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Betavoltaics: An Innovative Power Source Enabling Next Generation Low-Power Sensor and Communication Devices

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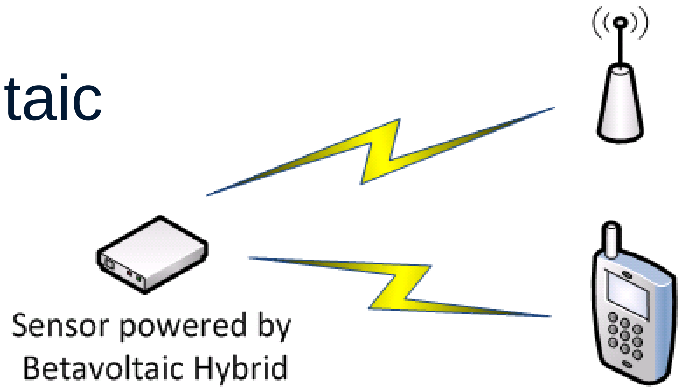
Current Situation

- Longevity of sensors & battery powered devices are severely limited by temperature, chemical instability and integrity issues associated with batteries.
- High risks & cost in replacing device or battery.
- Interfacing betavoltaics with electronics not well understood.
- Betavoltaic powered devices have not been demonstrated.
- Defense Science Board recommended vigorous investment of $25M / year over 5 years. ARPA-e solicitating betavoltaic development.

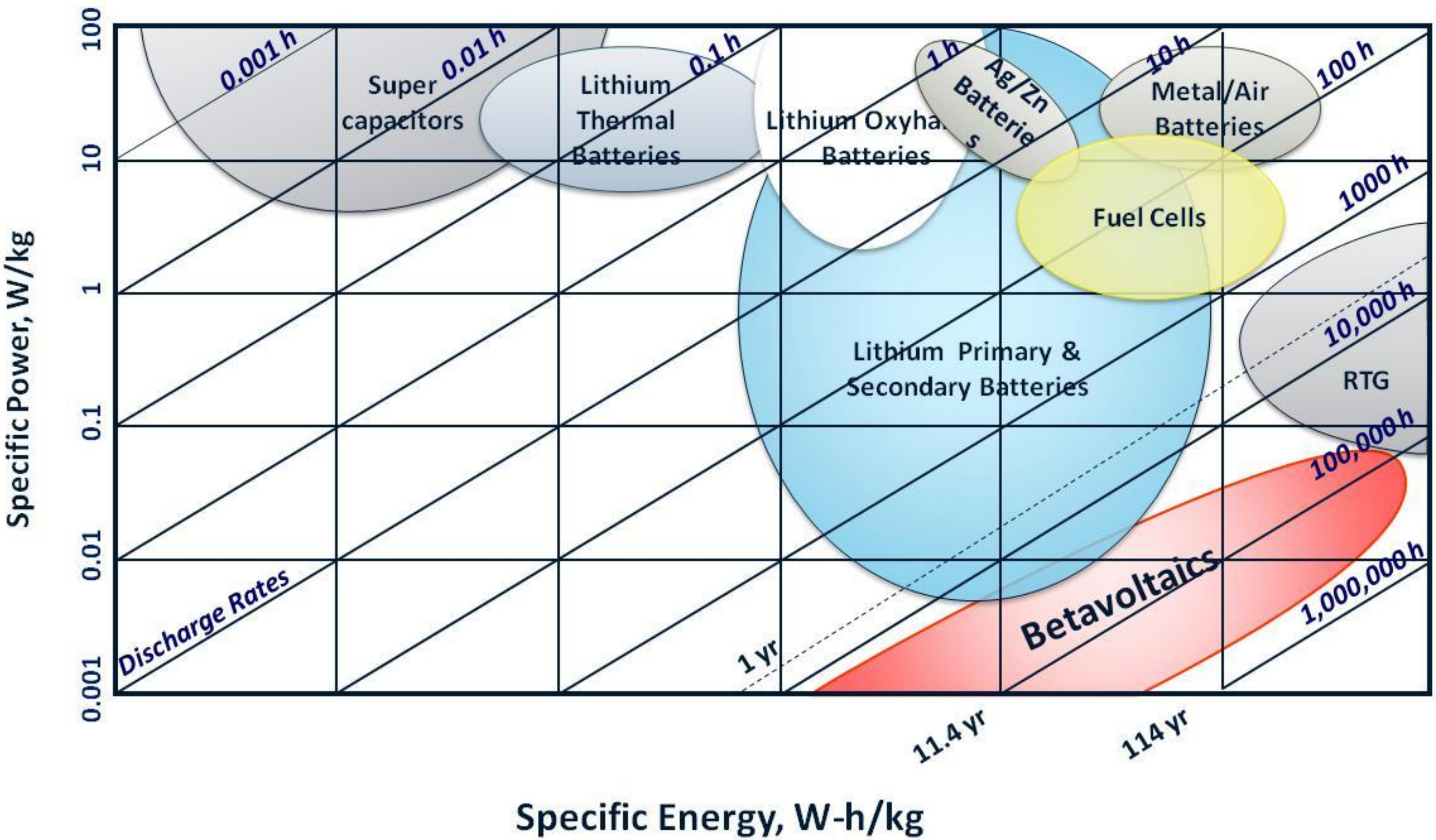
Solution

- Power sensors & devices with betavoltaic battery hybrid source
  - Ultra low power electronics
  - Long-operating lifetimes (>20 years)
  - Wide temperature range (-60°C to 150°C)
- Many uses of radioisotopes
  - Smoke detectors, exit signs, watches, gun sights, space exploration, paint, . . .
- Benefits
  - New capabilities & applications never imagined
  - Mitigate risks to Warfighter
  - Increased situational awareness
  - Significant cost savings



(Fiesta ware,1930-1985)

Ragone Plot



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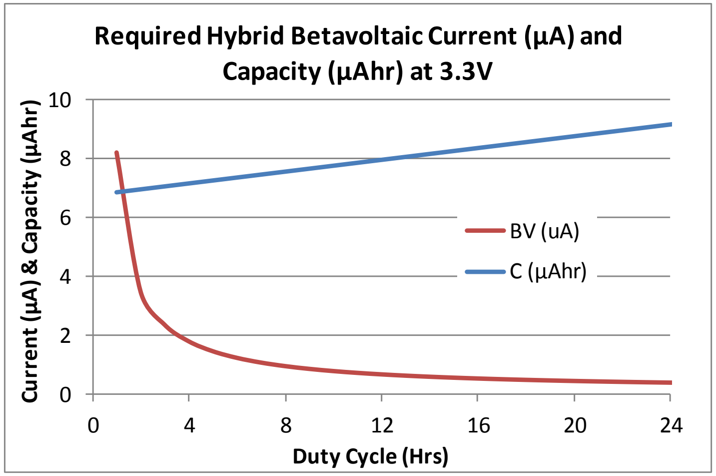
Risks/Challenges

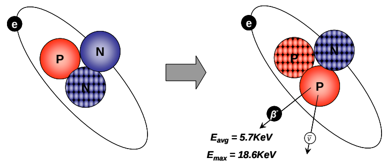
- Meeting power budget
- Betavoltaic manufacturers
- Regulatory handling and licensing
  - Obtaining NRMP and approved facility
  - Defer risk to off-site NRC facility at Purdue University
- Domestic radioisotope inventory
- Power requirements specific to batteries
- Perception of radioisotopes



Theory of Operation

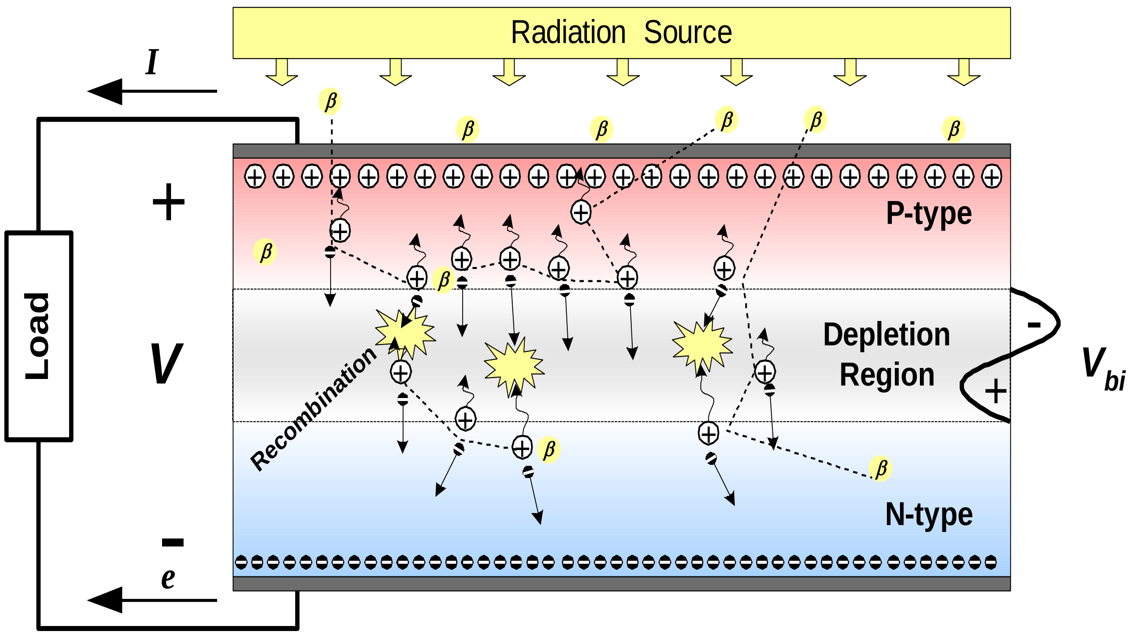
Similar to a solar cell

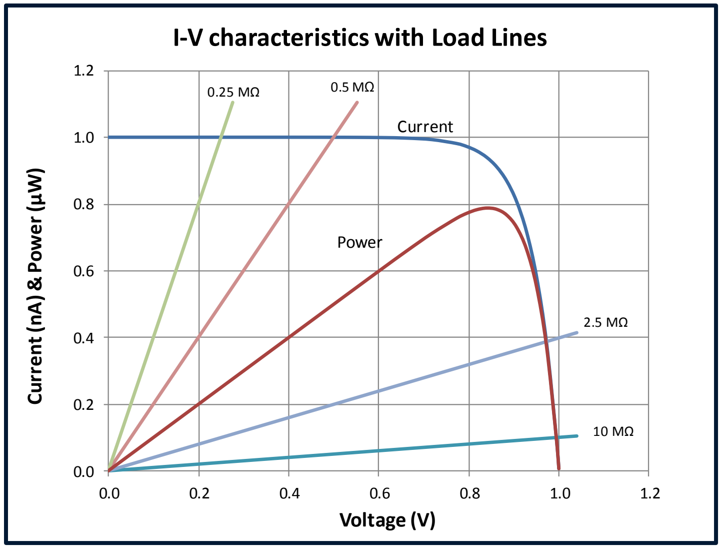
- Radiation source
- P-N junction
- Charge collectors



$$^{3}H \rightarrow {}^{3}He^{+} + \beta^{-} + \overline{\nu}$$

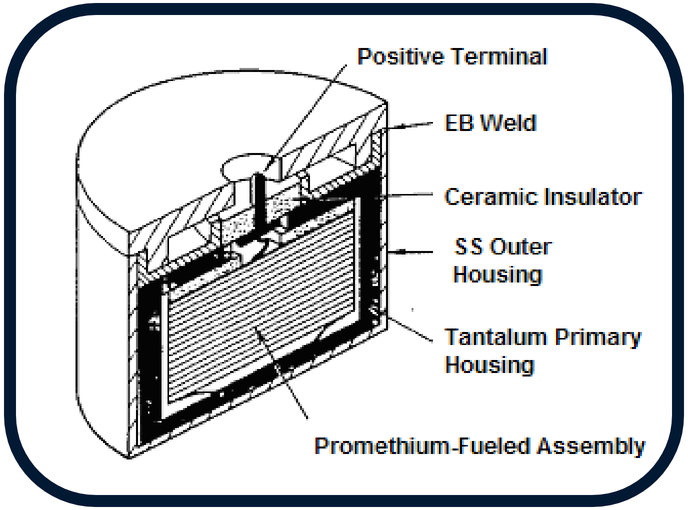
- Two modes of operation: constant current or constant voltage
- Maximum Power, Vm & Im, is the optimal point of operation
- As temperature increases, voltage and power decreases

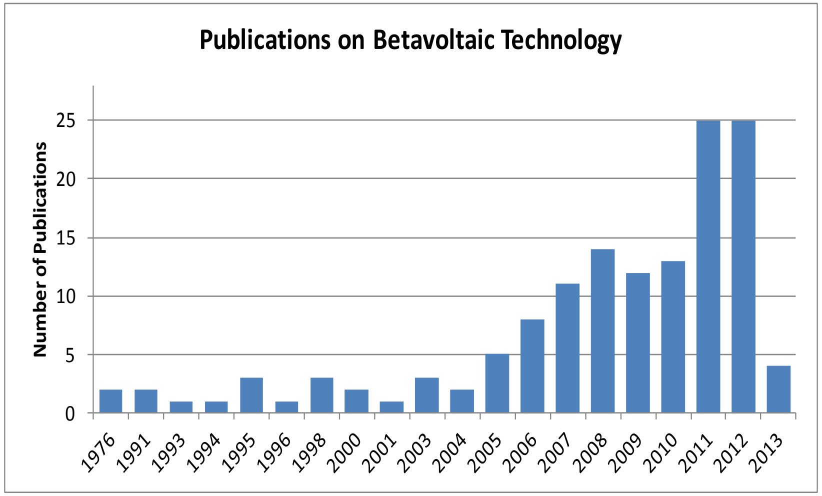




Betavoltaic History

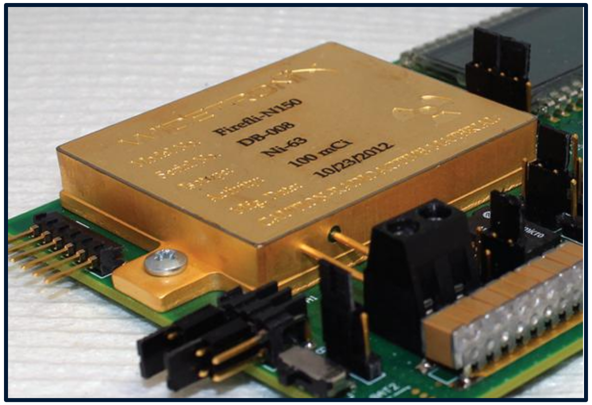
- 1953: Dr. Paul Rappaport
  - First to develop betavoltaics
  - Sr90-Y90 radioactive beta sources
- 1968-1974: Dr. Larry Olsen
  - Betacel Model 400
  - 400 µW, 4% efficient, 0.025 mW/cm^3
  - Pm-147 source, 2.6 year half-life
  - No degradation
  - Successfully implanted pacemakers in over 285 patients, 60 in US
  - Lithium batteries eventually cornered the pacemaker market
- Present: Two manufacturers
  - Dr. Peter Cabauy, City Labs
  - Dr. Chris Thomas, Widetronix





Status of Betavoltaic Technology

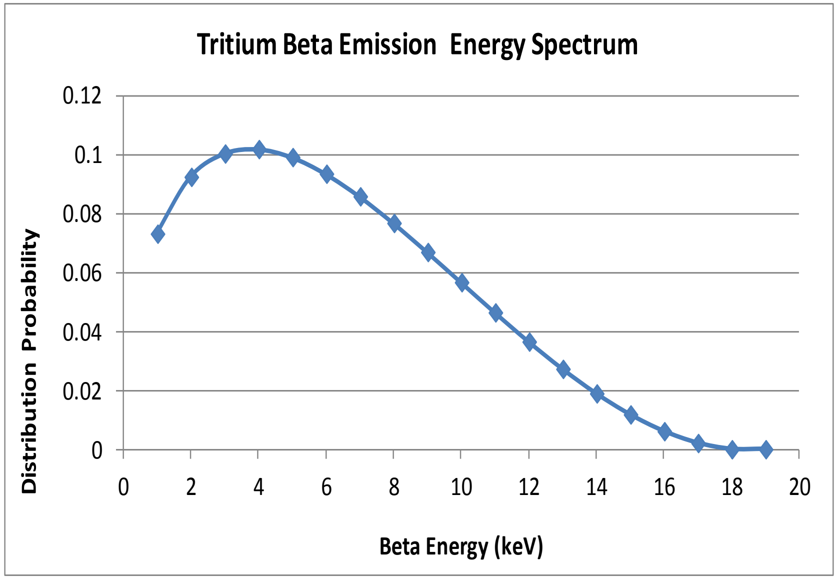
- Widetronix (www.widetronix.com)
  - Firefli, Tritium and Nickel-63 versions
  - SiC semiconductor
  - V_{oc} =2.0V
  - NRC specific license
  - No performance data available

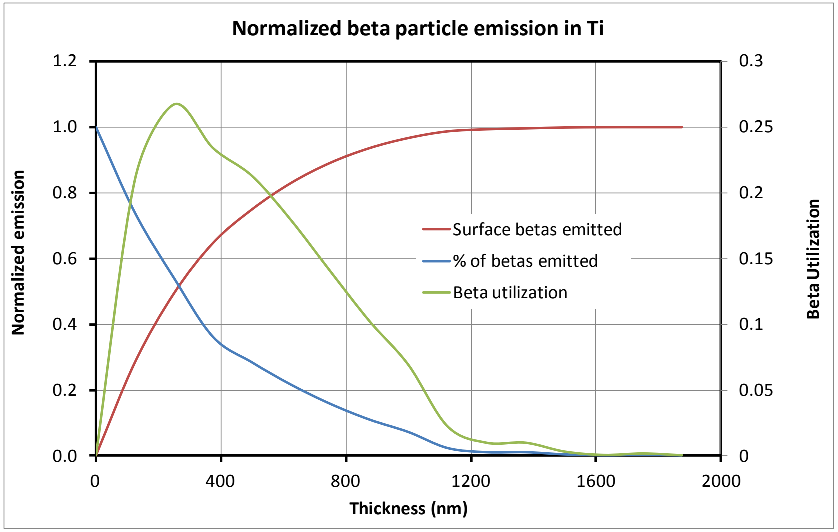


- City Labs (www.citylabs.net)
  - NanoTritiumTM
  - III-V semiconductor
  - V_{oc} = 0.8V
  - NRC general license
  - Some performance data available

Beta Source Considerations

- Betas are emitted isotropically in a spectrum
  - Average is 30% of maximum
  - Peak shifted to lower energy due to drag from attraction between positively charged nucleus and negatively charged beta particle
  - Bremsstrahlung radiation
- Beta energy greater than 300 keV can damage p-n junction
- Tritium, 300 nm optimal in titanium
  - MC-SET (Monte Carlo Simulation of Electron Trajectories)





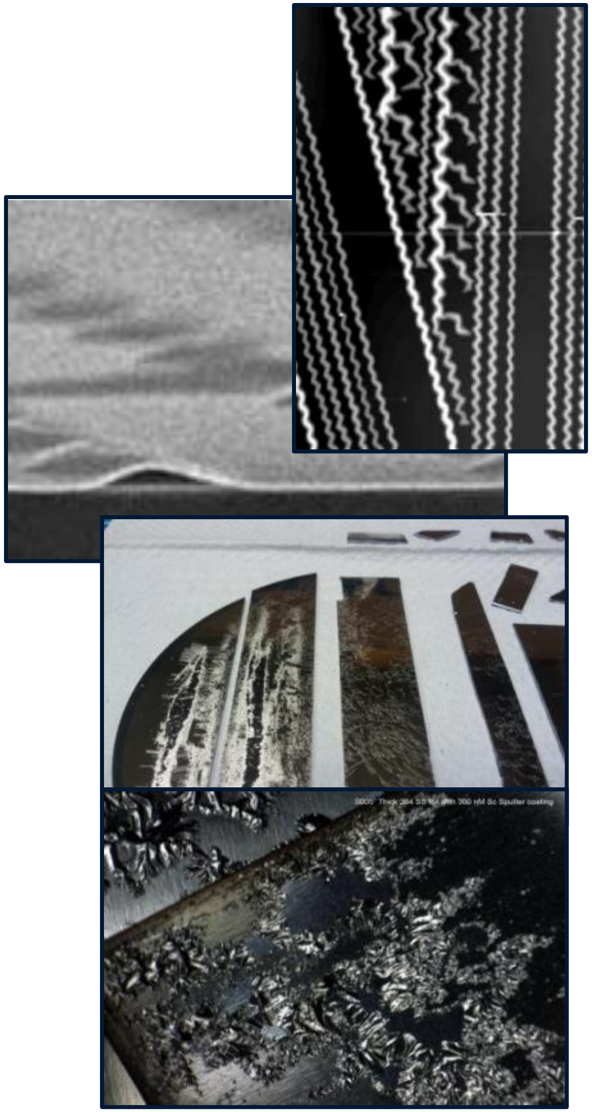
Radioisotope Availability and Selection

Isotope	E_{avg} (keV)	Specific Density Ci/g	$T_{1/2}$ (yrs)	Power in 1 Ci	Power, 10% efficiency	$/Ci	Ci/W	$/W
Tritium	5.7 keV/β	9,664	12.3	0.0338 mW	0.0034 mW	$ 4	295,942	$1,183,768
Ni-63	17.1 keV/β	59.2	100.1	0.1014 mW	0.0101 mW	$ 4,000	98,647	$394,589,414
Pm-147	65.0 keV/β	600	2.6	0.3853 mW	0.0385 mW	$ 1,000	25,952	$25,951,842

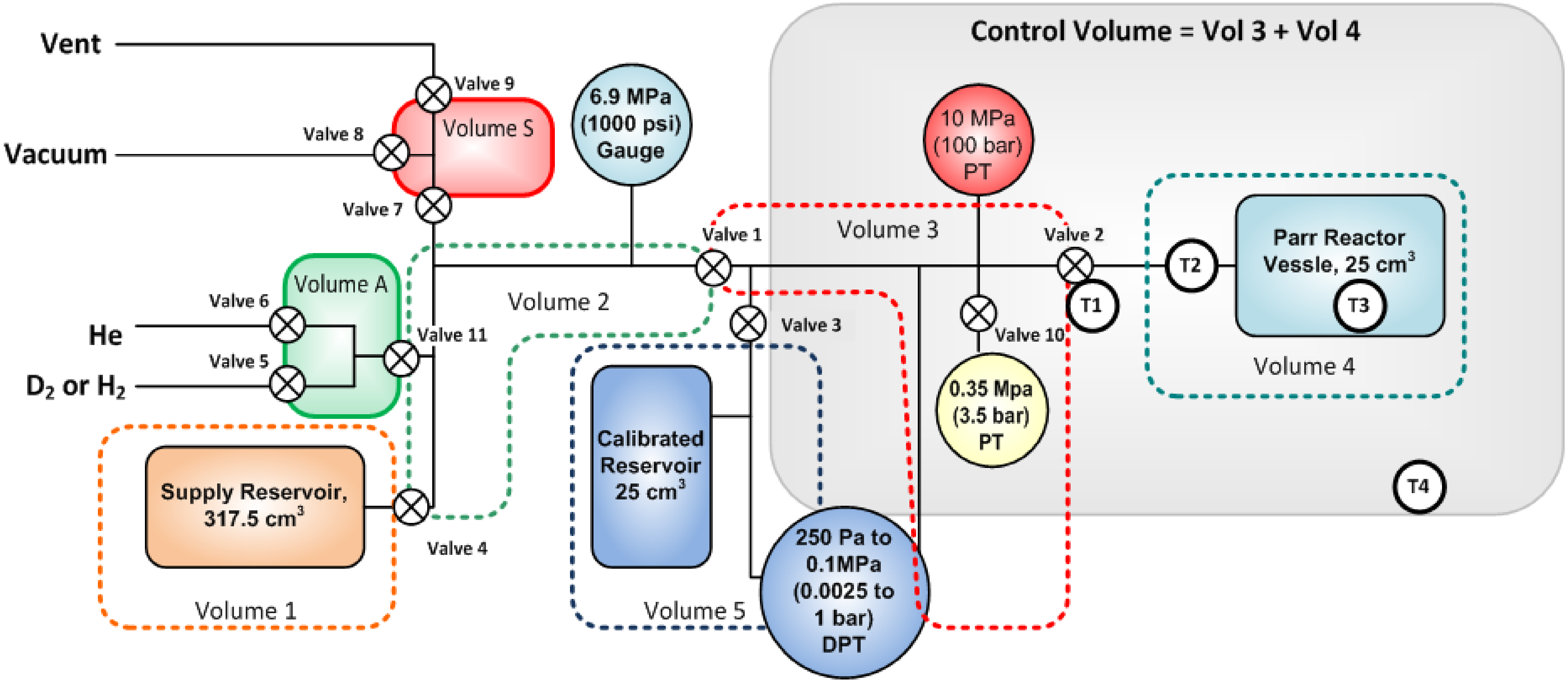
- Beta energy <300 keV to prevent semiconductor lattice damage
- Tritium (H-3), Available from Canada and Potential US supply from SRNL
  - No gammas, low shielding requirements
  - Stored as a solid in metallic film (TiT_2 and ScT_2) on foil substrate
- Nickel-63, Only available from Russia, but can be produced in HFIR at ORNL
  - Low flux and high gammas due to impurities and other nickel radioisotopes
  - NiCl or NiNO deposited on foil
- Promethium-147, Only available from Russia
  - Byproduct of spent of nuclear fuel, does not occur naturally
  - Some high energy gammas from other Pm radioisotopes
  - Pm_2O_3 deposited on a titanium foil

Tritium Beta Emitting Source

- Tritium is the only pure beta emitting isotope
- Solid form as tritide is over 1000 times more concentrated than as a gas
- Current loading process is limited and lacks control
  - Films tend to buckle and delaminate
  - Tritium pressure limited to 2 bar on actual system
  - Tritium concentrations vary film to film
- Experiment using hydrogen and new loading system



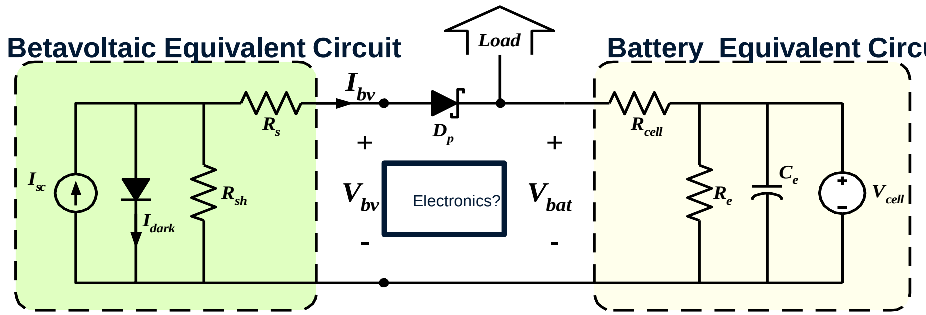
Hydrogen Loading System (HLS)



- Load materials with hydrogen with accurate control and high resolution measurements
- Resistivity measurements during loading

Hybrid Betavoltaic Design

- Betavoltaic in parallel with Li-SS rechargeable battery or capacitor; i.e. betavoltaic trickle charges a battery
- Battery
  - Li-SS for low self discharge
- Capacitor
  - Teflon, Tantalum polymer or aluminum polymer
- Electrical coupling
  - Impedance on betavoltaics much higher
  - Betavoltaic voltage follows a diode I-V curve
  - Diode protection needed?



I_{sc} – short-circuit current

I_{dark} – dark (reverse saturation) current

R_s – series resistance (Ω)

R_{sh} – bulk shunt resistance (MΩ)

V_{cell} – theoretical potential of electrochemical couple

R_{cell} – resistance from interconnections and electrodes (mΩ)

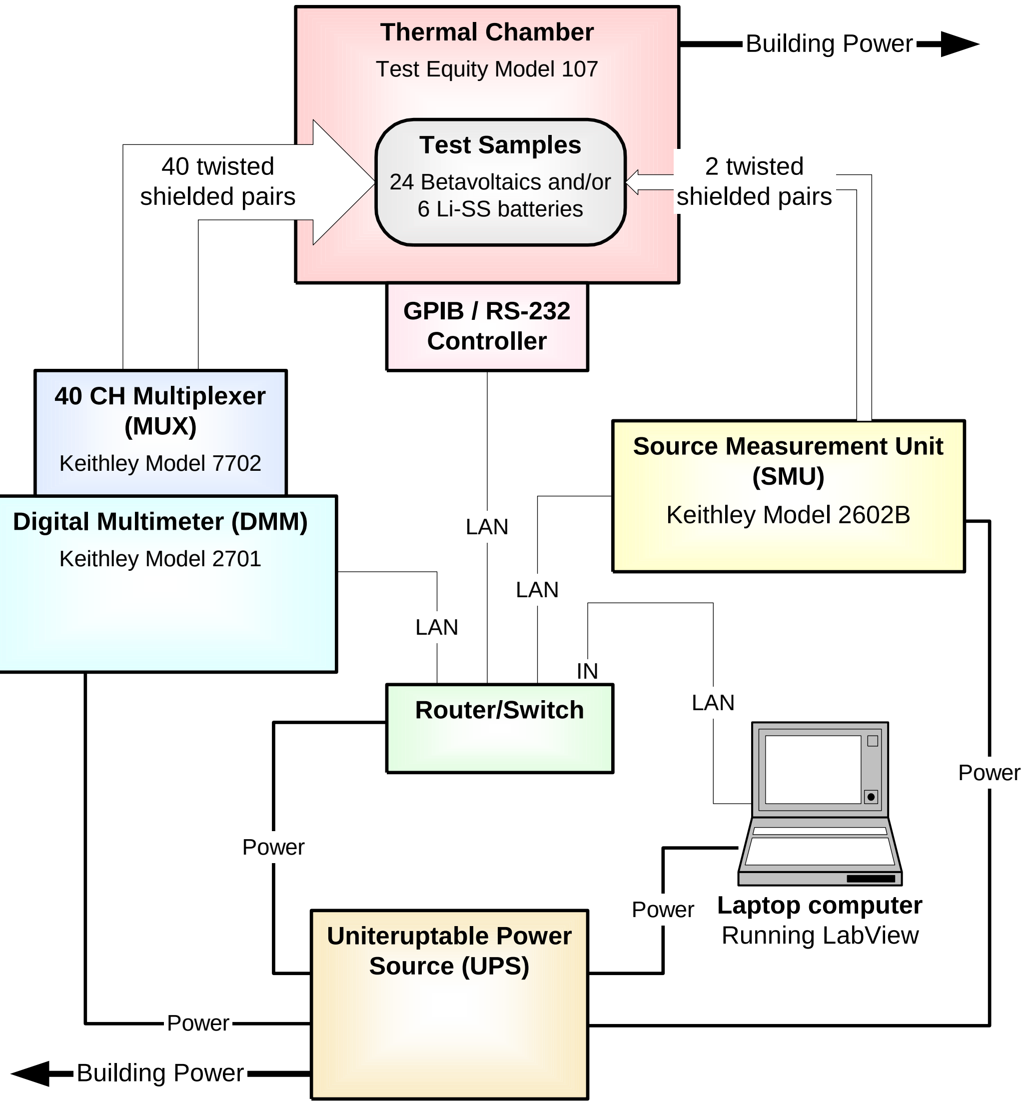
R_e – electrolyte resistance (mΩ)

C_e – electrode and electrolyte capacitance

D_p – diode protection (Schottky)

Low-Power Evaluation System

- System designed for betavoltaic, Li-SS battery, and hybrid battery evaluations
- Thermal Chamber
- Digital Multimeter with Multiplexer 40-Ch, Differential
- Source Measurement Unit (SMU)
- LabView test control console
- Uninterruptable Power Source (UPS)



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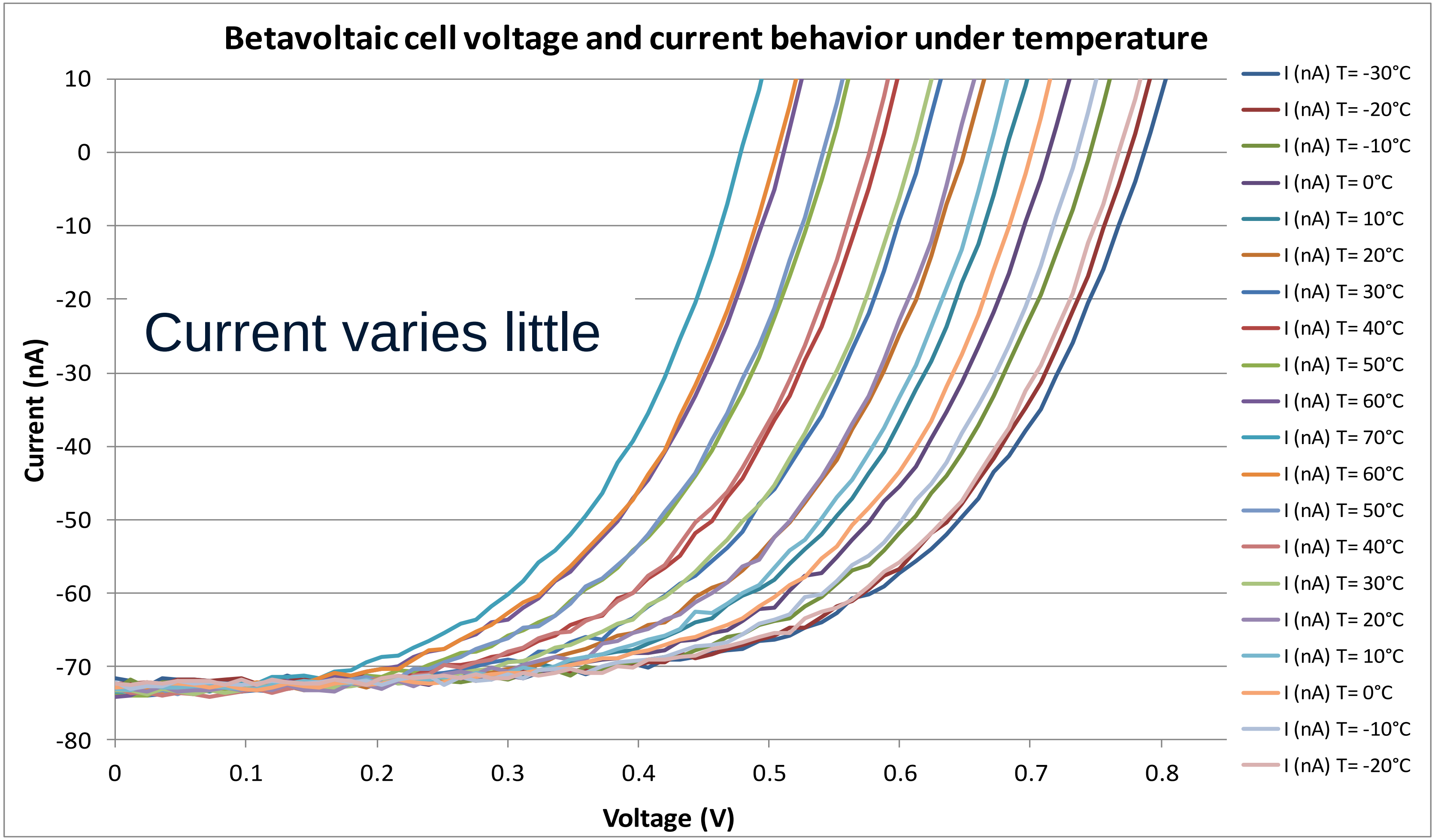
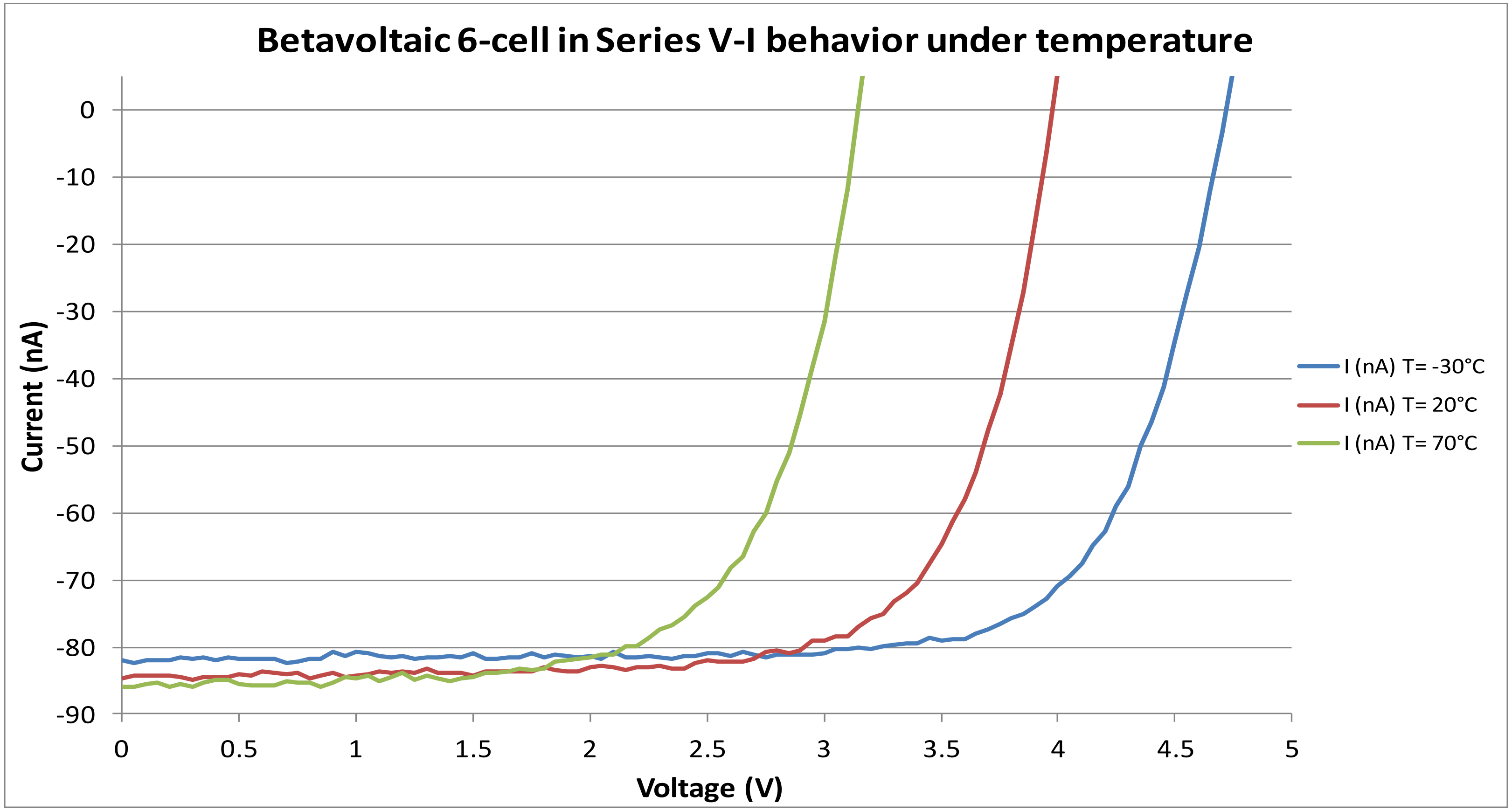
Temperature Effects

Individual performance versus temperature



Temperature Effects

Connected 6 betavoltaics in series



Opportunities

- Recently, US Government agencies have identified betavoltaics as a disruptive technology that is needed and should be pursued.
  - Defense Science Board (DSB) issued its report on Technology and Innovation Enablers in 2030. Project driven by DARPA
  - Advanced Research Projects Agency-Energy (ARPA-E) is wanting proposals for nuclear to electrical conversion in the form of betavoltaics
  - Defense Threat Reduction Agency (DTRA)and others want to investigate using betavoltaics to provide early warning of corona mass ejection events (CMEs) to protect satellites and space applications,
- Using direct program support provides best chance of success for the technology and for the student

Conclusions

- Successful operation of a betavoltaic / Li-SS hybrid battery will allow for significant extended operational mission life of existing platforms, as well as facilitate development of innovative applications not yet conceived.
- Data acquired from betavoltaic development and evaluation represents a first and will provide designers and program managers with needed information to insert into applications.
- Compliance with regulations is a requirement and issue that will be investigated.
- Public perception will change by technology demonstrations and education.
- Technology is advancing by both manufacturers. Application specific funding is needed to maintain this momentum.

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Questions?