High-Energy Dense Betavoltaics for Unattended Operation in Extreme Environments

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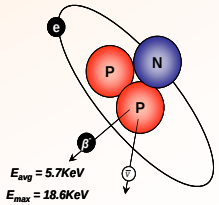

PURDUE UNIVERSITY | School of Nuclear Engineering

CITY LABS
Innovative Long-life Micro-power Solutions

NAVSEA
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NUCLEAR ENGINEERING

What is Tritium?

Lithium (Chemical) Batteries

- Permanent High Temperatures degradation outside of 0°C to 60°C range

- Lower power at Low Temperature
- Electrolyte leakage

- Safety hazard
- Power density: **25 mW/cm³**
- Energy density (15 years):
  - 1.3 Wh/cm³
  - 4.7 kJ/cm³

Size AA

Tritium (Nuclear) Batteries

- Operational at Extreme Temperatures: **-55°C to 150°C** range.

- Higher power at Low Temperature
- No electrolyte, solid-state

- Benign radiation
- Power density: 0.1 mW/cm³
- Energy density (15 years):
  - **10 Wh/cm³**
  - **36 kJ/cm³**

*Tritium battery is the **only** option for extreme temperatures and is equivalent to 8 AA batteries.

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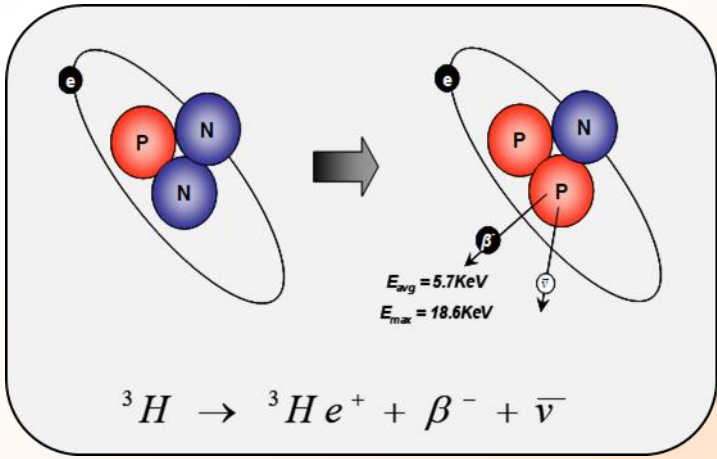
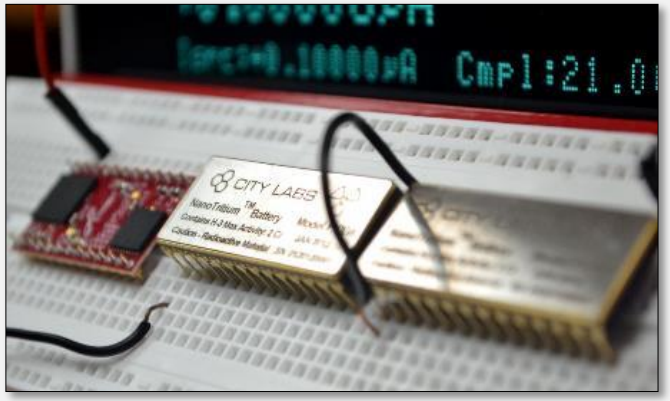
What is Tritium?

A Hydrogen Radioisotope (^3H) that decays into Stable Helium^3 via Emission of a Beta Particle and an Anti-neutrino

- Beta particles are high energy electrons that City Labs' technology uses to generate electric power.
- Tritium beta decay half-life is 12.3 years → 20+ years of power generation.
- Tritium is a relatively **safe** radioisotope found in exits signs, watch dials, and gun sights.
- Tritium Beta radiation can be stopped with a sheet of paper.





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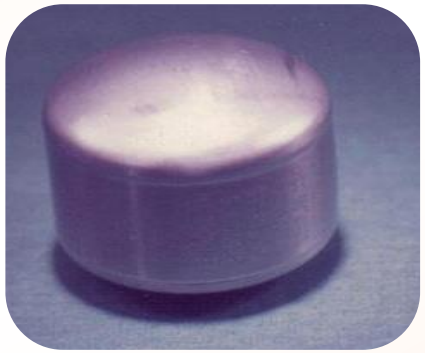
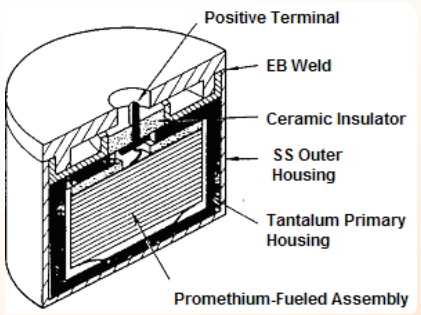
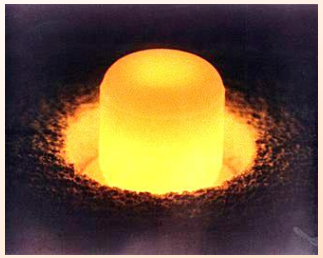
Proven Concept

- Betacel (1968-1974)
  - Promethium-147 Beta Source
  - 5.0 V; 50, 200 & 400 µW units
  - Power density: 0.025 mW/cm3
  - No radiation degradation
- Cardiac pacemaker
  - Over 285 patients, 60 in US
  - Lithium batteries emerged





- Radioisotope Thermoelectric Generator (RTG)
  - Space exploration and terrestrial
  - 100's of Watts
  - Pu-238 alpha source
  - Voyager 1 (Sep 5, 1977)
- Similar technology withstands radiation



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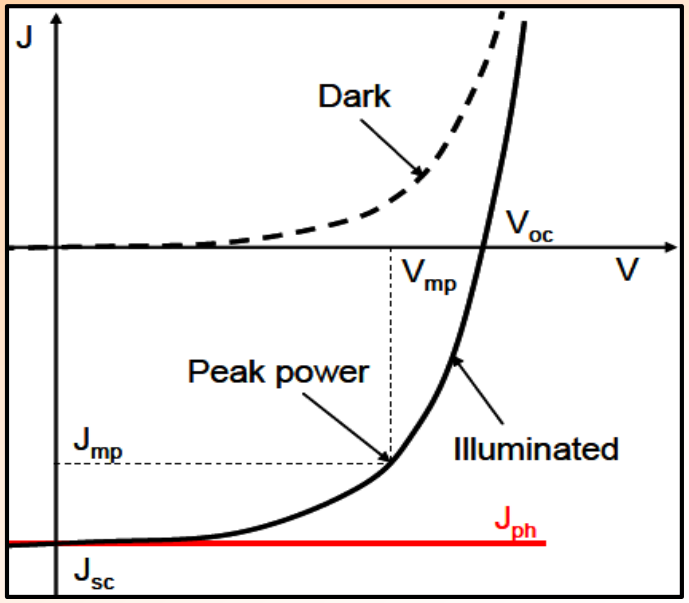
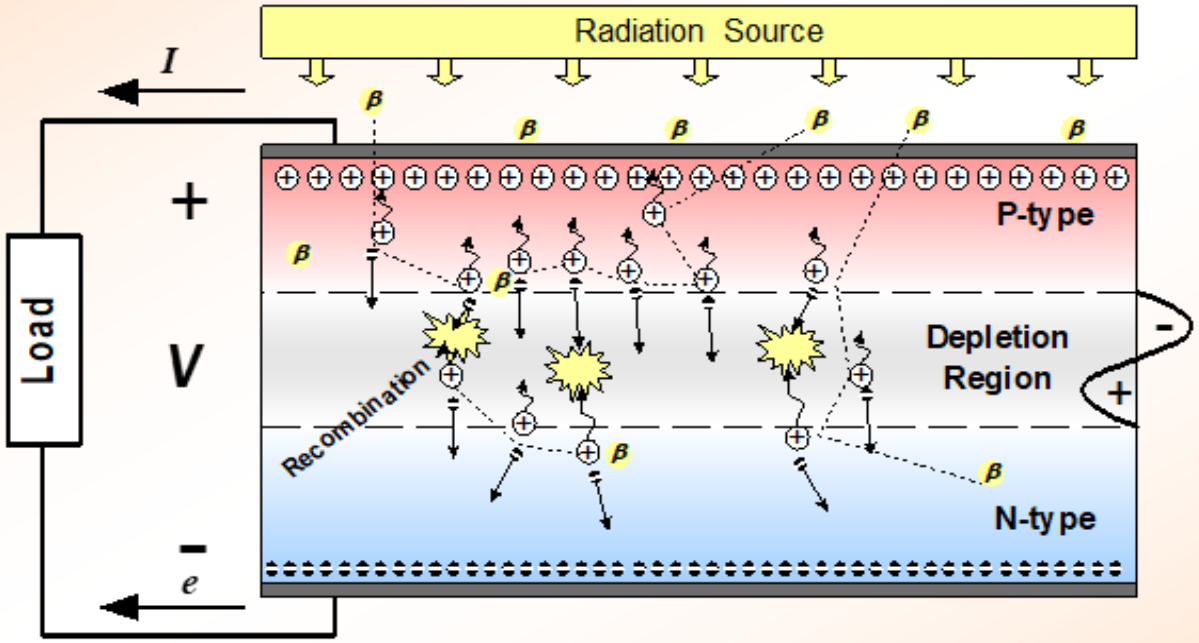
Nuclear Battery (Betavoltaic)





Firefli™ - Widetronix
Specific License

- Long-operating life (>20 years)
- Wide temperature range (-50°C to 150°C)
- High energy density
- Micro sizes possible < 10 um
- Ultra low power electronics
- No chemical reactions

NanoTritium™ - City Labs
USNRC Registered: General License for Model P100-P200 (up to 100 Curies)

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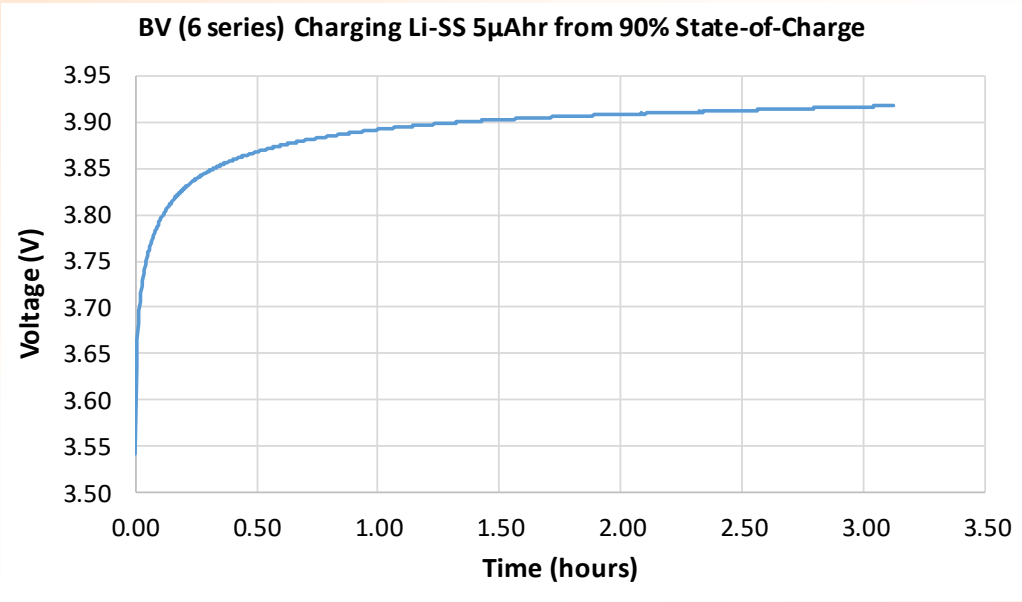
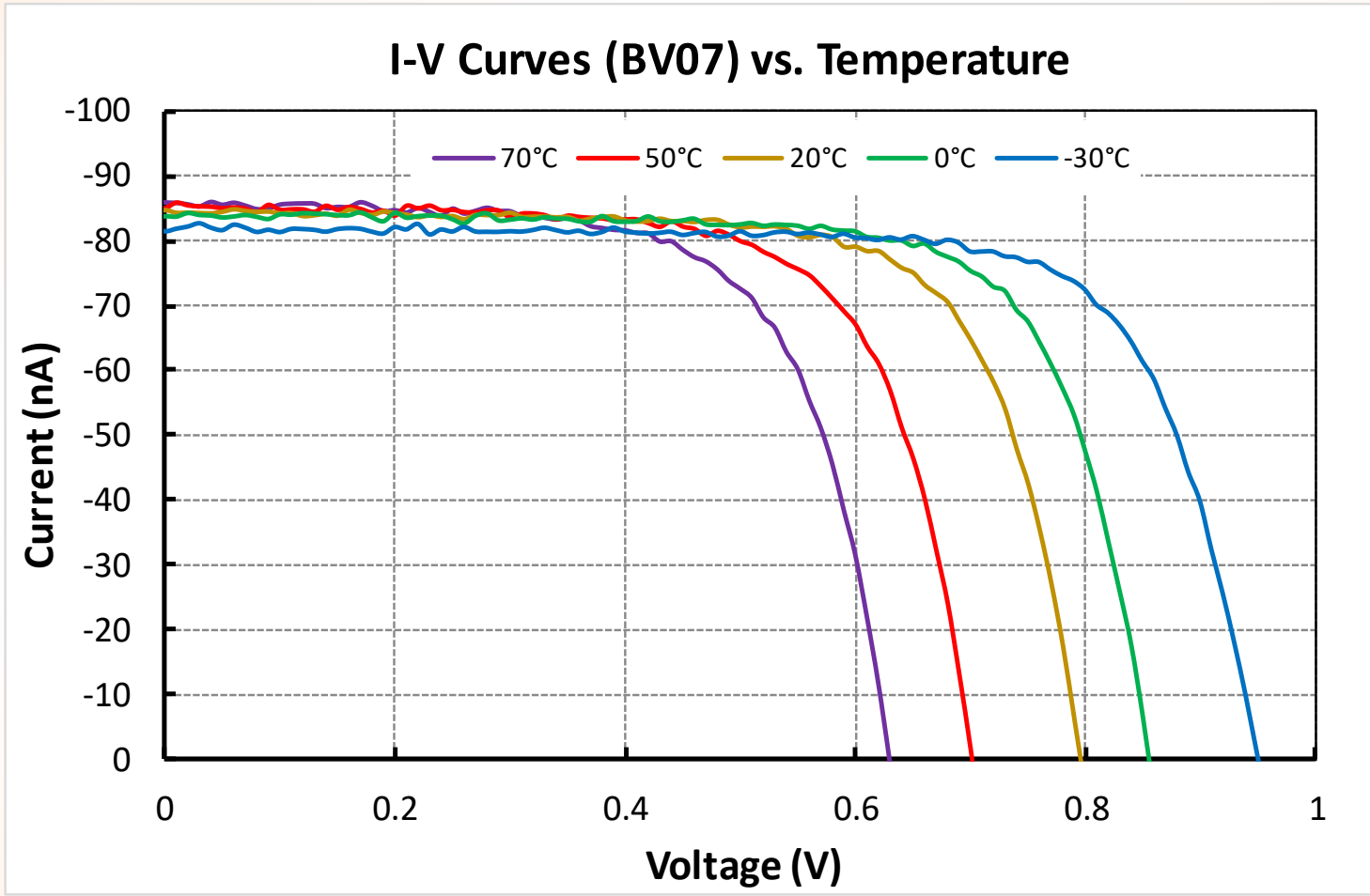
Betavoltaic Performance

- Energy increases at colder temperatures
- Two modes : constant I or V
- V_{oc} varies largely with Temperature
- Maximum power ~0.8Voc
- Parallel / Series verified





Six betavoltaics connected in series with 5µAhr Li-SS at 20°C

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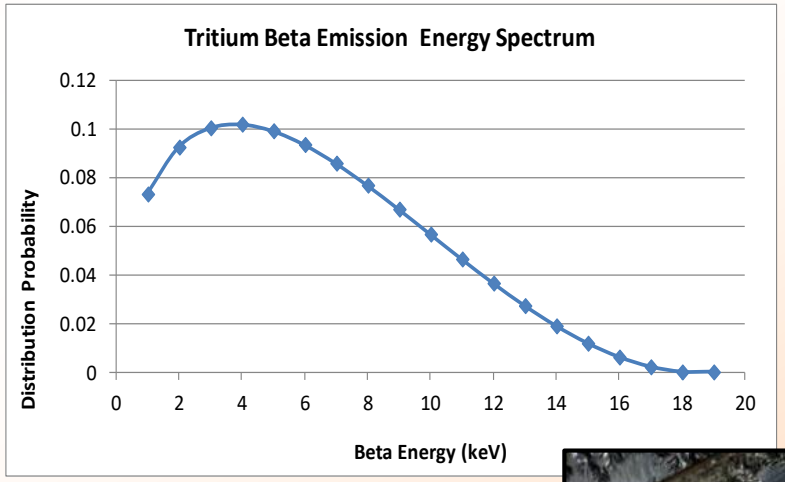
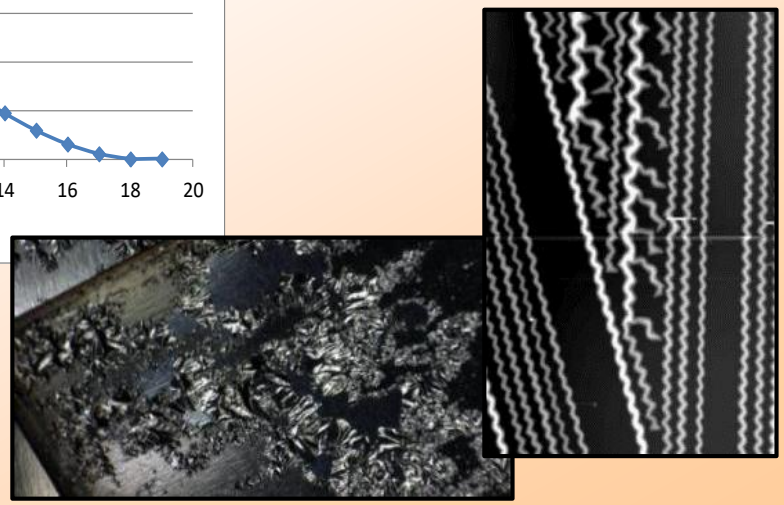
Tritium Source Challenges

- Tritium is the choice beta emitter
  - Only pure beta emitting isotope
  - Metal tritide is more concentrated than tritium gas (1000x) or liquid (2-5x)
- Films ~300 nm thick to avoid self-shielding losses
- Low beta efficiency
  - Isotropic, multi-energy emission
    - ~ 2% reaches surface
- Tritium loading process
  - Films tend to buckle and delaminate
  - Developed hydrogen loading system based on SRNL; control, accuracy and resistivity



(Zhao 2005)



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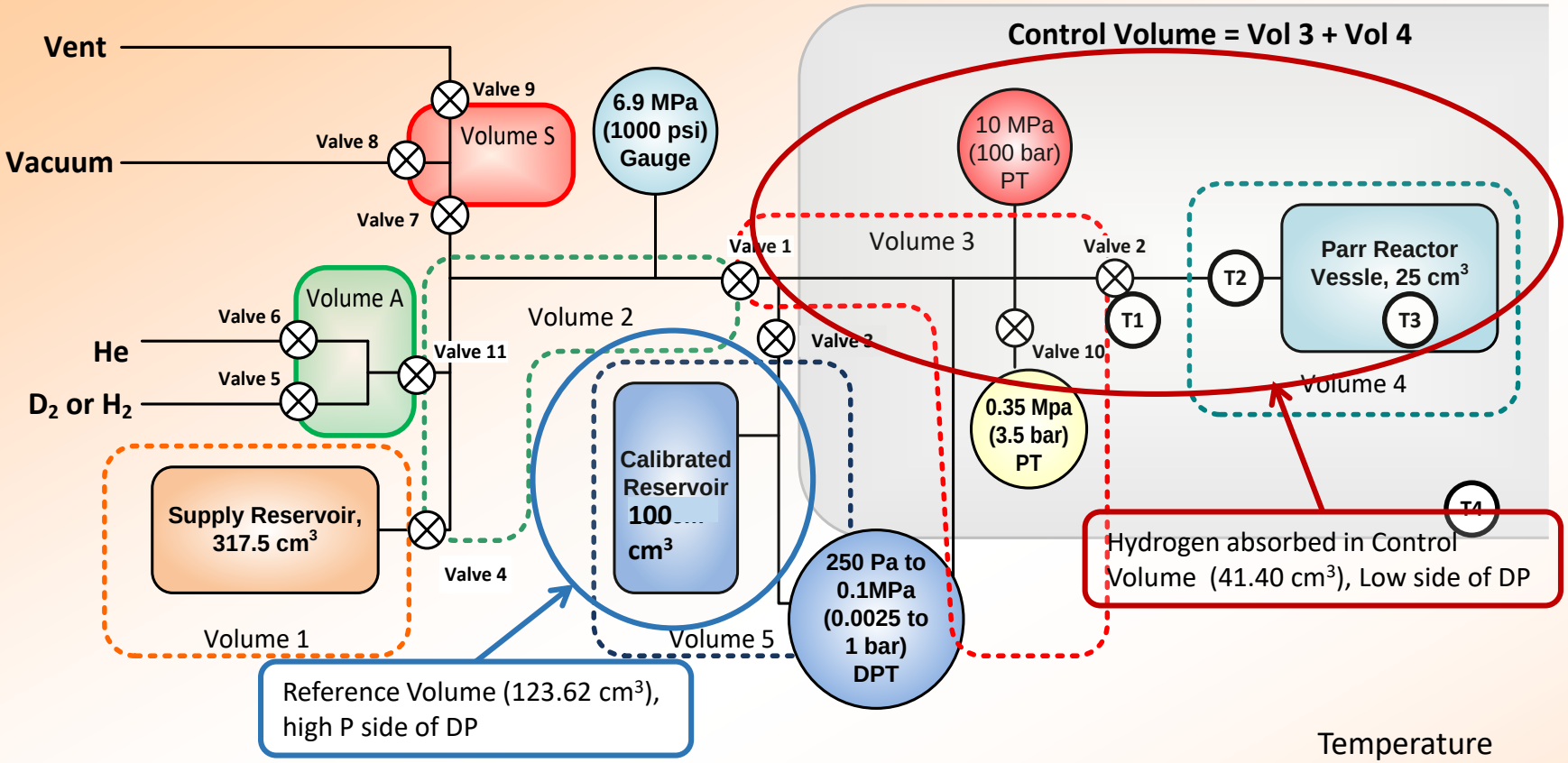
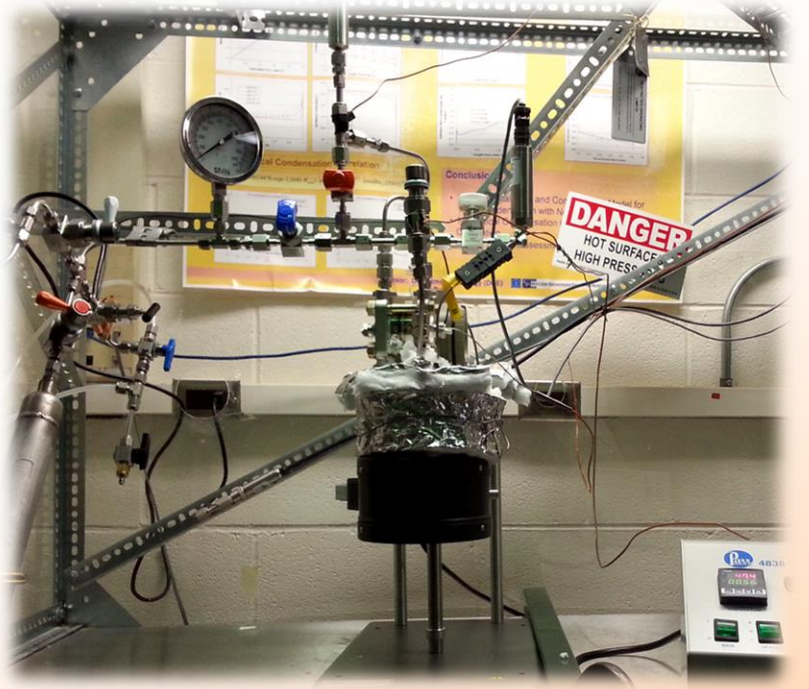
Hydrogen Loading System (HLS)





Key Attribute is the ability to measure small pressure changes with the Honeywell Smart Differential Pressure Transmitter

Specifications

Temperature	Controllable up to 500°C
Pressure	10^{-3} torr to 1000 psia (70 bar)
Min. pressure range	0 to 41 mbar
Max. pressure range	0 to > 1000 psi
Pressure sensitivity	< 0.41 mbar, < 0.10% accuracy
Test or control volume	< 10 cm³
He leak rate	< 10^{-9} cm³/s

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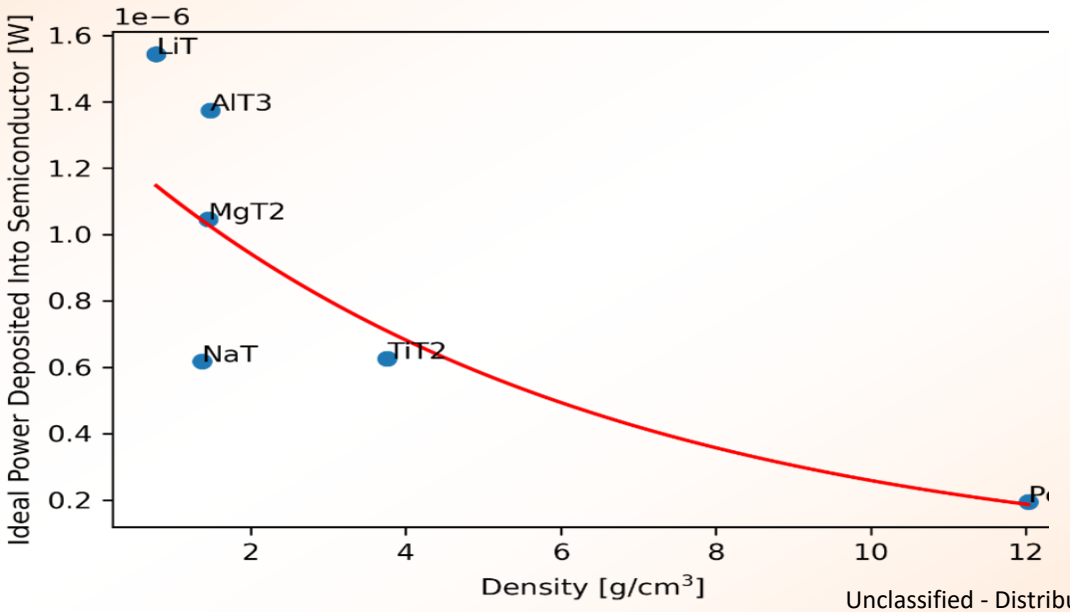
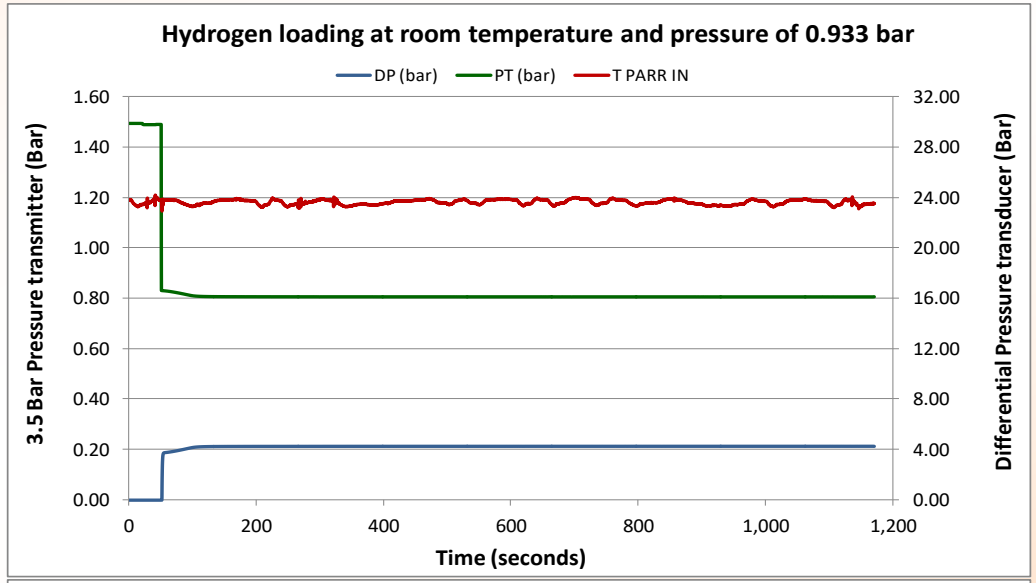
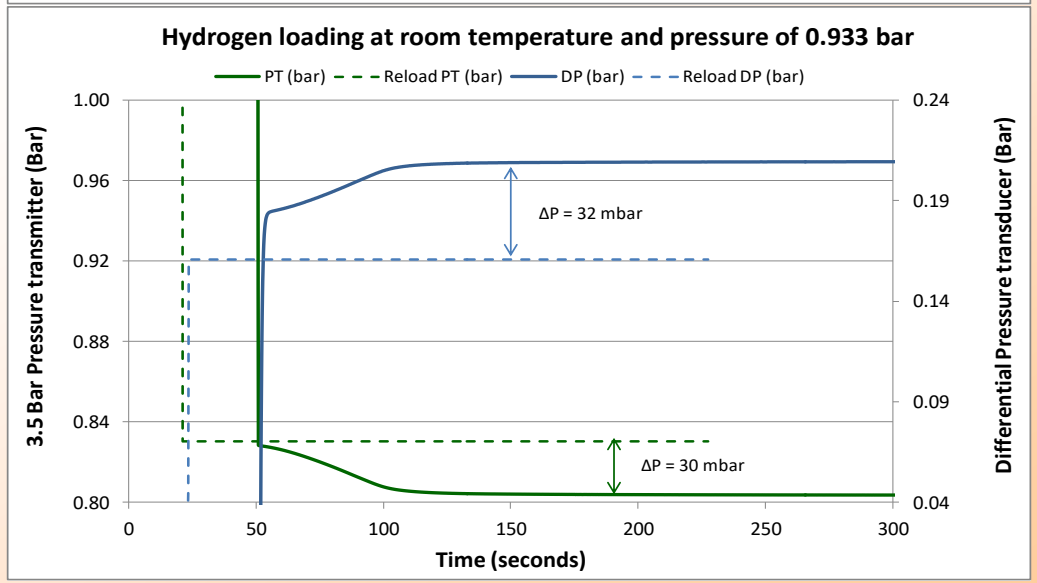
Ti w/Pd film Loading at Room Temperature

- Developed system to load hydrogen into nano-films for tritium storage
  - Accurate control and high resolution measurements
  - *In situ* resistivity measurements
- Loading at Room Temperature
  - 6 Ti 300 nm/Pd 82.5 nm films at 0.933 bar
  - Loading occurred within 200 s; Pd coating protected Ti surface







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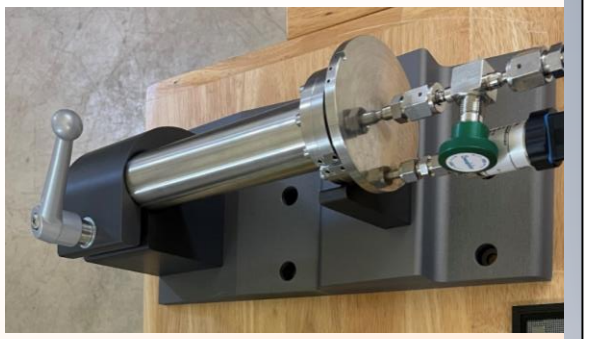
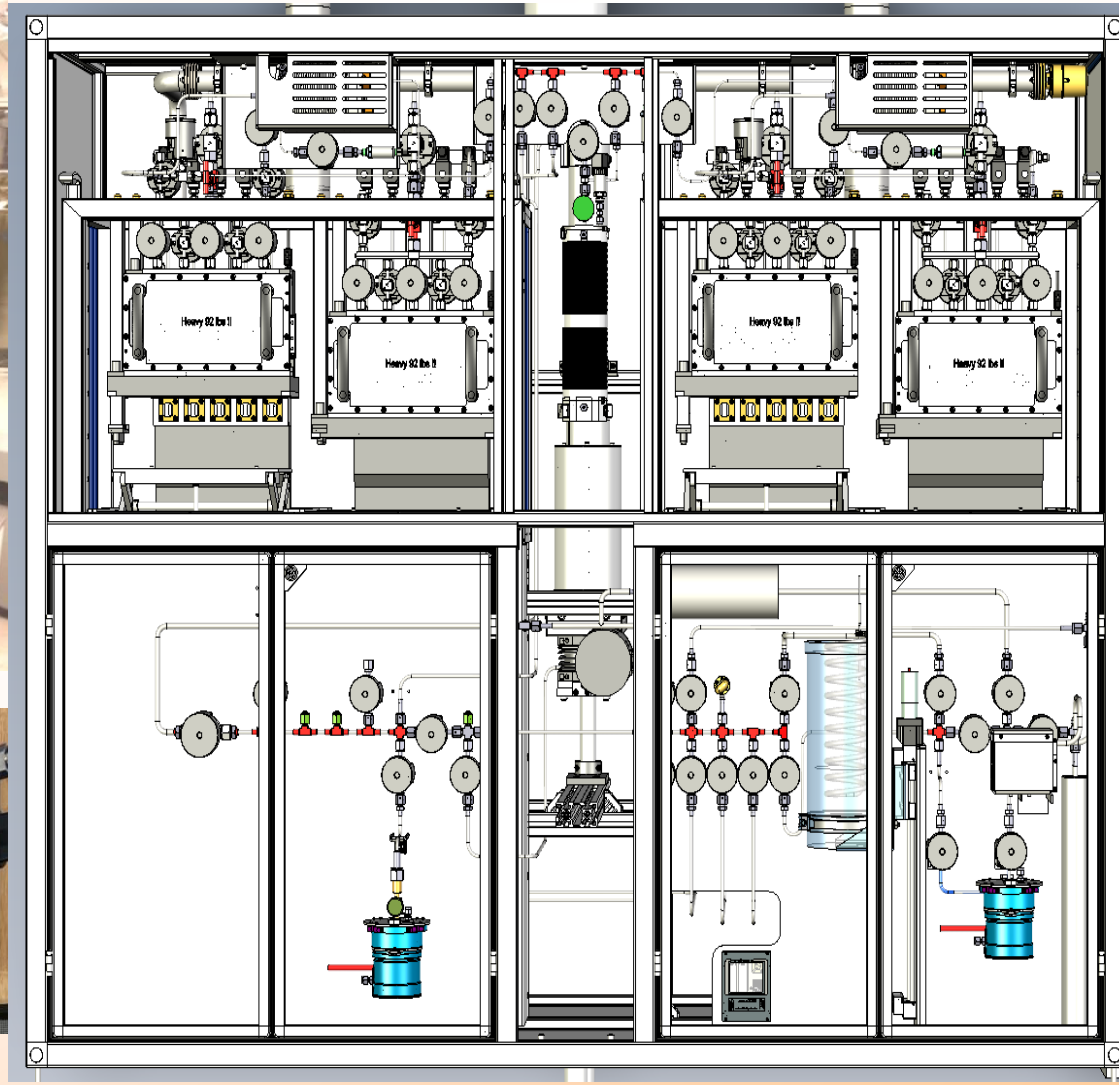
New Test & Production Hydride Loading

- Characterize tritium loading with deuterium (D) surrogate
  - Reduces cost
  - Confirm loading parameters
  - Characterize semiconductor performance after loading
- New tritium loading laboratory
  - State of the art system
    - 20 bar tritium pressure
    - 600°C in process chambers
    - 10-gram (60k Ci) tritium storage (expandable)
    - Completely automated loading process





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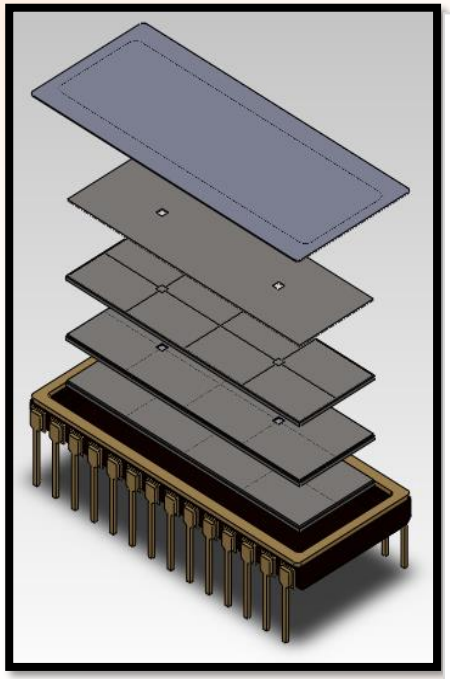
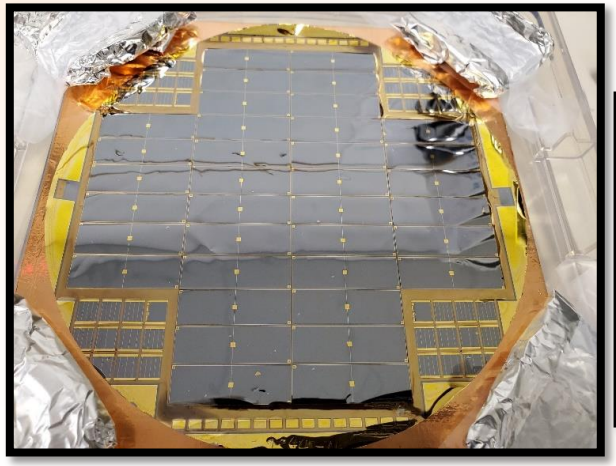
Progression of Thin Betavoltaics

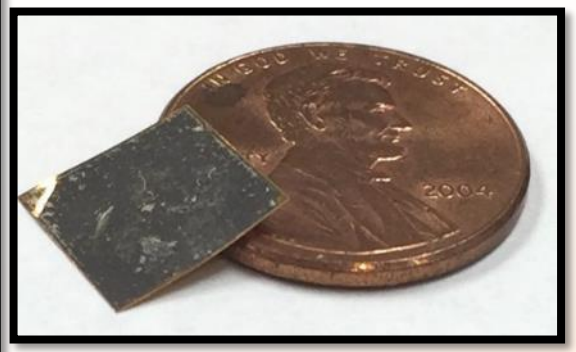
- Model P100 and P200
- Cell Development – thinner, larger, stacking, higher yield
- Hydride material advances
- NASA and DAF high power missions driving design



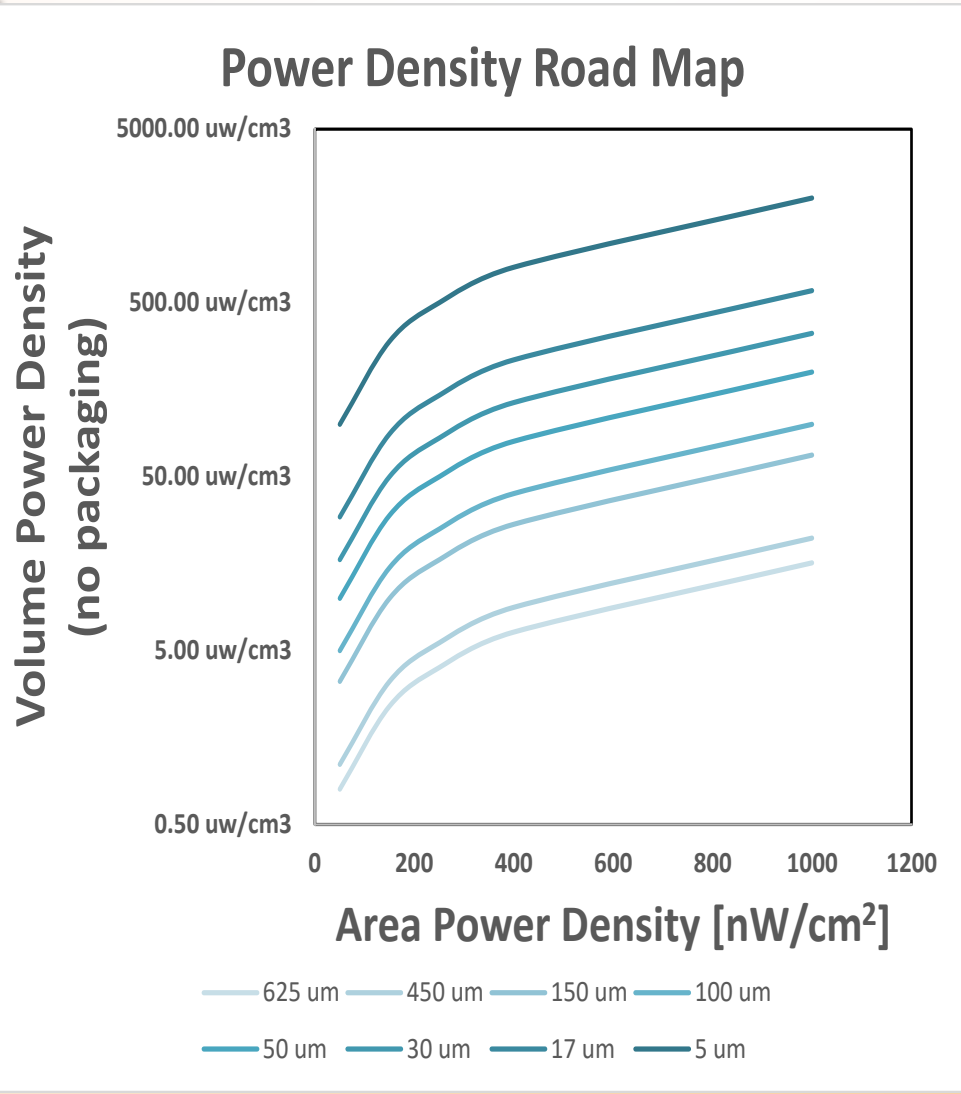
P100a betavoltaic
1x3cm^2 by 625 µm



6” Wafer with 5 µm



Single BV cell layer
1x1 cm^2 by 10 µm



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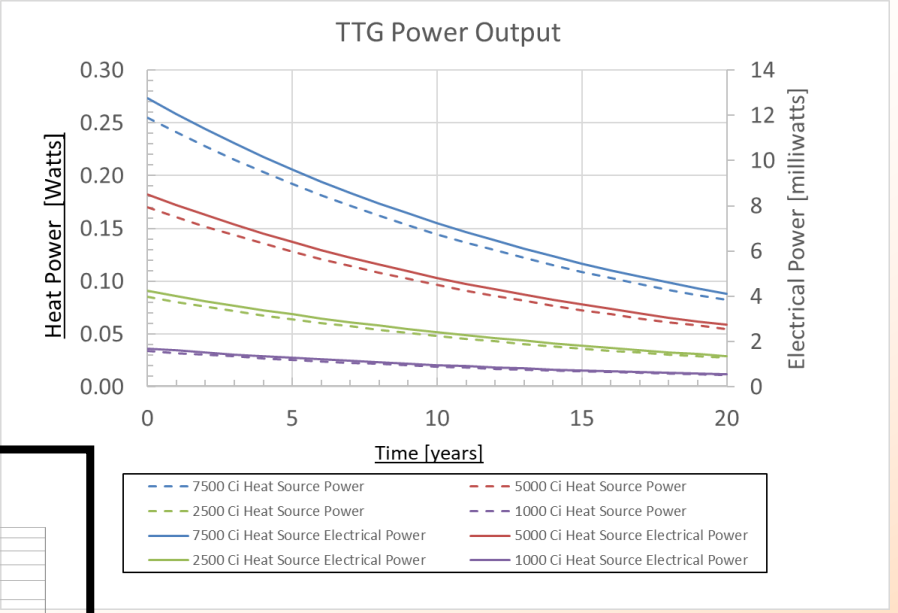
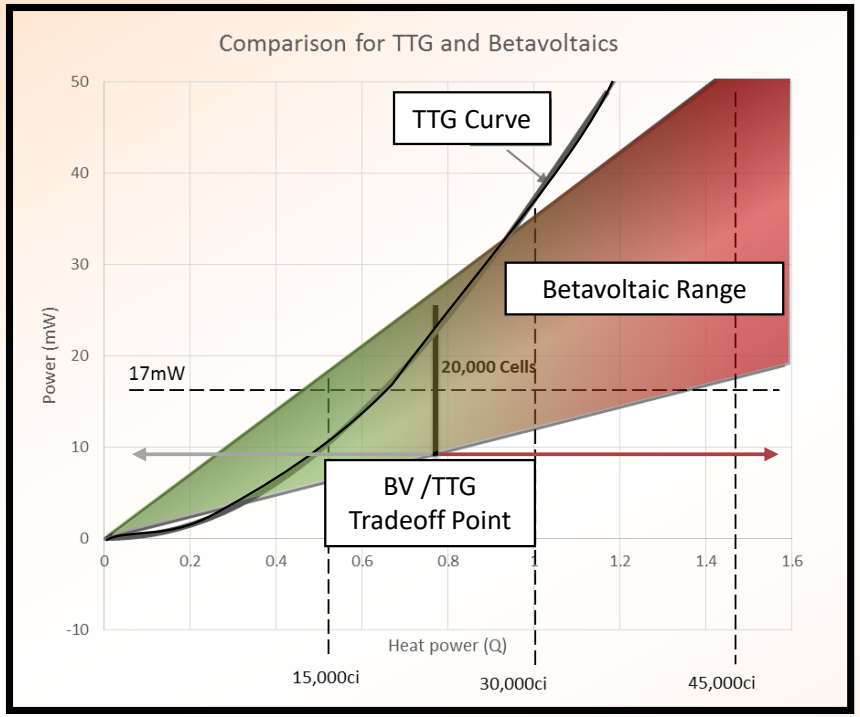
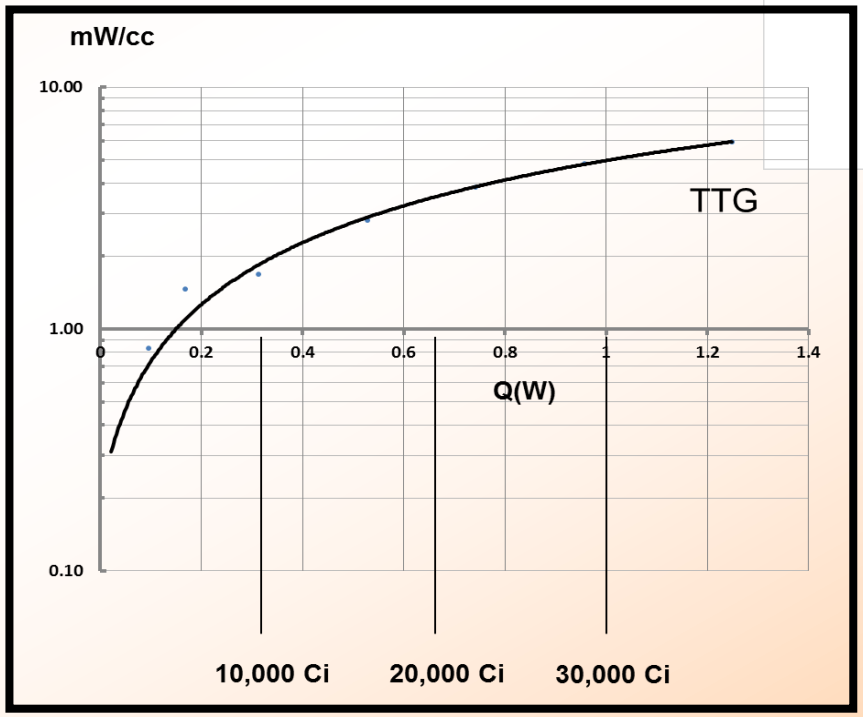
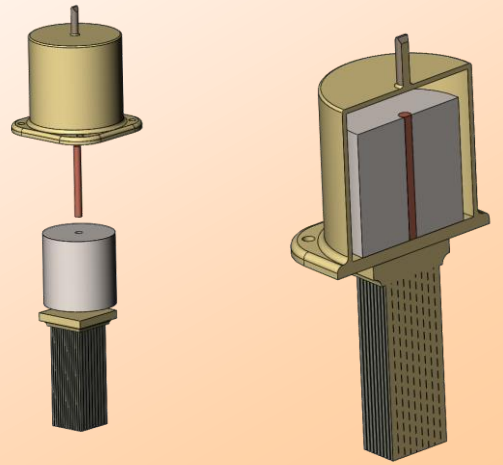
Tritium Thermoelectric Generators (TTG)

- Self-shielding effects less significant betavoltaics
- Power output surpasses betavoltaics at a threshold greater than 1-2 grams of tritium (10k-20k Ci)
- More cost-effective in the 1-2 gram tritium range
- Tritium capable of generating ~ 0.34 watts/gram of thermal power
- TTG may present cost & regulatory benefits over traditional RTG









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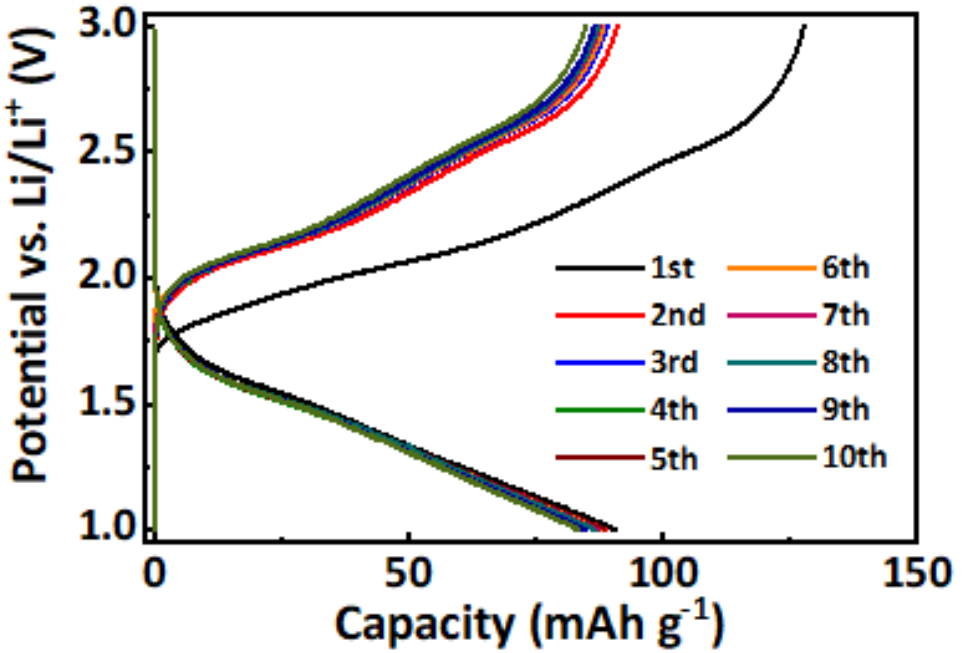
Li-Ion Battery that Operates at -100°C

- Modifying previous electrolyte NbWO||Li battery
  - Niobium, Excellent rate capability
  - Pentagonal tunnels offer a large structural opening and highly interconnecte 2D Li+ pathways
  - Abundant lithium intercalation sites
  - High capacity and large voltage window

Receveived Guisnnes World Record for Operation at -100°C

- Electrolyte
  - Needed proper electrolytes which have wide liquid temperature range and ability to form thin and robust SEI
- Electrode
  - Avoid bulk intercalation (surface-controlled capacitive materials)
  - Plating/stripping reaction of the Li metal anode
- Extreme Low Temperature System (ELTS)
  - LN2 cooling to -190°C with Fiberfrax insulation
  - Validated with cycling on LIB coin & pouch cells a pouch cell with accurate results.
  - Replicating the cell connections, minimizing LN2 usage, and reducing electrical noises



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The Need: Low-Power & Long-Life Sensors

General purpose wireless autonomous sensors suitable for **Remote & Inaccessible** applications and can endure **Harsh & Extreme environments:**

- **Internet-of-Things (IoT) Sensors** → Deployable for defense and commercial applications (ex: temperature, motion, pressure, imaging, etc.)
- **Industrial Sensors** → Deep-oil well logging & infrastructures
- **Performance Health Monitoring** → Ordnance and munitions
- **Arctic environments** → Provide uninterrupted monitoring for logistics and situational awareness
- **Deep-sea & High Pressure/Temperature environments** → Exploration and tracking
- **Command & Control Assistance in aerospace military & commercial systems** → deep-spacecraft,
  Fighter aircraft & high-altitude UAVs
- **Biomedical implants** → Pacemakers, Spinal cord stimulators, and other life-saving devices
- **Environmental & Structural monitoring** → weather balloons, tectonic movement, buildings & bridges

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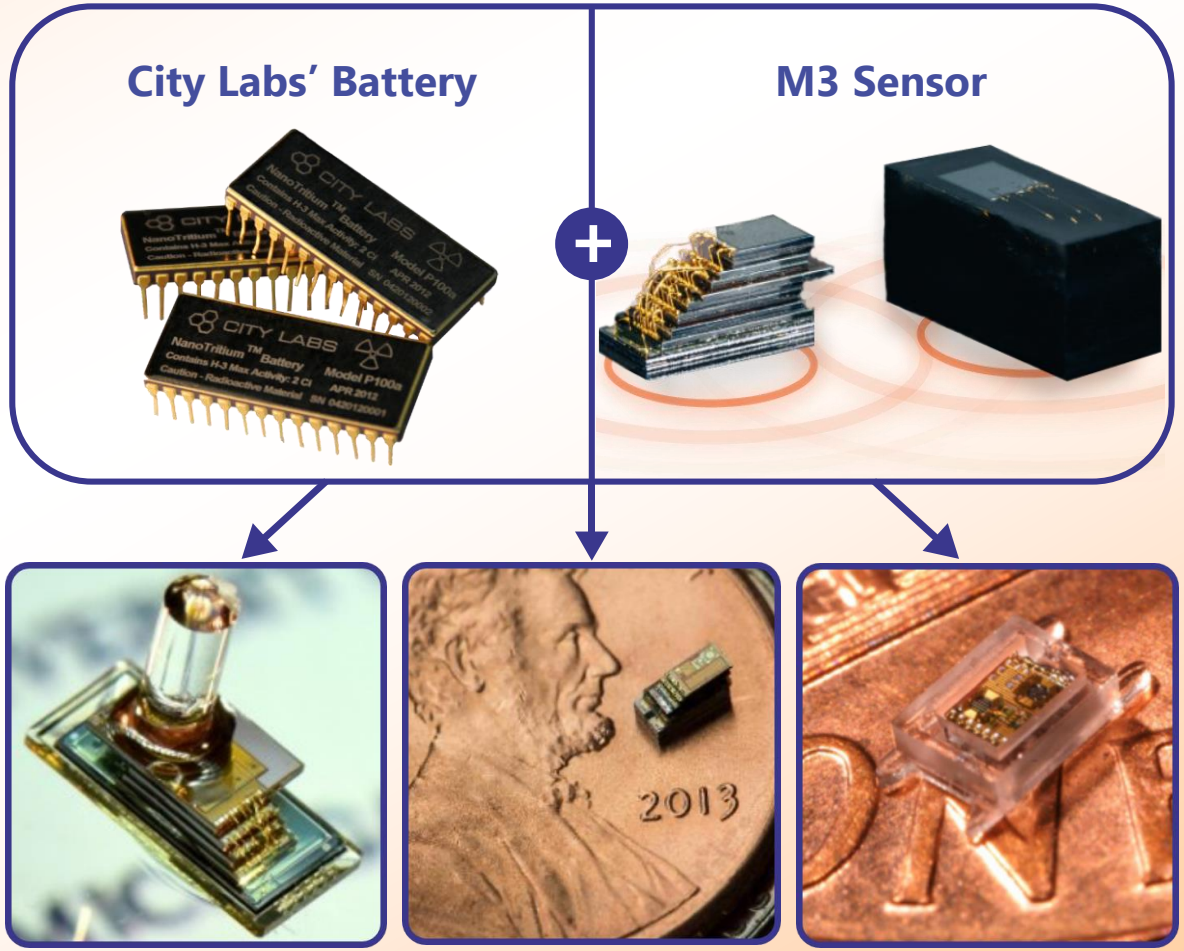
Nuclear Powered Sensor Platform

Centimeter-scale autonomous sensor platform powered with a tritium battery:

- Tritium (nuclear) battery + M3 Sensor (world's smallest computer!)
- Modular: Integrate with imager, temperature sensor, pressure sensor, RF transceiver, antenna, other COTS sensors
- Operational lifetime: 20+ years
- Onboard neural network processing
- Autonomous operation: sensing, recording, transmission, reception
- Small form factor: <1 cm^3
- Rugged in harsh environments, Resilient in hazardous environments
- Extreme Operating Temperature Range: -55°C and 150°C (soon to be tested at -100°C)



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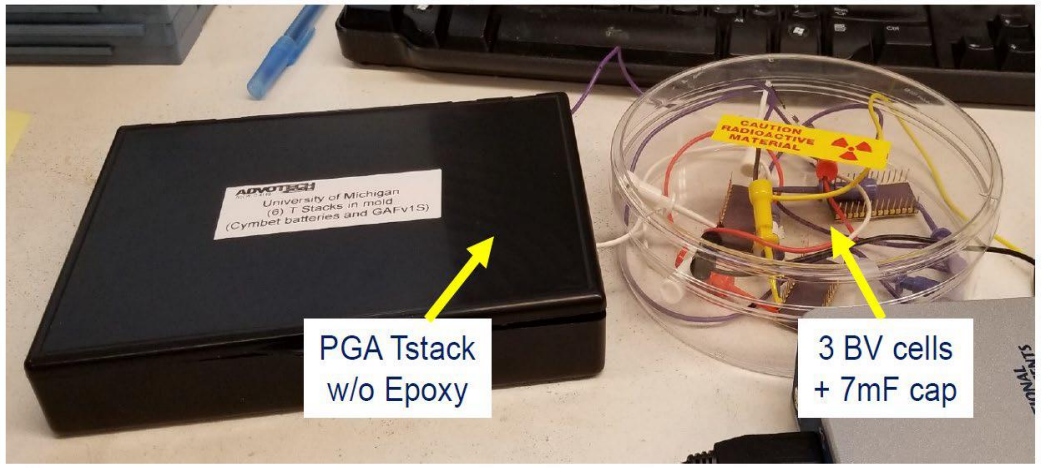
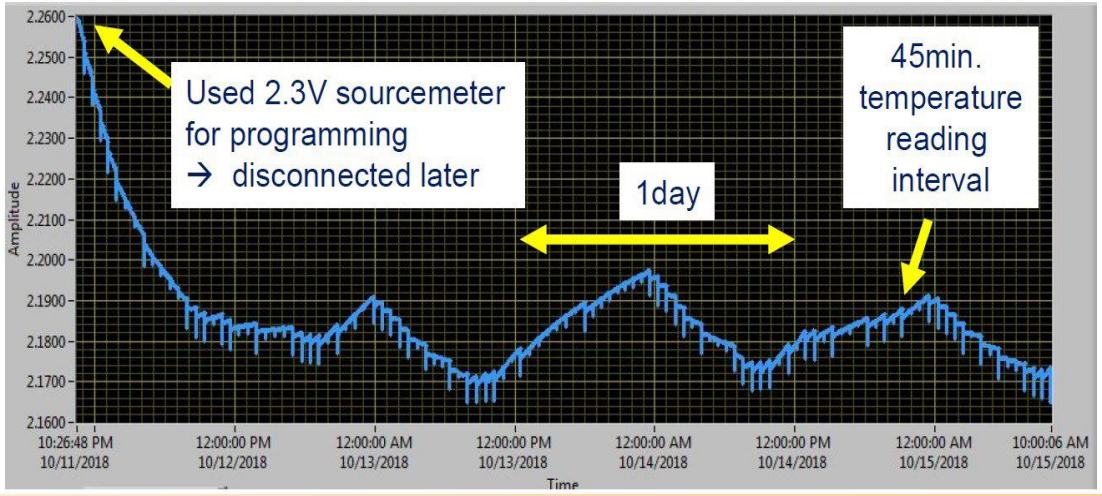
MVP Tritium (Nuclear) Powered Sensor Demonstration

- M3 Sensor with P100 tritium (nuclear) battery
- 2008 tritium (nuclear) power source
- Measured temperature and transmitted to computer 20 meters away every hour
- The system actively monitored for three years (2018-2021)
- Projected to last another 15 years
- Preparing for next demonstration for 100 meter coverage





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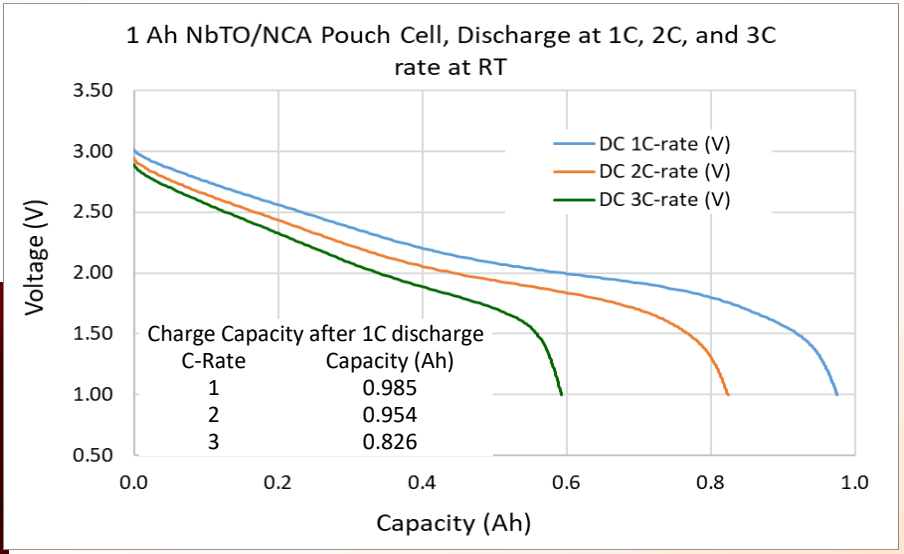
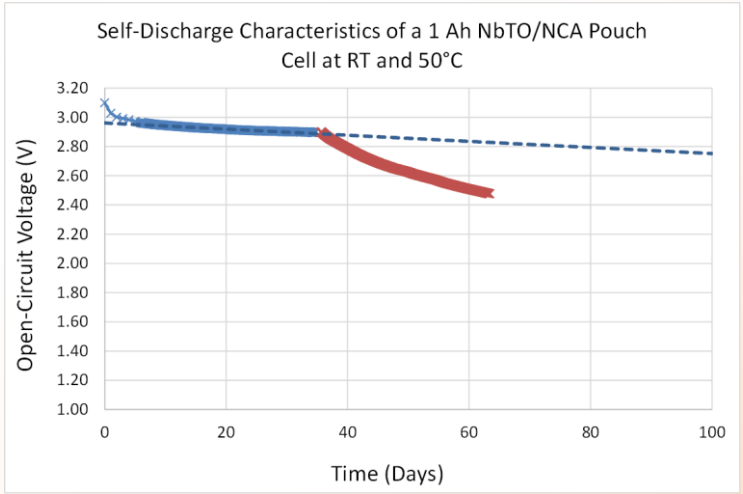
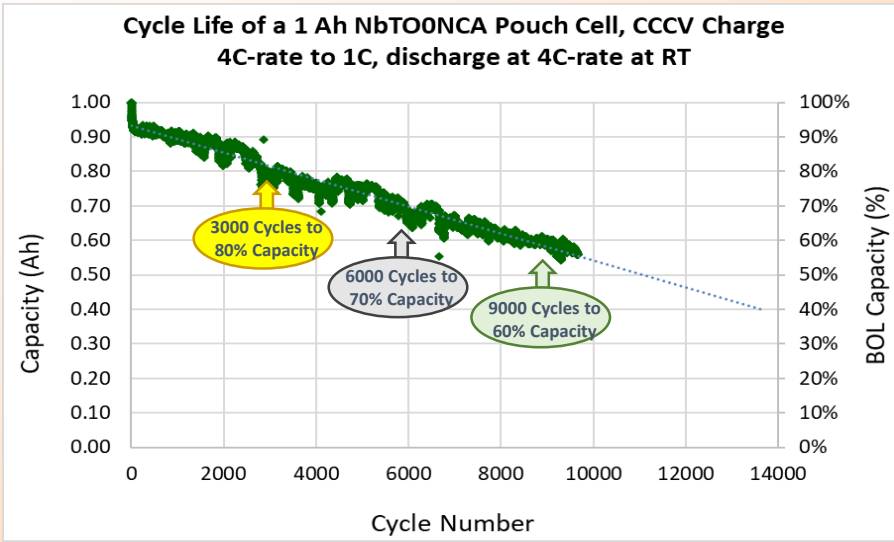
Battery Streak Niobium (Nb) Battery Technology

- Battery Streak 1.0 Ah Pouch Cell, NbTO / NCA
  - NbTO Anode, NCA Cathode
  - Replacing NCA Cathode with LVPF → Cobalt Free!
  - Niobium improves capacity retention & high charge rate capabilities,
  - Lower internal impedance to reduce cell temperature → Safer
  - Long Cycle Life, High Current Rates
  - CBMM is the world's leading supplier of niobium
- Cycle Life Evaluation at RT and 0°C
  - 100% Depth of Discharge (3.2V – 1.0V)
  - Charge and Discharge at 4C-rate
  - At RT, 80% Capacity after 3000 cycles
    - 70% Capacity after 6000 cycles
    - 60% Capacity after 9000 cycles
  - At 0°C, 5% Capacity loss after 500 cycles
    - Capacity is 60% of RT capacity
- Self-discharge at 100% SoC
  - 2.1 mV/day at RT → 1.0V in 2.6 years
  - 14.3 mV/day at 50°C
  - Evaluate rate at 0°C and at lower SOC







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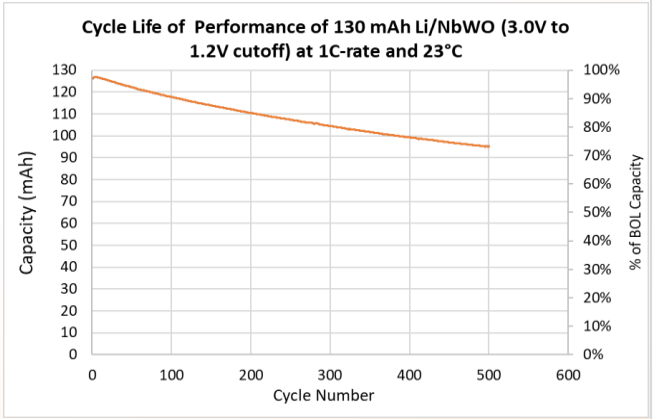
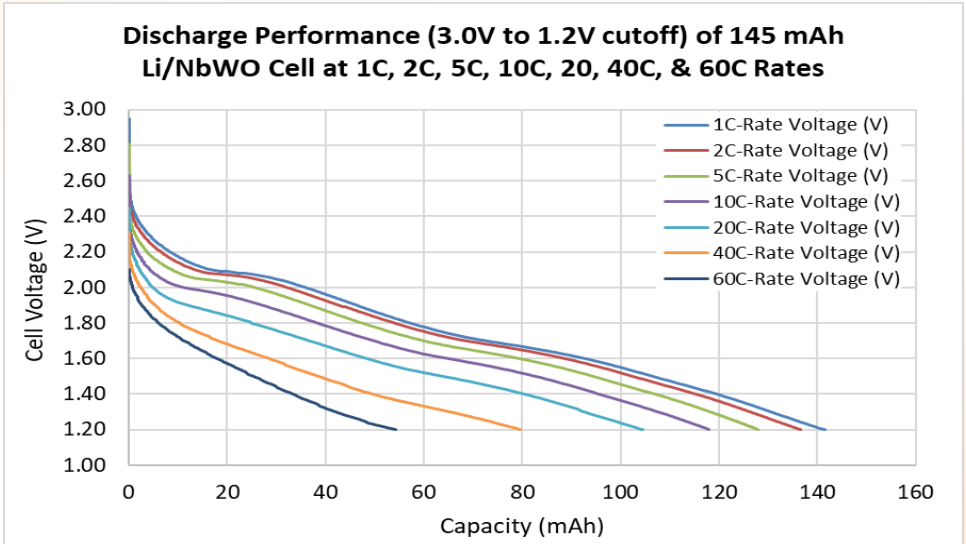
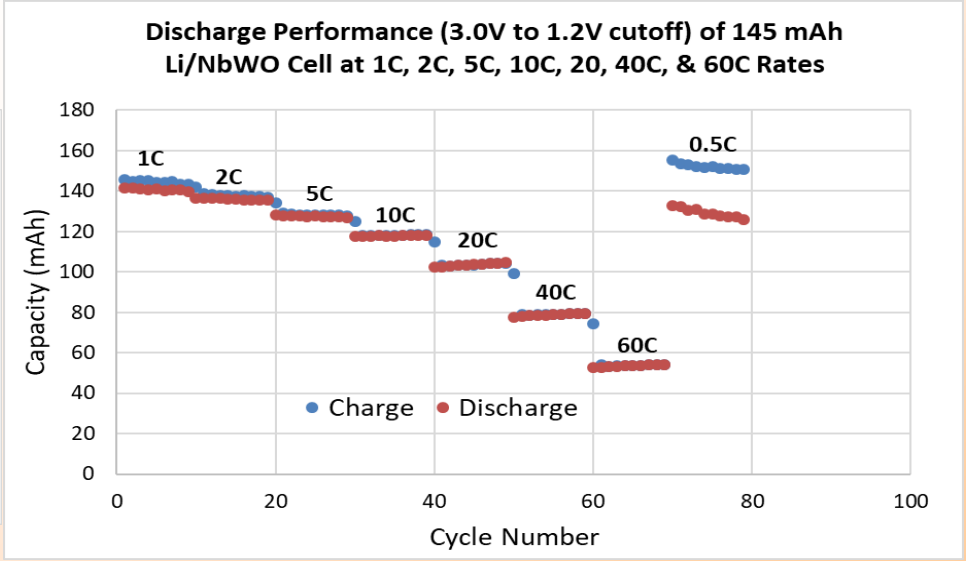
Purdue NbWO Li-ion Cell

- Purdue Niobium Tungsten-oxide NbWO Cathode, Li metal Anode
  - NbWO Cathode → Cobalt Free!
  - NbWO structural advantages for Li+ diffusion and fast Li+ reaction process
  - Good cycle life and excellent low-temperature performance (<-100°C)
  - High Charge and Discharge Current Rates
- Cycle Life Evaluation at RT
  - 100% Depth of Discharge (3.0V – 1.2V)
  - Charge and Discharge at 2C-rate
  - 80% Capacity after 200 cycles
- High-Rate Charge/Discharge
  - 5C rate loses 7% capacity
  - 60C rate loses 60% capacity
- Currently fabricating 1.0 Ahr pouch cells with hard-graphite anode







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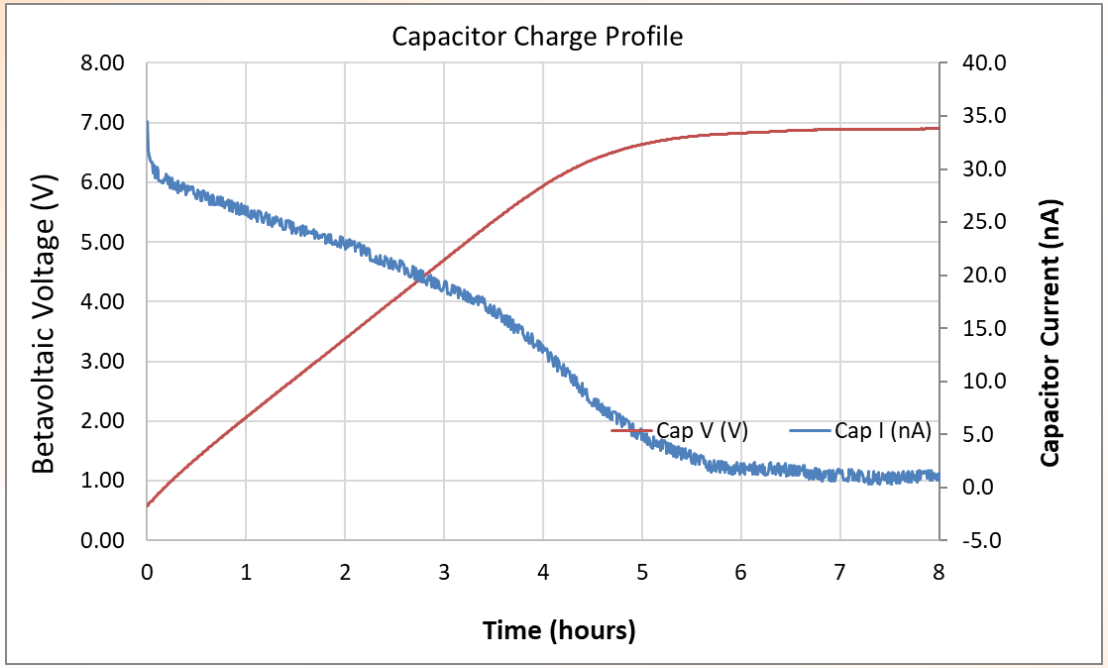
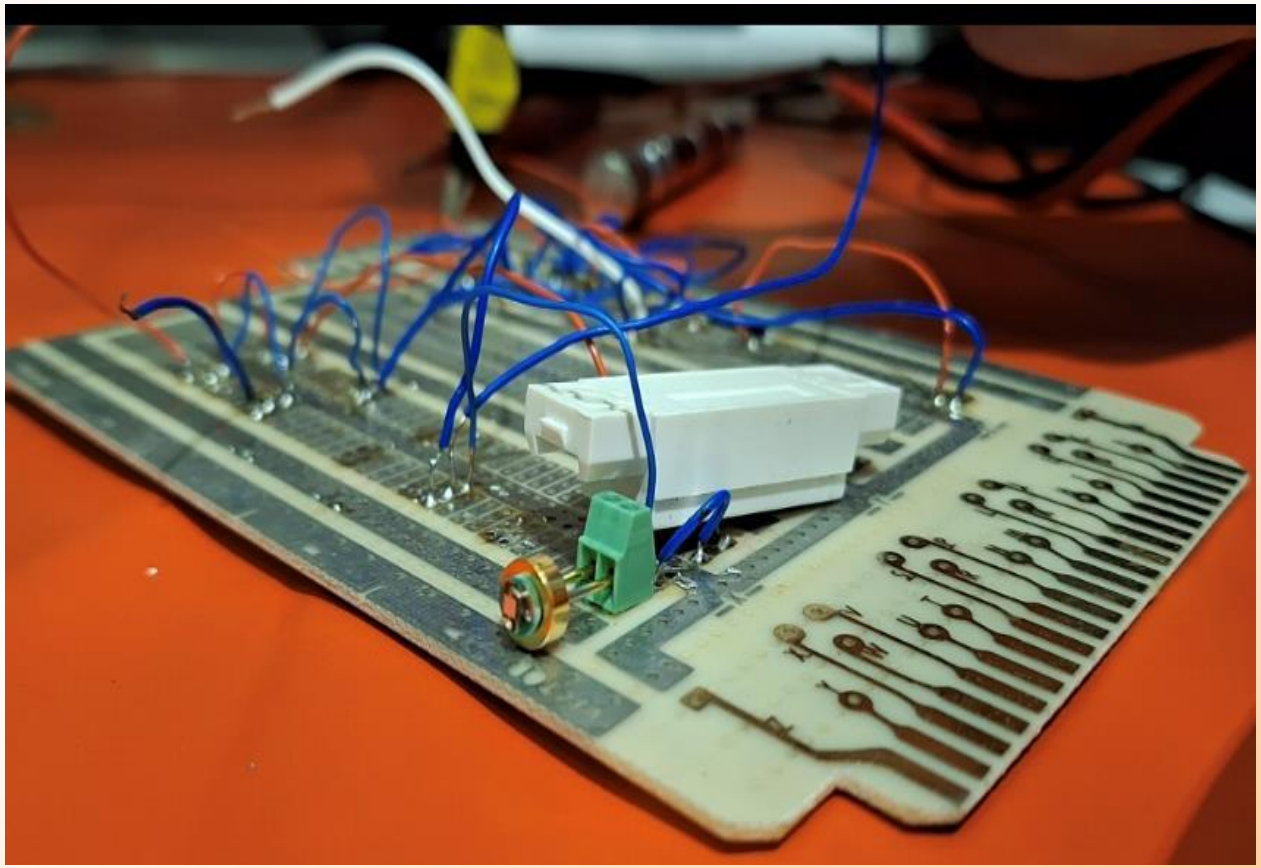
Thermite Activation

- 10 betavoltaics (2014) in Series
  - Six 100µF capacitors in parallel
  - 40 nA current (70nA at BOL)





NRC Licensure for Tritium Power Source

NRC Sealed Source Device Registration (SSDR)

- Exempt License (mCi devices)
  - Illumination for gunsights, watch dials, etc
  - Can be bought/resold without a NRC radiation license
- General License (SSDR)
  - Exit signs, City Labs' betavoltaics
  - Publically available without NRC radiation license
- Specific License (SSDR)
  - Requires NRC radiation license for possession

Shipping

- Exempted Packages
  - <200 Ci, regular courier, UN 2911 labelling
- Type A Packages
  - <1080 Ci, regular courier, UN 2915/Class 7 labelling
- Type B Packages
  - >1080 Ci, Special Courier, UN 2916/Class 7 labelling
  - Containers available at SRNL and Canada

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Thank you

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