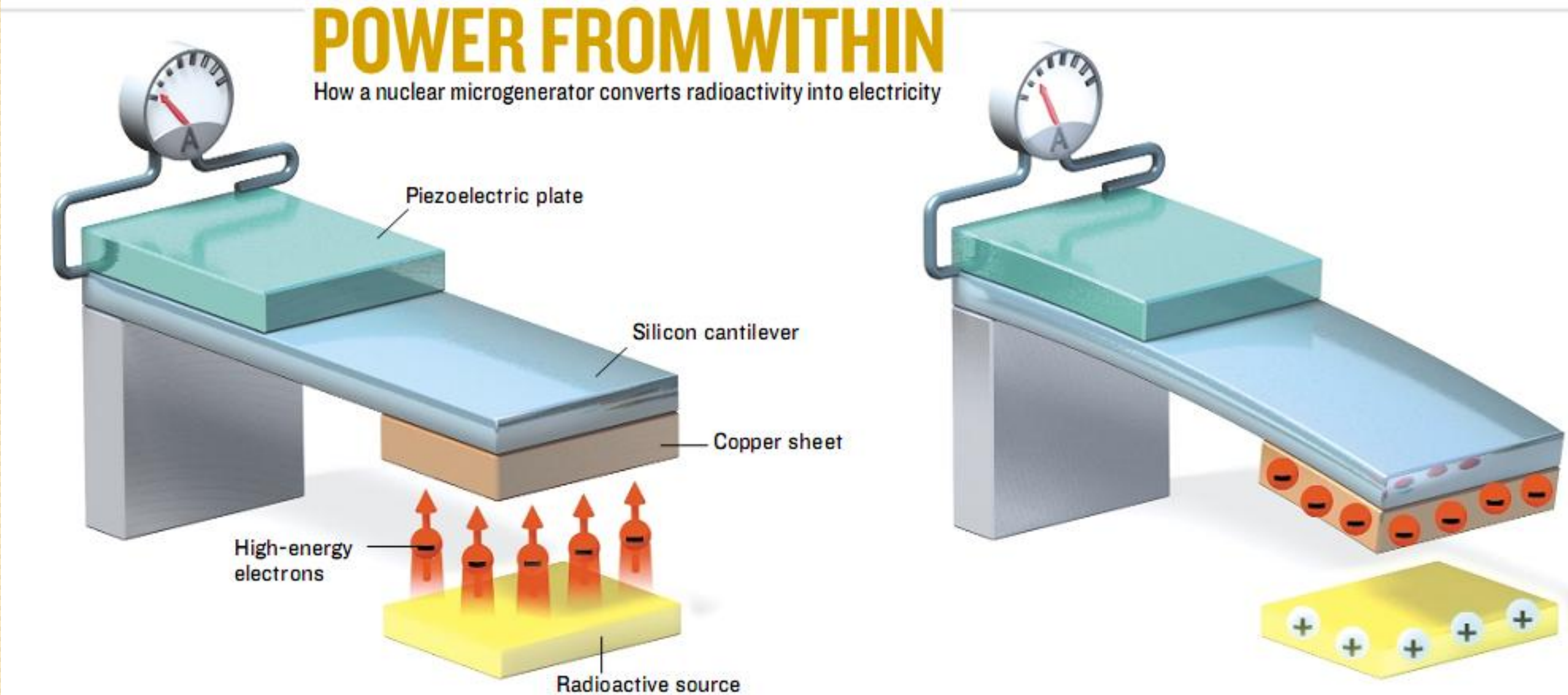




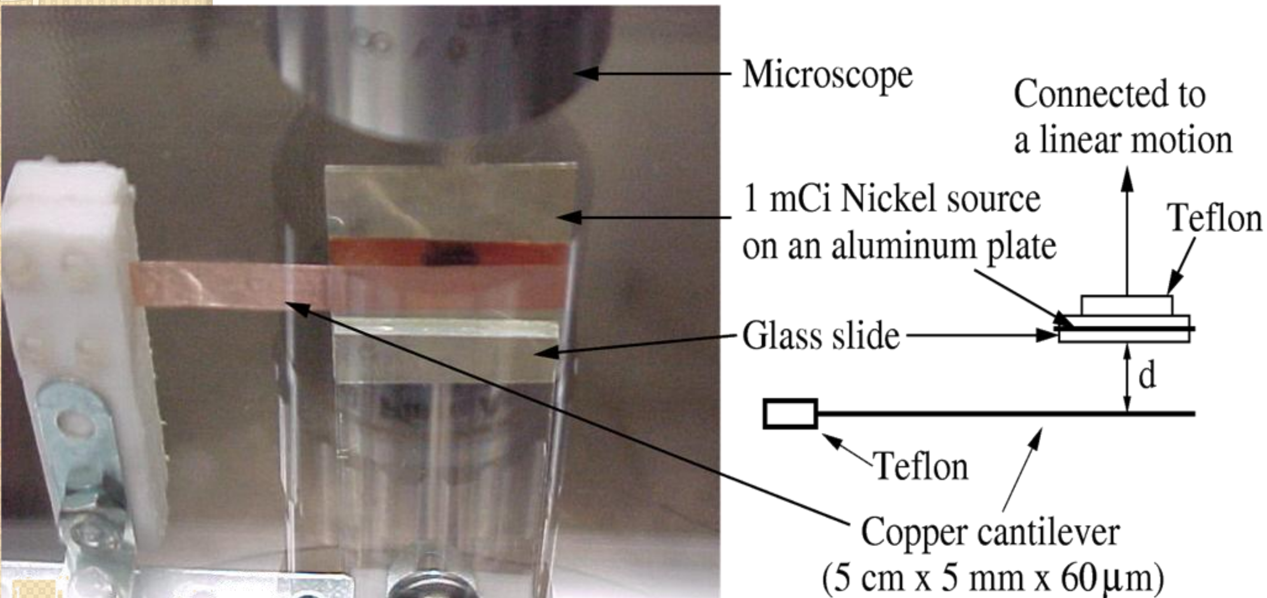
Silicon Carbide

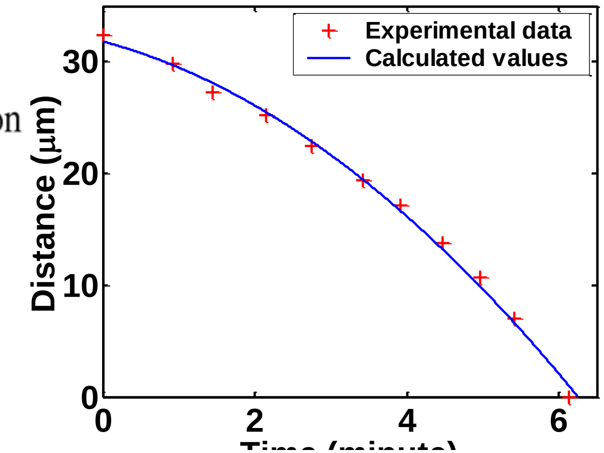
- Wide Bandgap semiconductors offer hope for larger efficiencies
- Simulations indicate on the order of 25% conversion efficiency

A "New" Concept



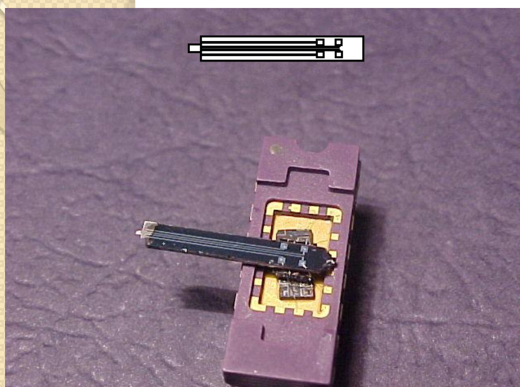
Self reciprocating cantilever

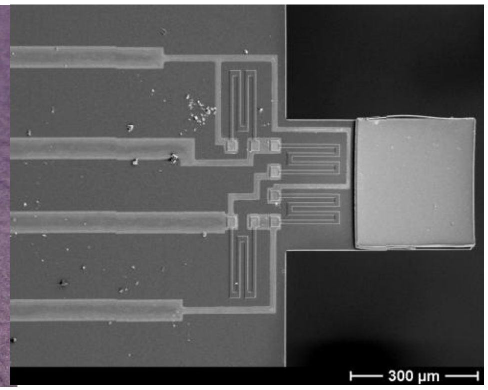


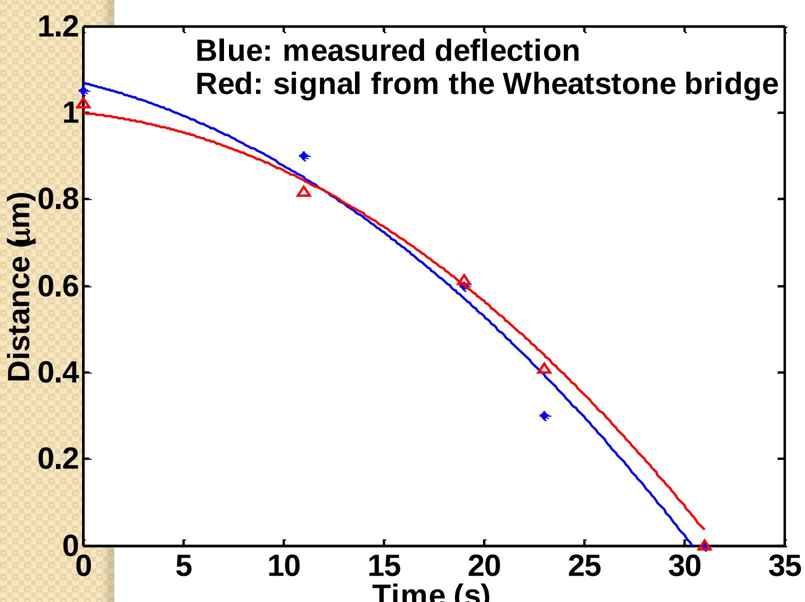


- Initial gap (d_0): 33 μm
- Period: 6 min. 8 sec.
- Residual charges: 2.3×10^{-11}C
- Peak force (kd_0): 10.1 μN
- Assumed Collection efficiency (α): 10%

Self-reciprocating SiN cantilever







- The cantilever is made of low stress SiN thin film with dimensions 500 $\mu m \times 300 \mu m \times 1.7 \mu m$.
- The cantilever is mounted on a DIP package for wire bonding.
- Four poly resistors form a Wheatstone bridge to measure the deflection of the cantilever.
- The signal from the Wheatstone bridge is sent to an instrumentation amplifier and then output from the amplifier is measured.

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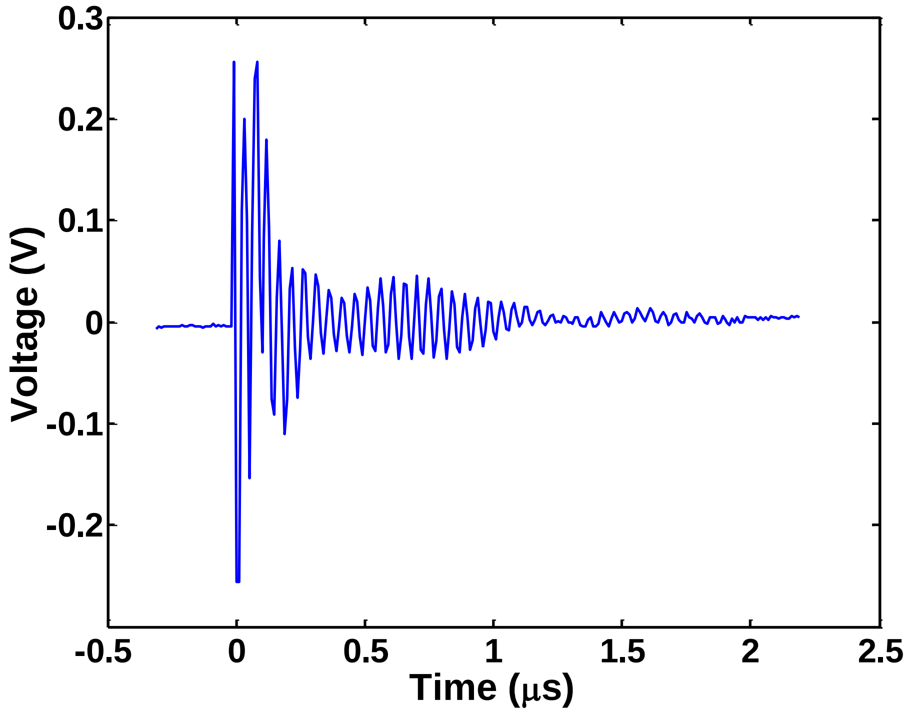
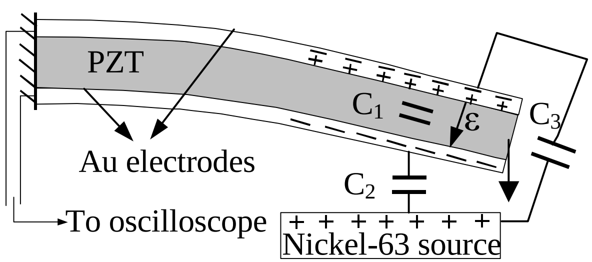
Self-powered Sensor/Actuator/Transmitter





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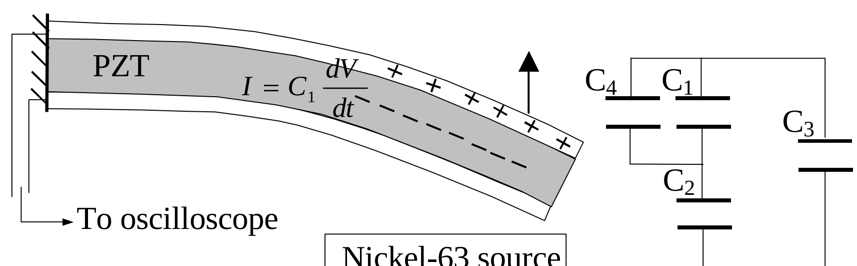

(b)

Bottom Line

- Market is applications which can justify cost and risk of using radioisotope fuels
- Advantage is very long life

Comparing Technologies