Radioisotope Batteries for MEMS

Jake Blanchard
University of Wisconsin

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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

What is a Nuclear Battery?

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

Comparison

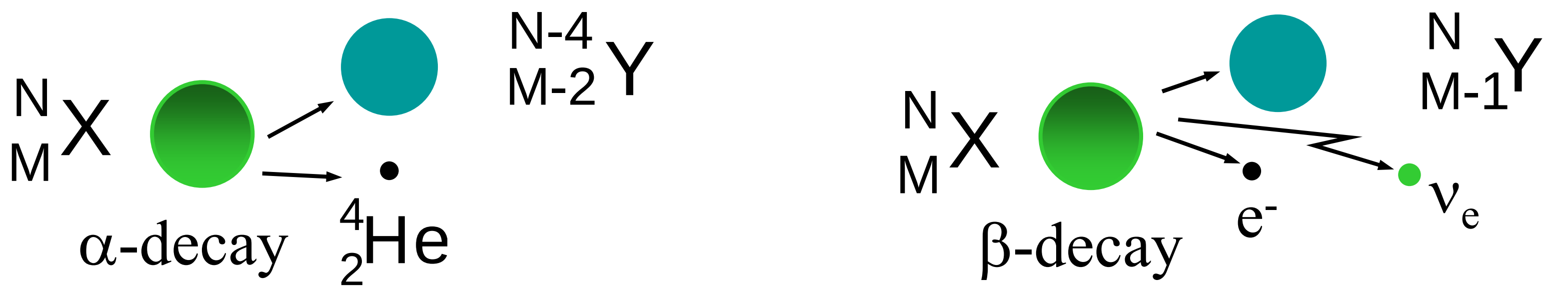
- Consider 1 mg for power source

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

Isotope Selection

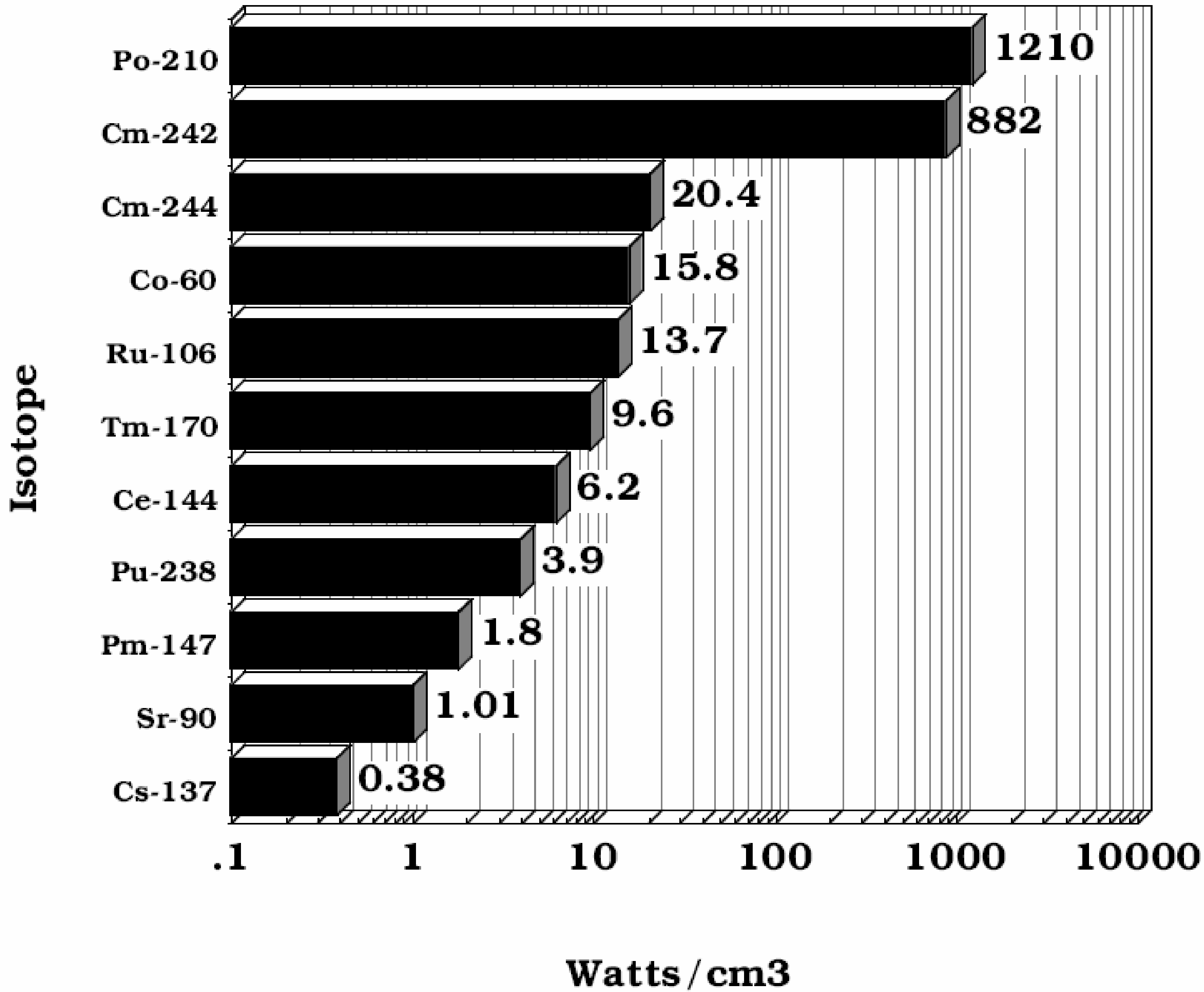
- Type of radiation
  - Alpha
  - Beta
- Half-Life
  - Long -> Long battery life
  - Short -> Higher power
- Avoid gammas in the decay chain
- Watch out for (alpha, n) reactions
- Watch particle range

Radioisotopes and decay

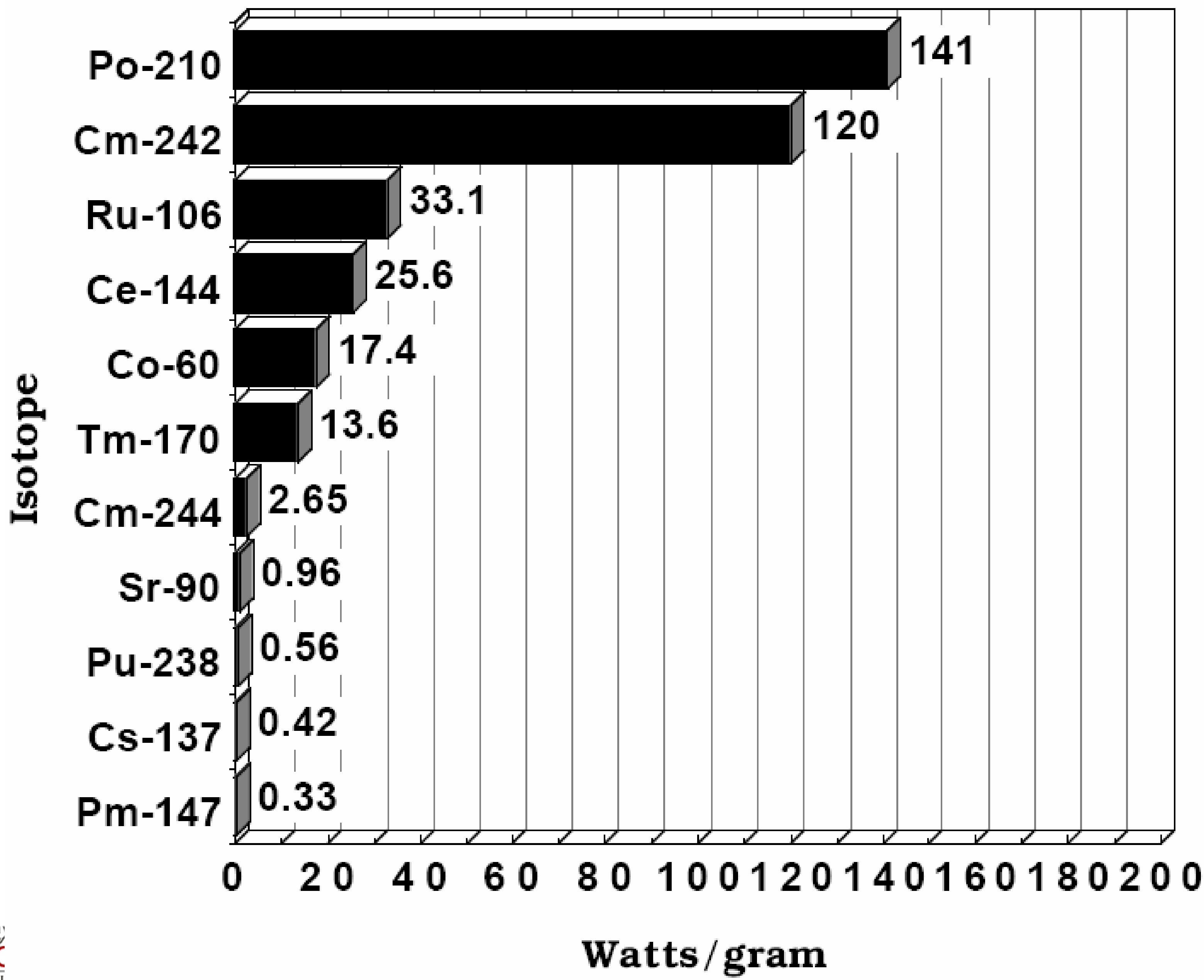


Isotope	Average energy	Half life	Specific activity	Specific Power	Power Density
	(KeV)	(year)	(Ci/g)	(W/g)	(W/cc)
63-Ni	17	100	57	0.0067	0.056
3-H	5.7	12	9700	0.33	-
90-Sr/ 90-Y	200/930	29/2 d	140	0.98	2.5
210-Po	5300	0.38	4500	140	1300
238-Pu	5500	88	17	0.56	11
244-Cm	5810	18	81	2.8	38

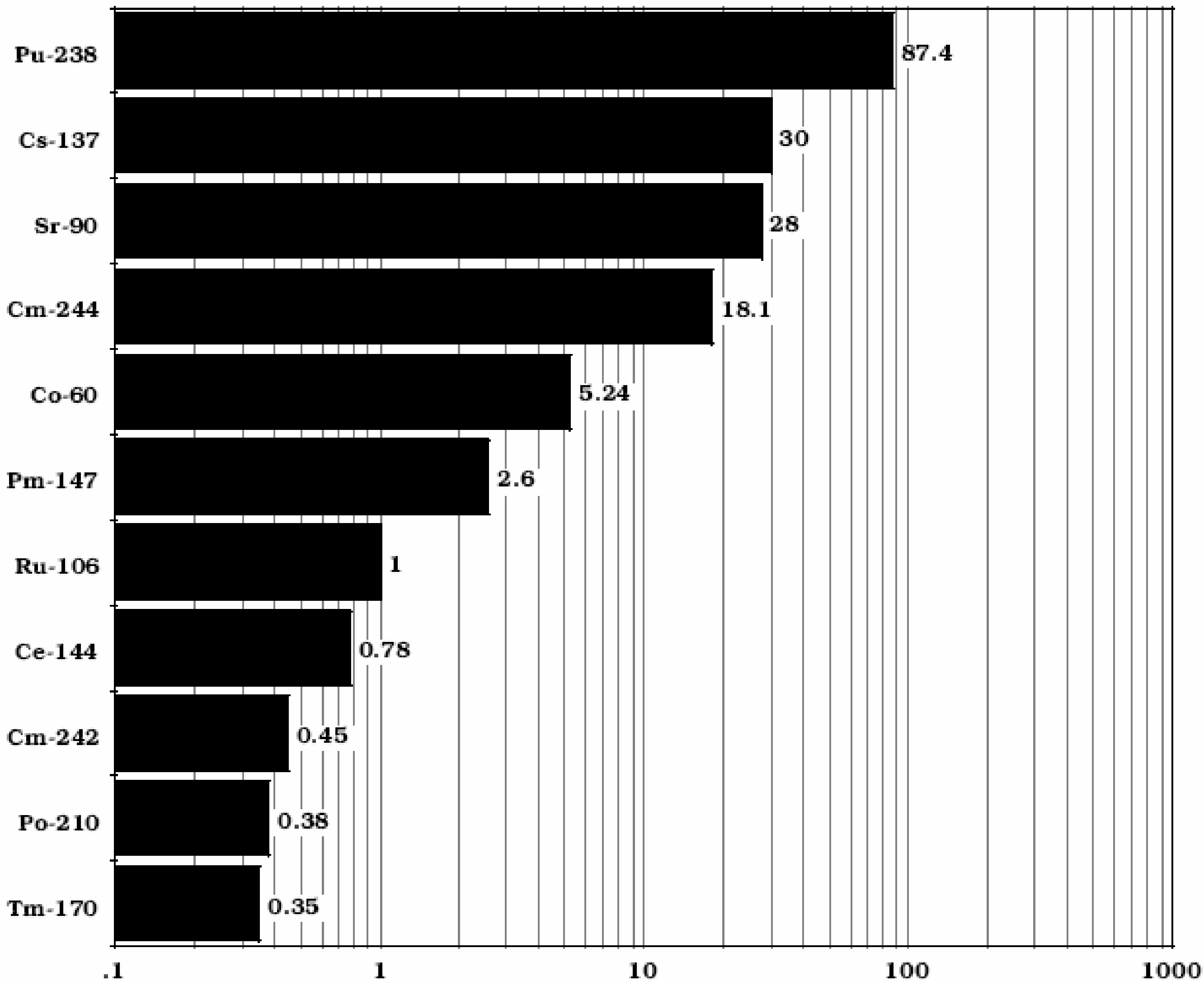
Specific Power Density of Leading Radioisotopes



Power Density in RTG Isotopes

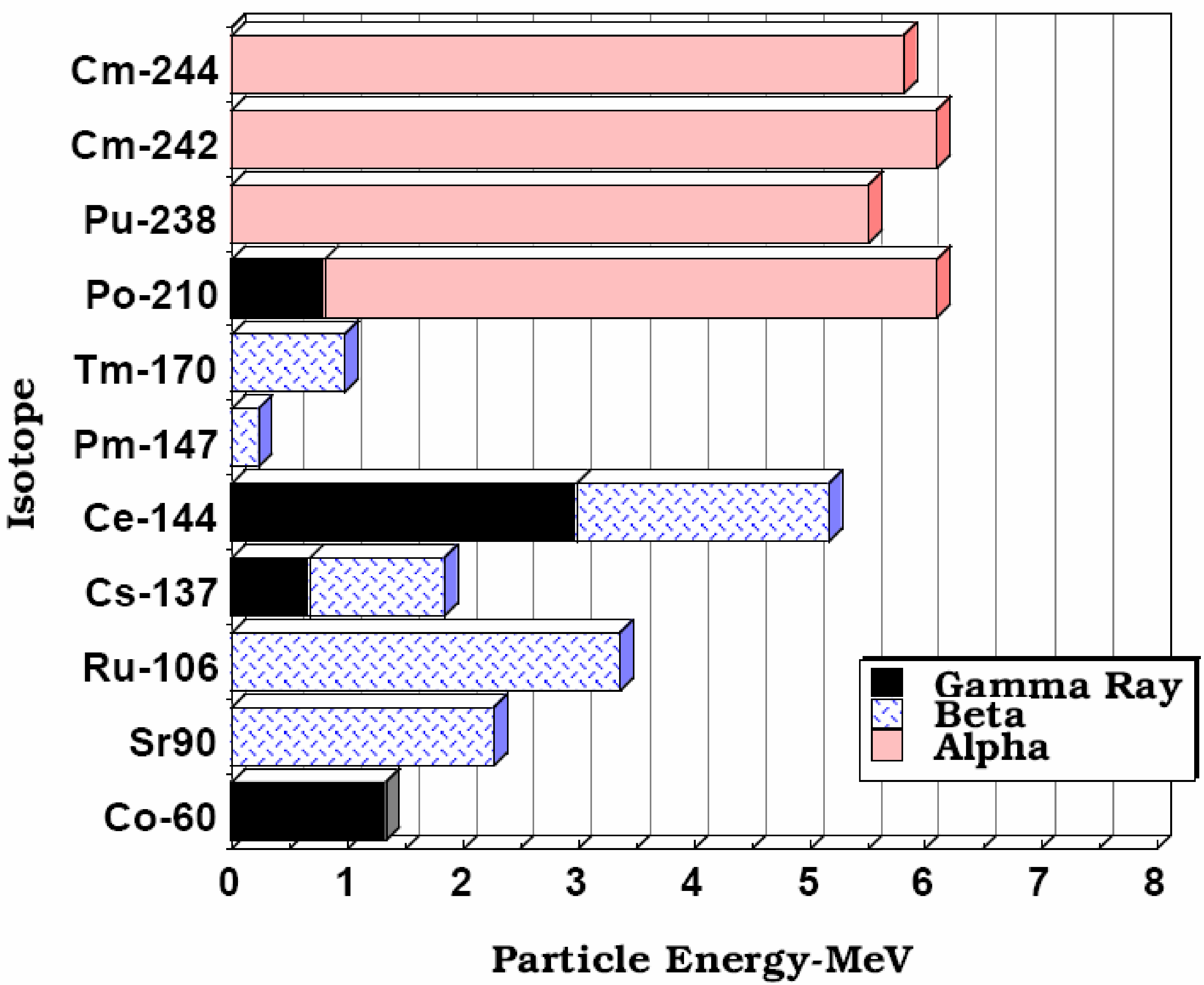


Half Life of RTG Fuels

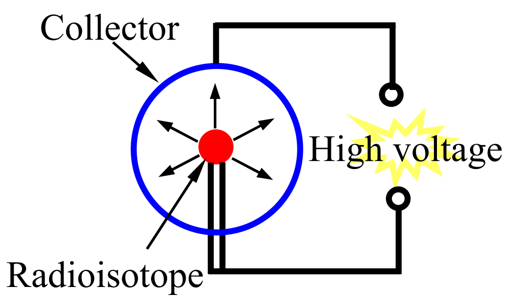


Half Life-Yr

Decay Energy of Radioisotopes



Direct conversion nuclear battery



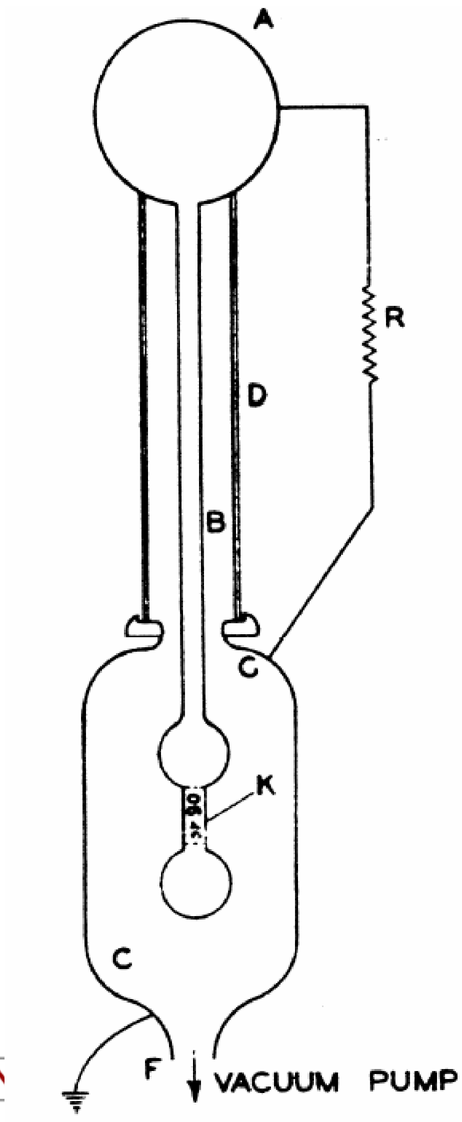
- Direct conversion nuclear battery: collecting charges emitted from radioisotopes with a capacitor to achieve high voltage output

  (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

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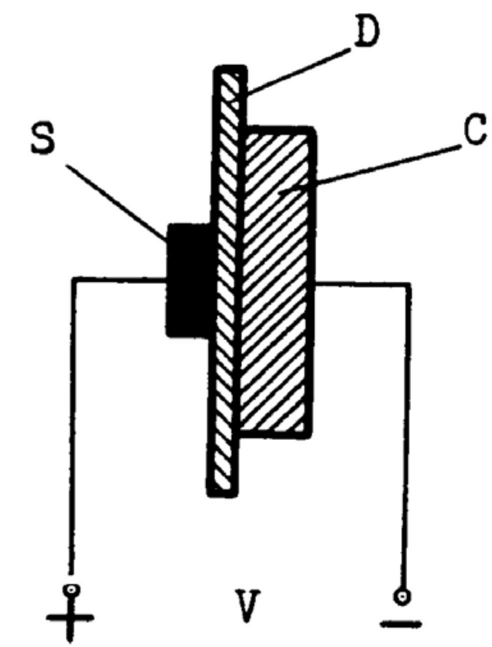
Linder, Rappaport, Loferski

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

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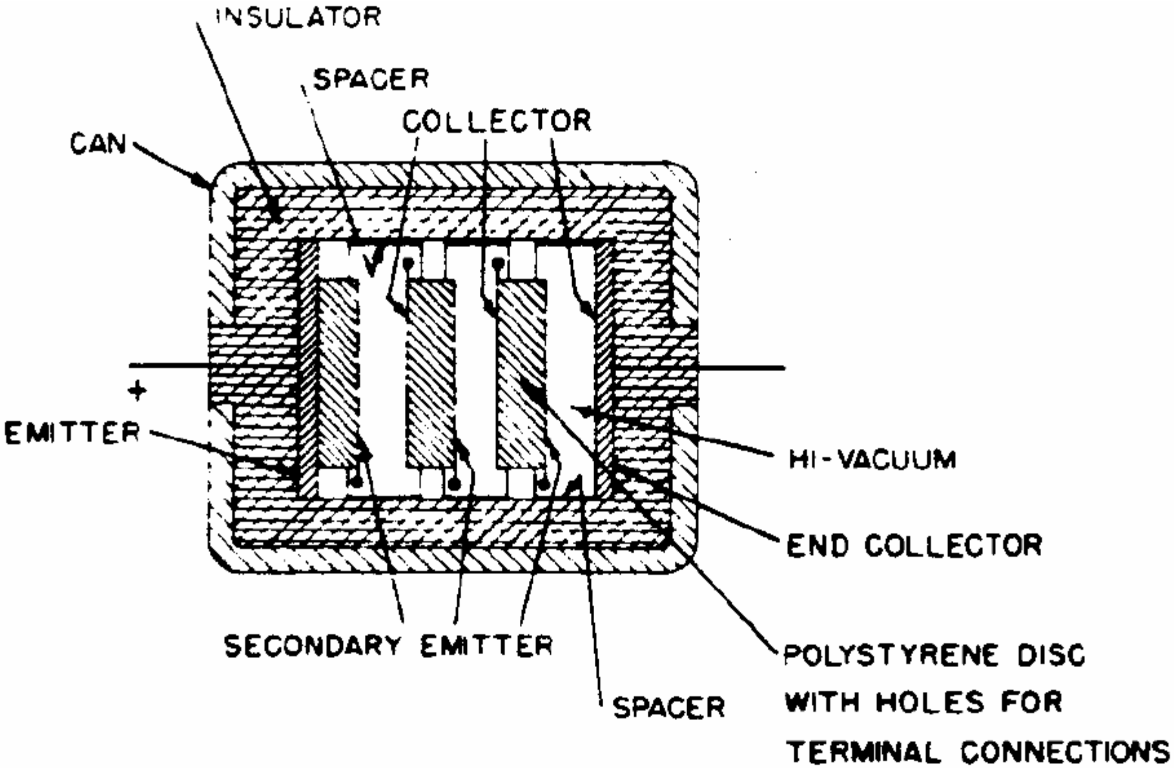
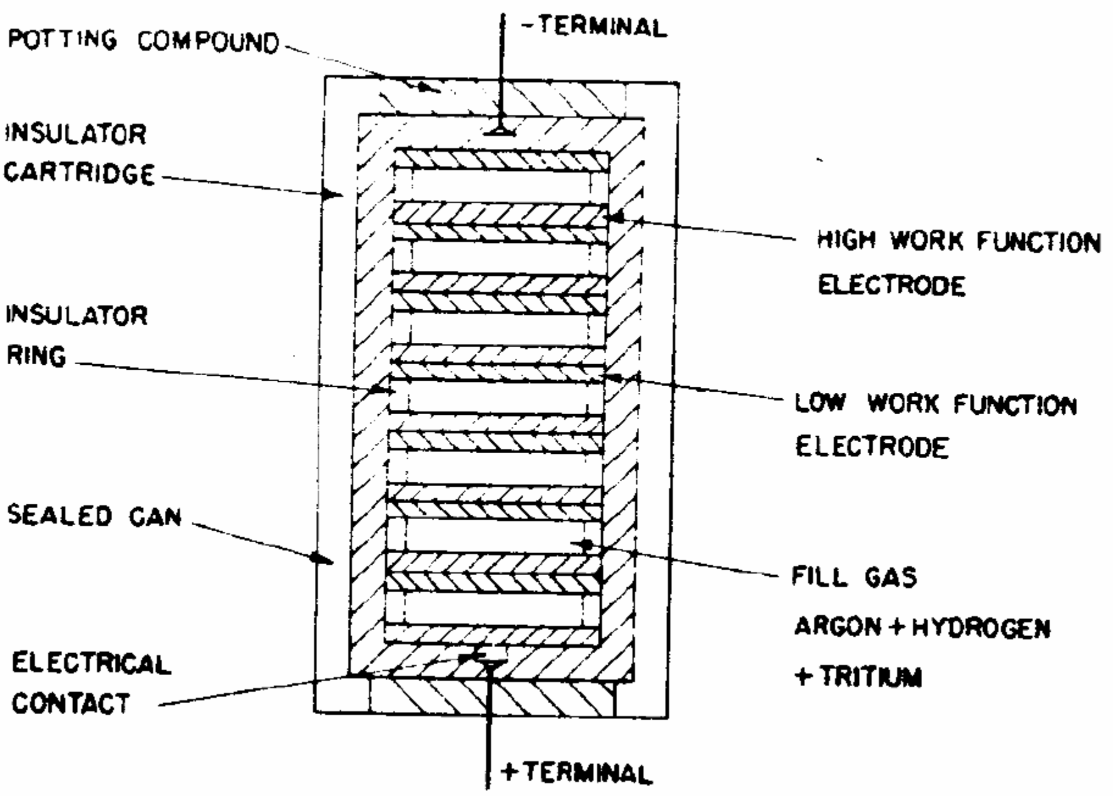
Secondary Collector



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

Shorr

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 1-2 V

Shorr

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

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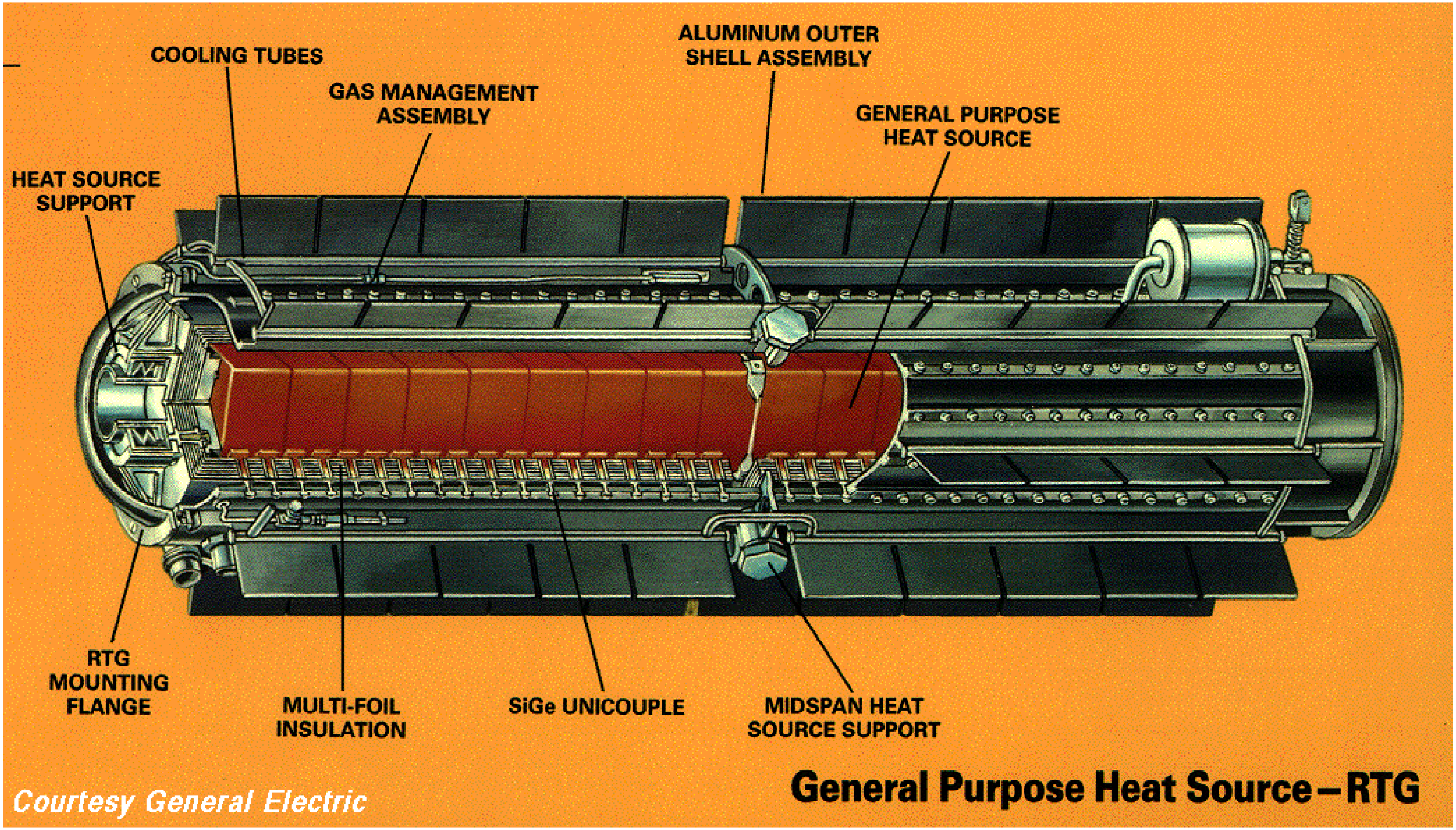
http://www.naspe.org/library/electricity_and_the_heart/

Radioisotope Thermoelectric Generators (RTGs)

- Used in many NASA missions
- Use radioisotope (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

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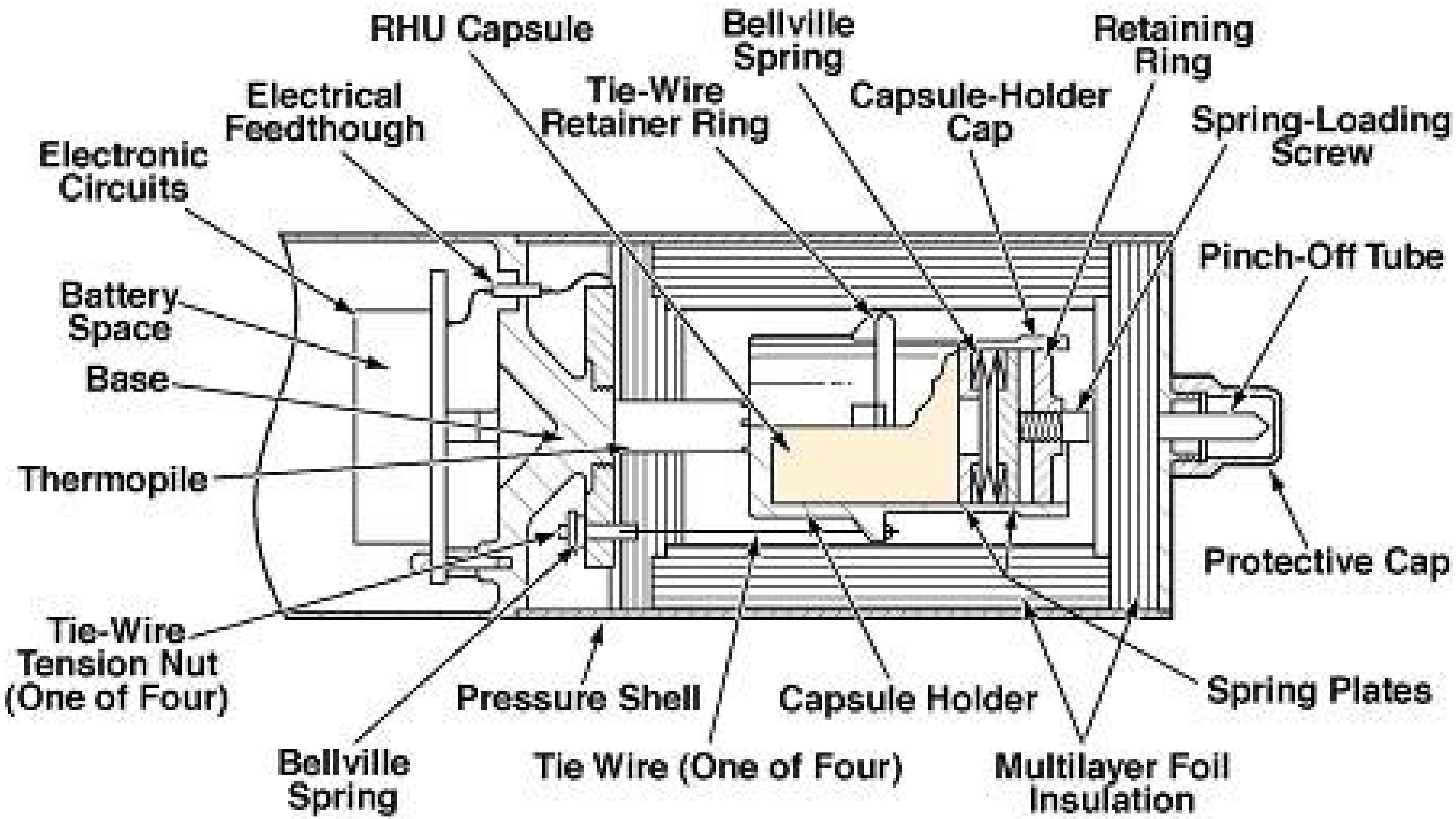
http://nuclear.gov/space/rhu-fact.html

A Compact Thermoelectric



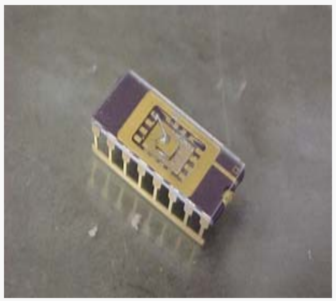
40 mW electric power

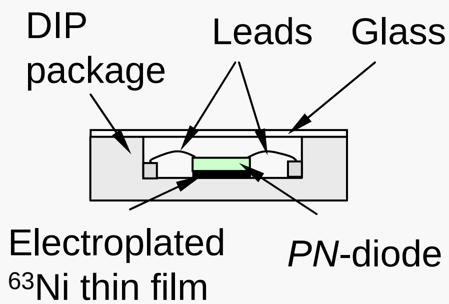
240 cm^3, 300 g total weight

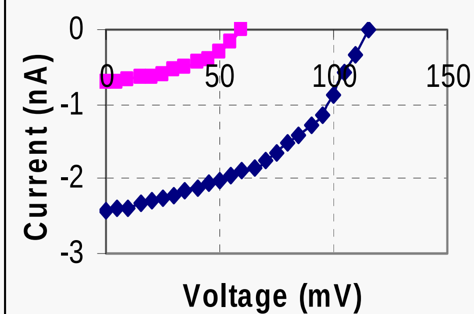
John H. Glenn Research Center, Cleveland, Ohio
Hi-Z Technology and JPL

Betavoltaic Microbattereis

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



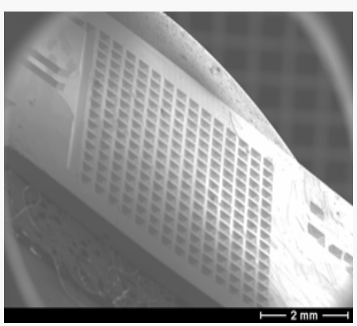


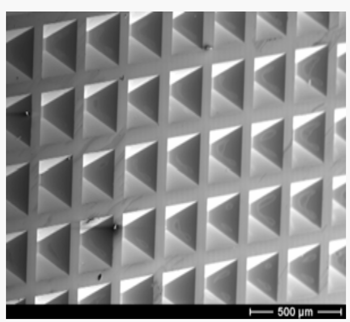


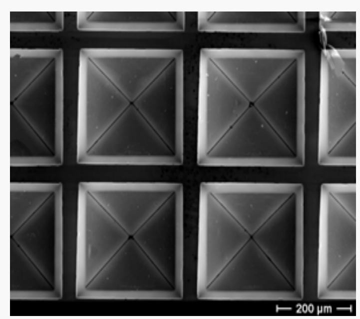
	0.25mCi	1mCi
I_p	0.71nA	2.41nA
V_{oc}	64mW	115mV
P_{max}	0.04nW	0.24nW

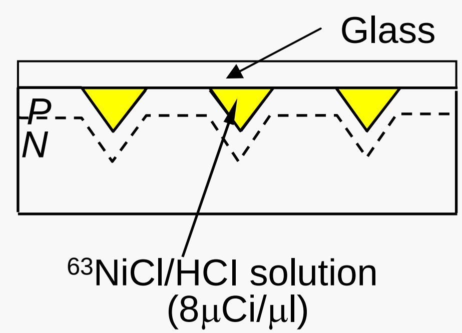
- Nanopower(0.04~0.24nW) obtained/ - No performance degradation after 1 year

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







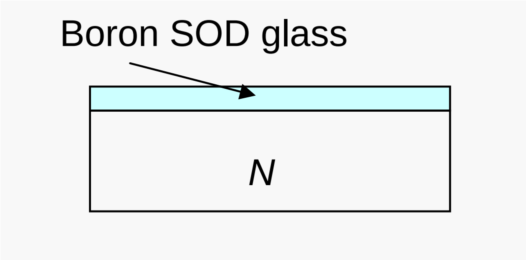


- Area magnification: 1.85 / - 0.32nW (128mV/2.86nA) obtained

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

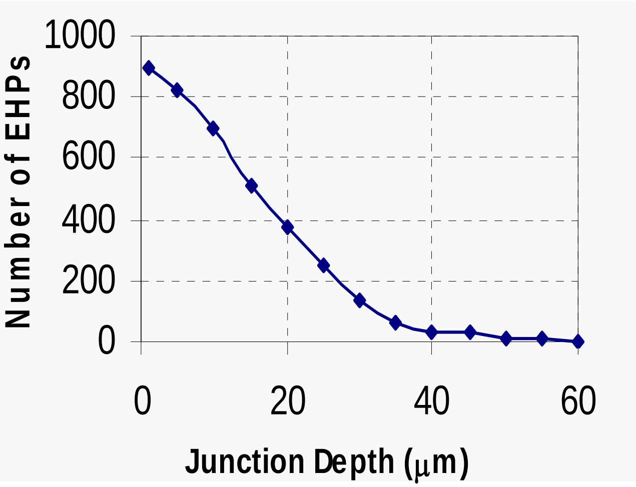
Electron-Hole Pairs Generation

- **Different junction depths using spin-on glass dopant diffusion**
  - Boron dopant glass from ***Filmtronics*** is spinned on n-type wafer
  - diffusion time up to 72hours at 1050ºC



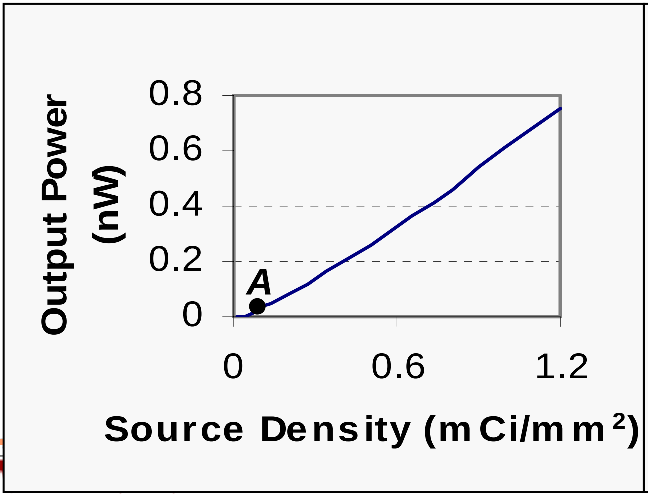
- **Determination if generated electron-hole pairs(EHPs)**
  - 0.25mCi is used
  - short-circuit current is tested for each device
- - Number of EHPs is obtained by dividing short-circuit current over flux of emitted electrons ($0.25\times10^{-3}\times3.7\times10^{10}\times1.6\times10^{-19}$)
- **Ability of ^{63}Ni current multiplication:**

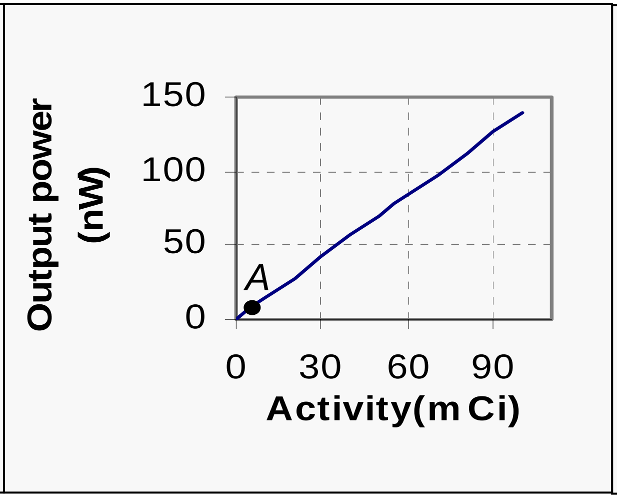
  1 electron/betas can generate ~920 EHPs in average.
- **The electron emitted from Ni^{63} could travel in silicon up to ~40 μm. Thus, minority carrier diffusion length L_N > 40 μm**

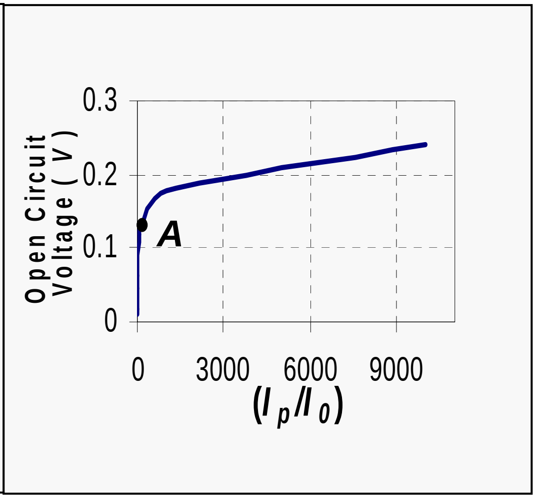


MicroPower Prediction Using Higher Radioactivity

- **Currently 1mCi of ^{63}Ni is used**
  - Source density of~0.0625mCi/mm^2 ⟶ 2 ~8nW/cm^2
- **10mCi~100mCi of ^{63}Ni is expected to be used**
  - Source density is ~1~2mCi/mm^2
  - 100nW ~200nW can be obtained ⟶ 100~200nW/cm^2
- **Energy conversion efficiency of 0.5~1% is expected to be achieved**
  - Theoretical conversion efficiency: 3~5%
    (920EHPs vs. 5200 (=17.3Kev/3.5eV) EHPs)
  - Leakage current density (1.5pA/mm^2 vs. 0.3pA/mm^2) still can be reduced.







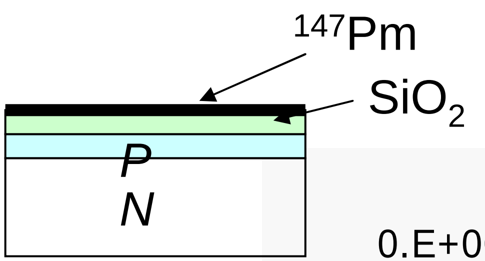
Latest Development : Using Radioisotope ^{147}Pm

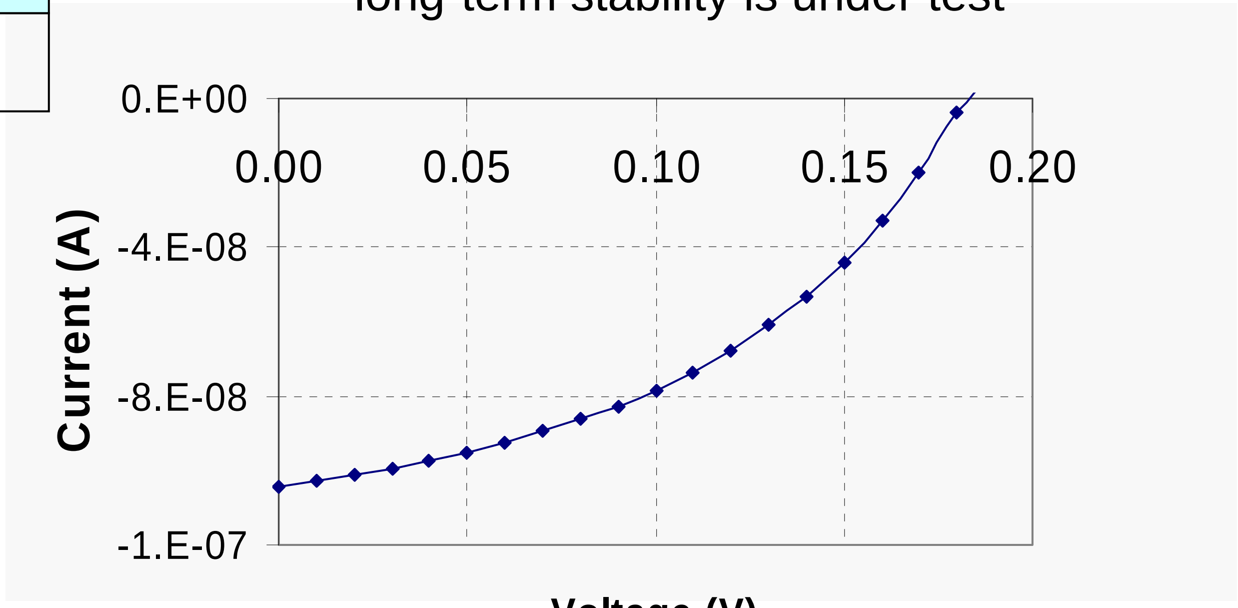
- **Another way to raise power output : using high energy power source**

  - ^{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.

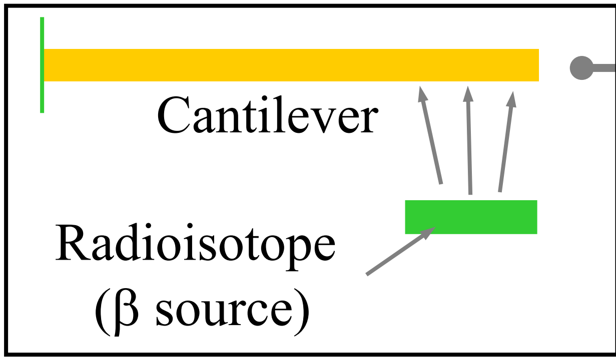
- **Preliminary Results**

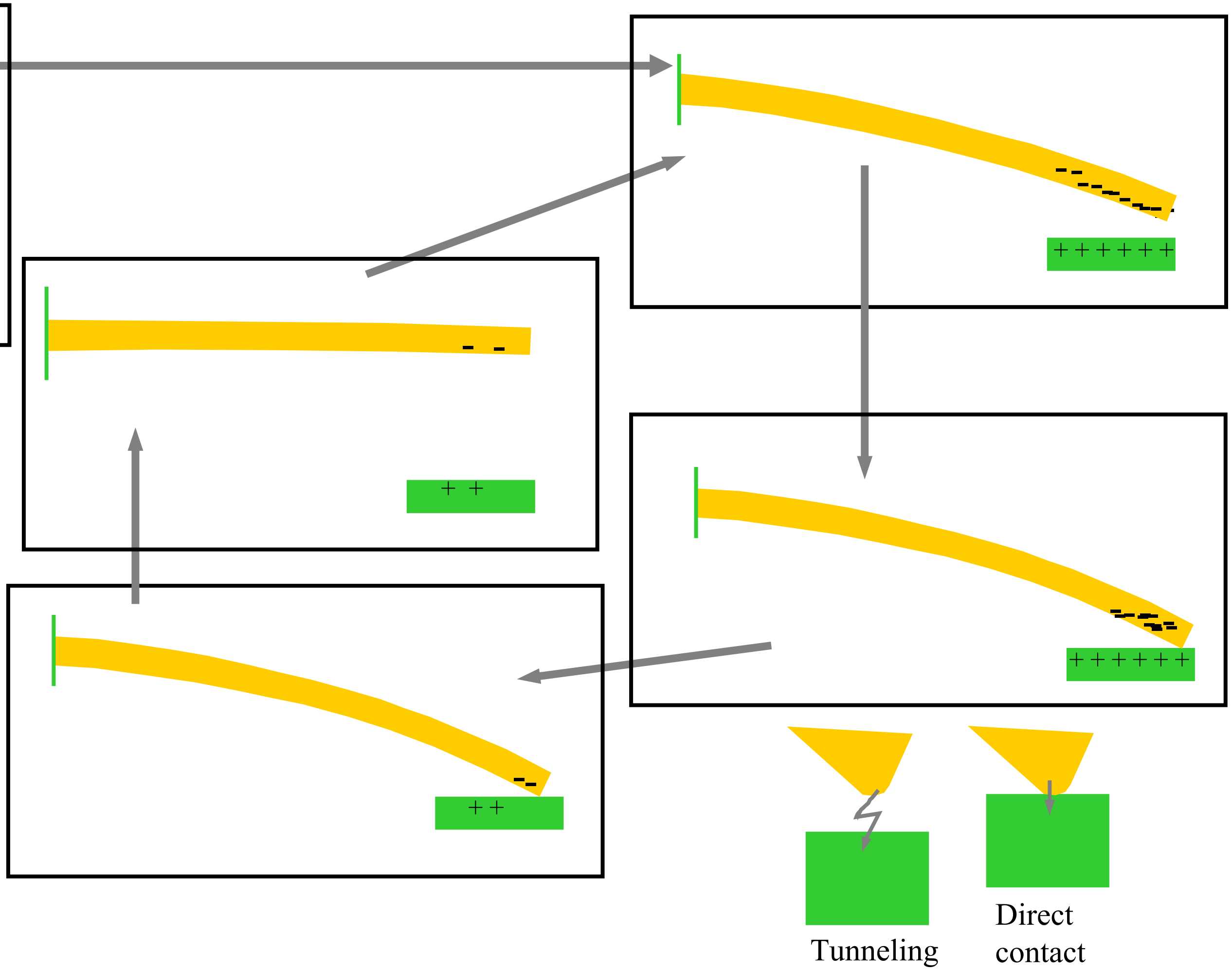
-1μm of SiO_2 is used as protection layer
- Device area : 2mm ×3mm
- 5mCi of ^{147}Pm is used
- test result : Is= 140nA, Voc=183mV, Pmax = 16.8nW
- Conversion efficiency: 0.62%
- long-term stability is under test





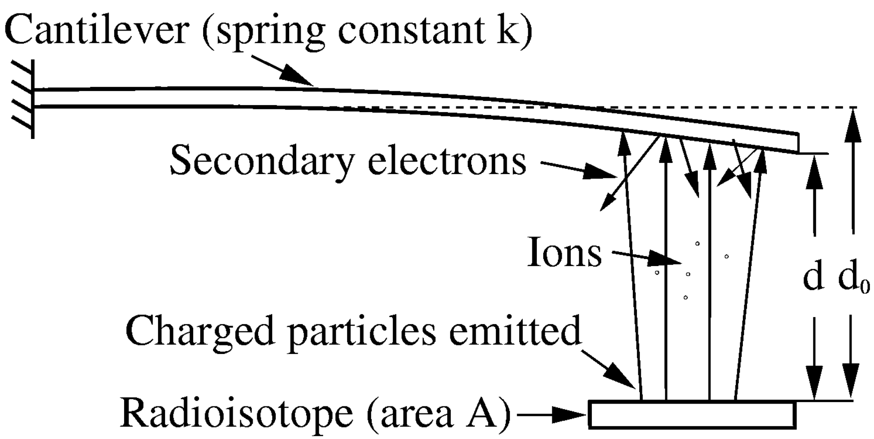
Direct conversion of emitted charges to mechanical motion

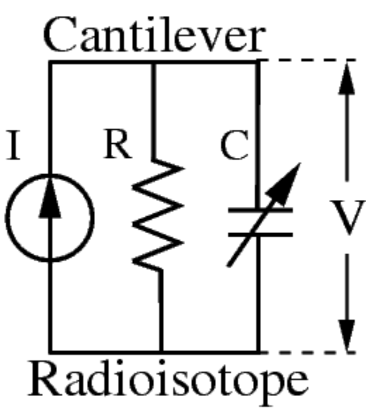




- Low energy from source is integrated over time to achieve high instantaneous power.
- Continuous reciprocation for 4 weeks has been achieved.

Electromechanical model





Charge conservation:

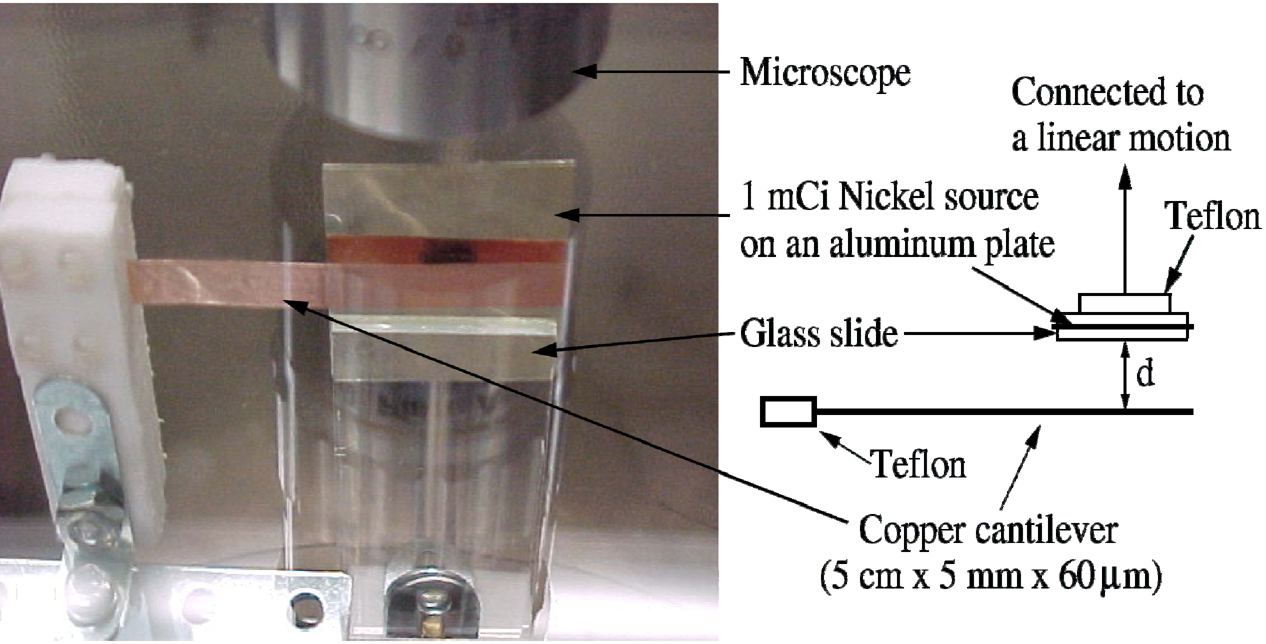
$$\frac{\alpha I}{A} - \frac{V}{RA} - \varepsilon_0 \frac{\partial}{\partial t}\left(\frac{V}{d}\right) = 0$$

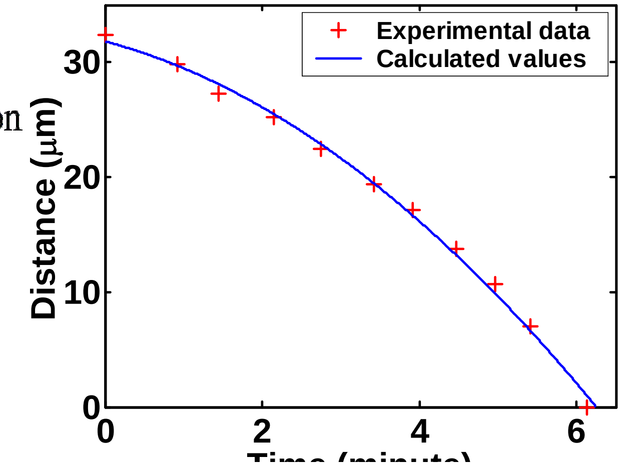
Force balance:

$$k(d_0 - d) - \varepsilon_0 A \frac{V^2}{d^2} = 0$$

$$\frac{\partial d}{\partial t} = \frac{2}{\varepsilon_0 RA}(d_0 - d)d - \frac{2\alpha I}{\sqrt{\varepsilon_0 kA}}\sqrt{d_0 - d}$$

Previous work: self reciprocating cantilever: SIZE





- 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%

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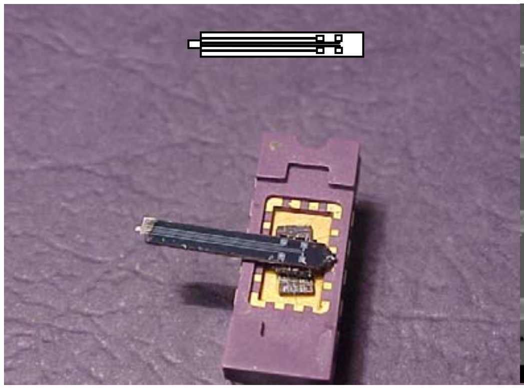
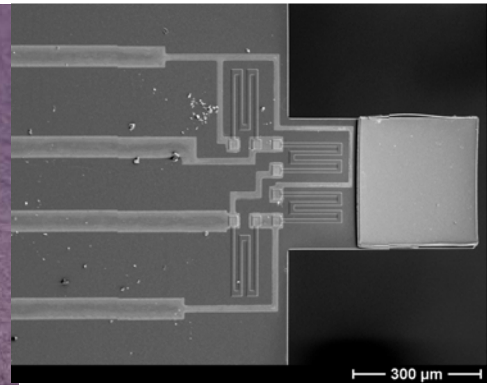
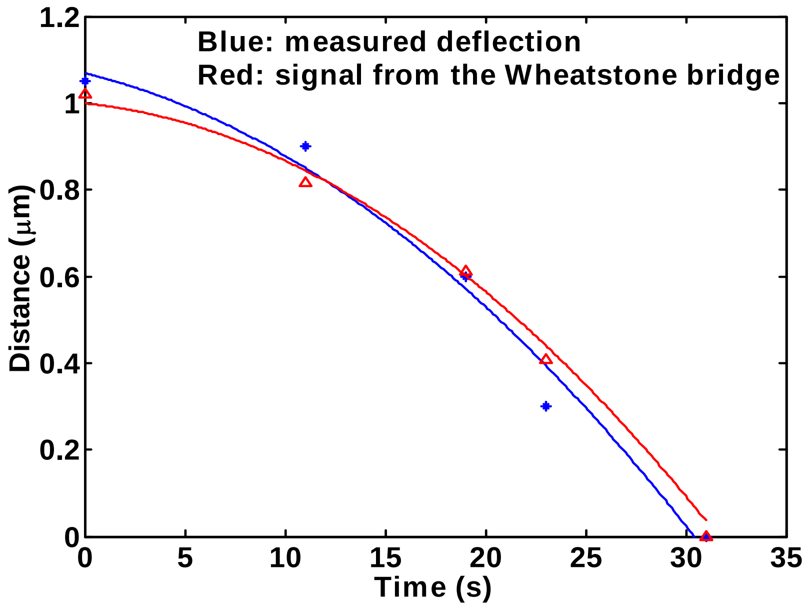
Self-reciprocating SiN cantilever







- The cantilever is made of low stress SiN thin film with dimensions 500 μm $\times$ 300 μm $\times$ 1.7 μm .
- 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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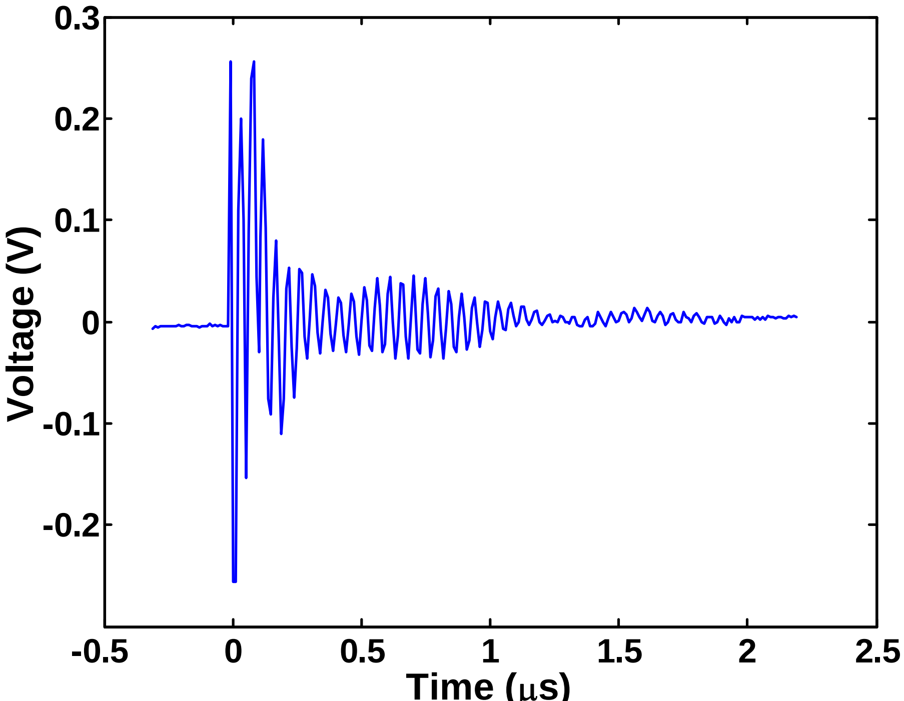
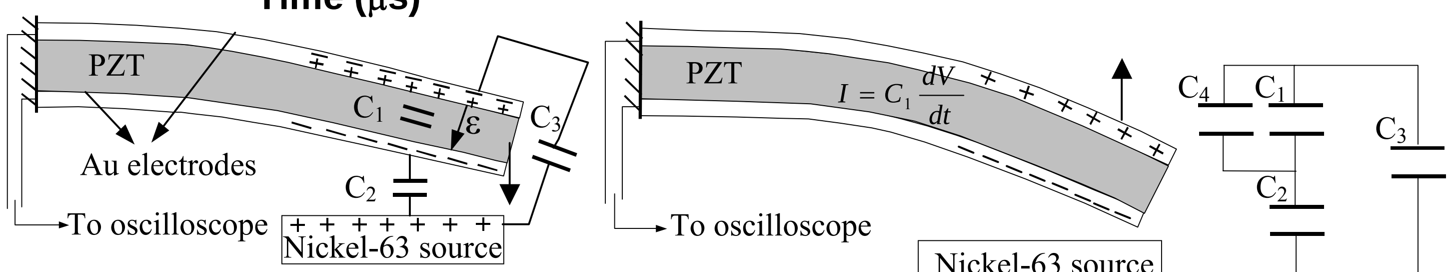
Self-powered: Sensor/Actuator/Transmitter: Reciprocation of a PZT beam results in RF output



- Sudden current release results in excitation of electrical and mechanical modes of the system
- RF frequency of 60-260 MHz due to distributed waveguide
- Thickness mode of PZT at 21 MHz results in modulation of RF => mechanically sensed signal can be transmitted as RF in a highly compact manner



(a) (b)

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Self-powered RF Pressure Sensor

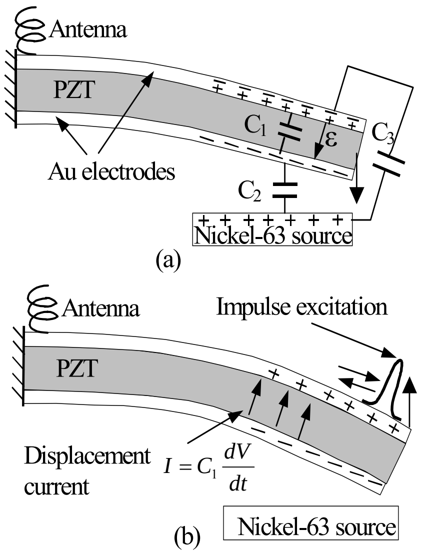

Figure 5. (a) The capacitance of the piezoelectric cantilever builds up an electric field as the charges are built on the two electrodes. (b) The sudden shorting of the charge on one side results in a sudden release of the electric field and hence the voltage across the cantilever. This results in a current $I = C_1\, dV/dt$ that excites the dielectric RF mode of the PZT.

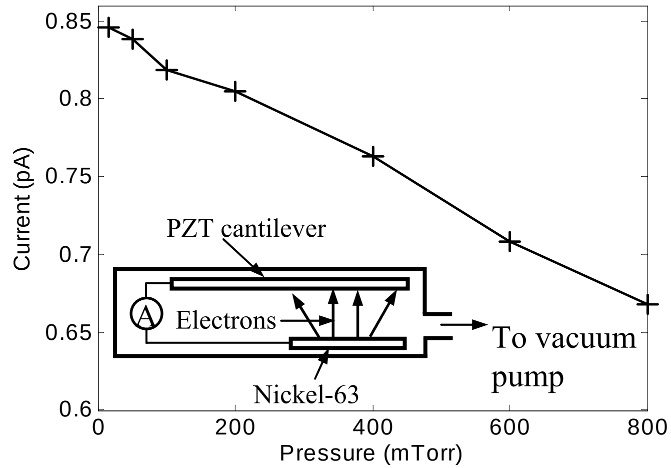

Figure 2. The current provided by the ^{63}Ni source varies with the pressure.

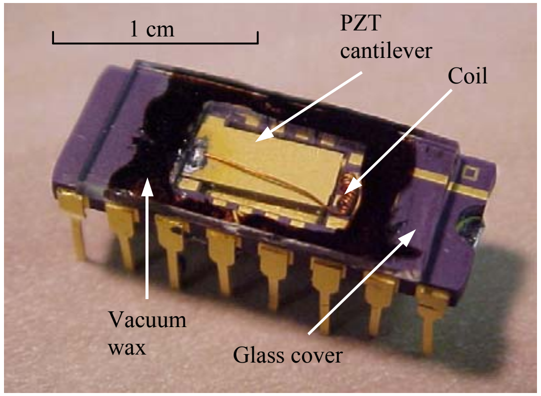

Figure 8. A PZT cantilever is mounted inside a chip carrier. A self made coil is soldered to it. The glass cover is glued to the package with a high molecular weight vacuum wax that can provide good sealing for the vacuum needed. An inlet on the backside provides connection to a vacuum system.

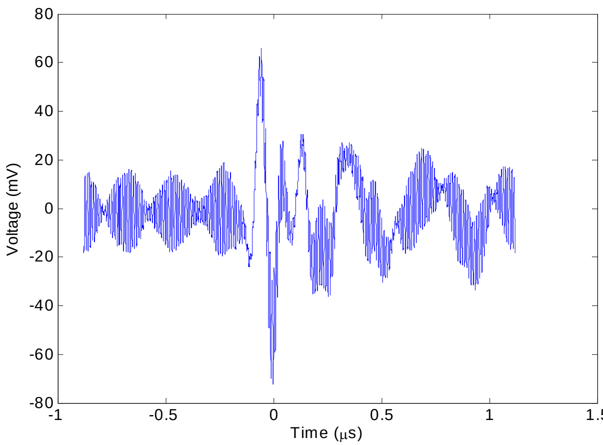

Figure 9. A typical pulse detected by the coil placed 0.1 m away from the DIP package. The frequency is 100 MHz. The peak-to-peak voltage is 138 mV.

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Summary

- Radioisotopes provide a high energy density power source suitable for many applications
- They are outstanding for small scale power