Compact, Low Specific-Mass Electrical Power Supply for Hostile Environments

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CSNR

Power can be the key

- Research and exploration inevitably lead to operations in hostile environments
- Mobile, robust, compact power sources can often ENABLE research in extremely hostile locations
- Exploration of space entails operations in vacuum, extreme cold, extreme heat, intense radiation, and sometimes reactive gases
- Radioisotope power sources have enabled exploration of the outer planets, lunar surface, Mars surface, and beyond the solar system (?)

Why Nuclear Energy?

Radioisotope power sources have been used in the US space program since the early 1960s

Over 29 successful robotic missions have been flown in the hostile environments of space and on planetary surfaces

The energy contained in 1 kg of Plutonium-238 is 160,000 times that of chemical sources, i.e. 1.6e06 MJ/kg

Assuming a 25% conversion efficiency, a Radioisotope Power Source (RPS) would have 400,000 MJ/kg (electric) compared to 0.72 MJ/kg for Li-ion batteries

The technologies to utilize radioisotope decay have been proven

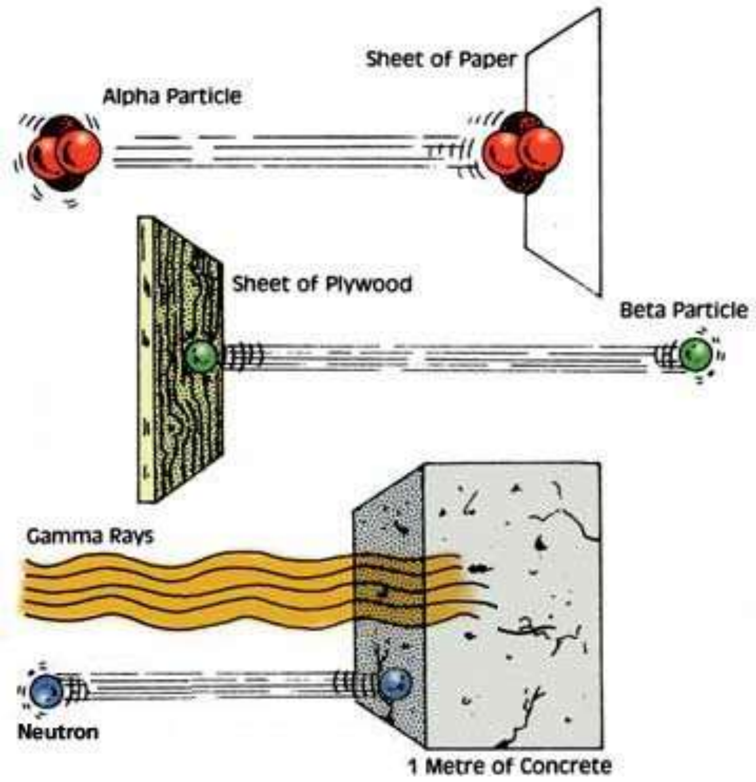
Shielding Radiation

Radioisotopes emit three types of radiation

Gamma rays deposit energy weakly, i.e. require heavy shielding

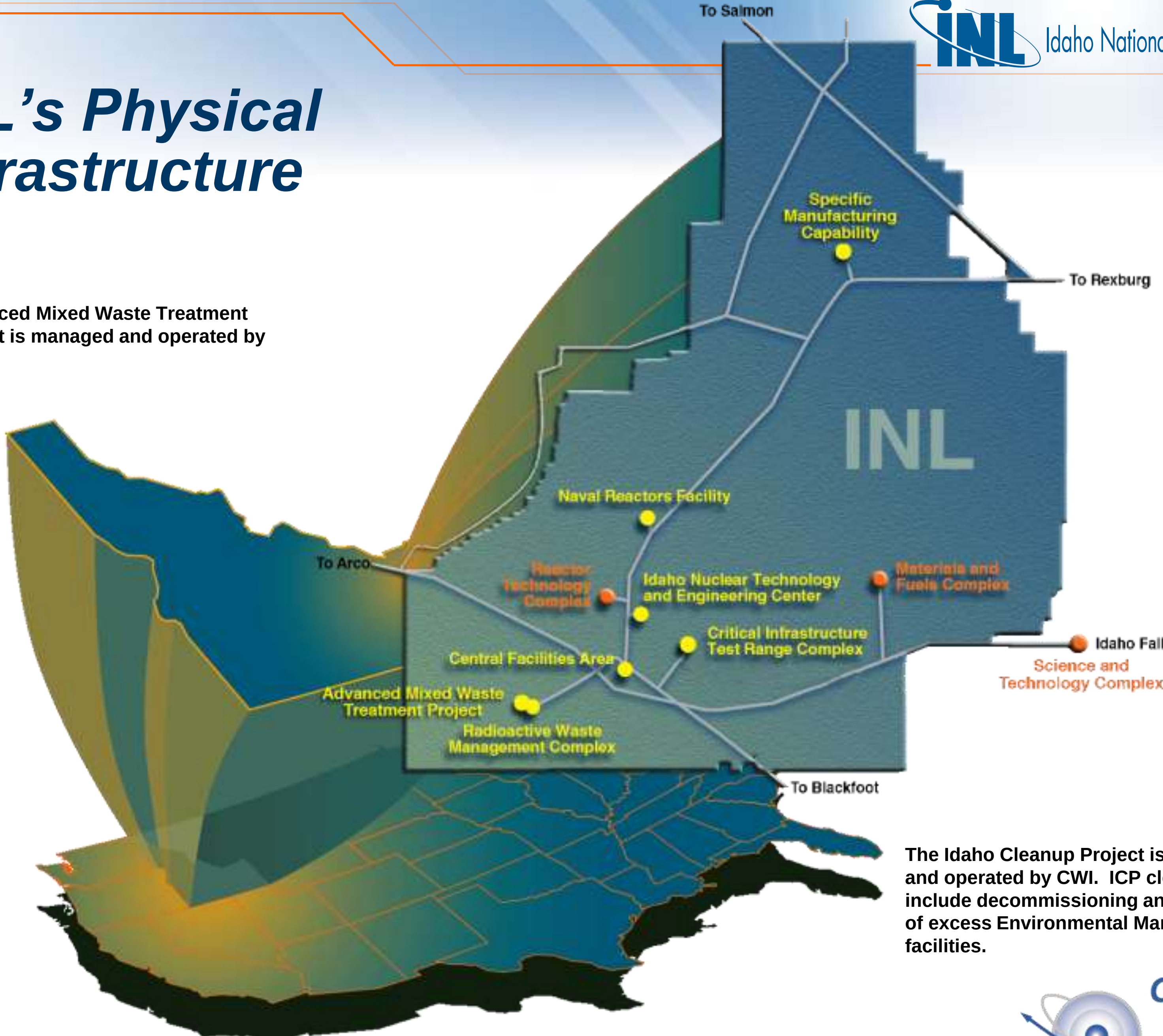
Beta decay with high energy produce photons and require shielding

Alpha decay deposits energy locally, requires little shielding, and is the most suitable source



INL's Physical Infrastructure

Advanced Mixed Waste Treatment Project is managed and operated by BBWI



The Idaho Cleanup Project is managed and operated by CWI. ICP cleanup efforts include decommissioning and dismantling of excess Environmental Management facilities.

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INL's Unique Facilities

Advanced Test Reactor

Hot Fuels Examination Facility

Space and Security Power Systems Facility

Transient Reactor Test Facility

Fuel Cycle Facility

Zero Power Physics Reactor

Fuel and Storage Facility

Idaho currently plays a key late-stage role in RPS for space missions

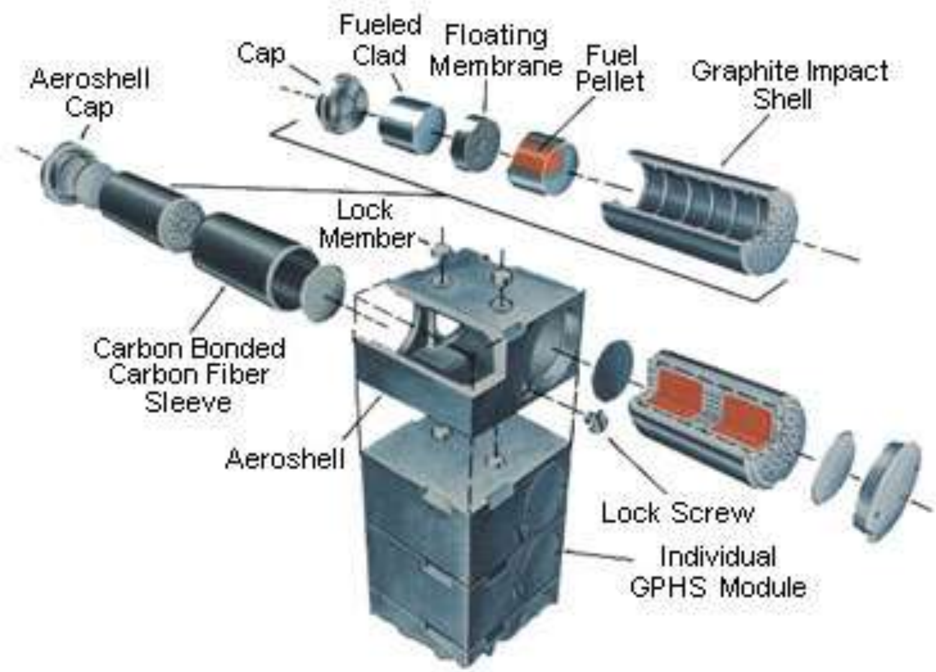
- **INL is responsible for final assembly and testing of Radioisotopic Thermoelectric Generators (RTGs)**
- **The New Horizons mission to Pluto – the highest-priority exploration mission of the decade – depended on INL fabrication**

General Purpose Heat Source (GPHS)

- Fuel is assembled into GPHS
- Pu-238 is used for fuel
  - Half life of 87.7 years
  - Requires 1.8 gm to produce 1-thermal watt of power
- Each MMRTG contains 8 GPHS modules
- Each GPHS module contains

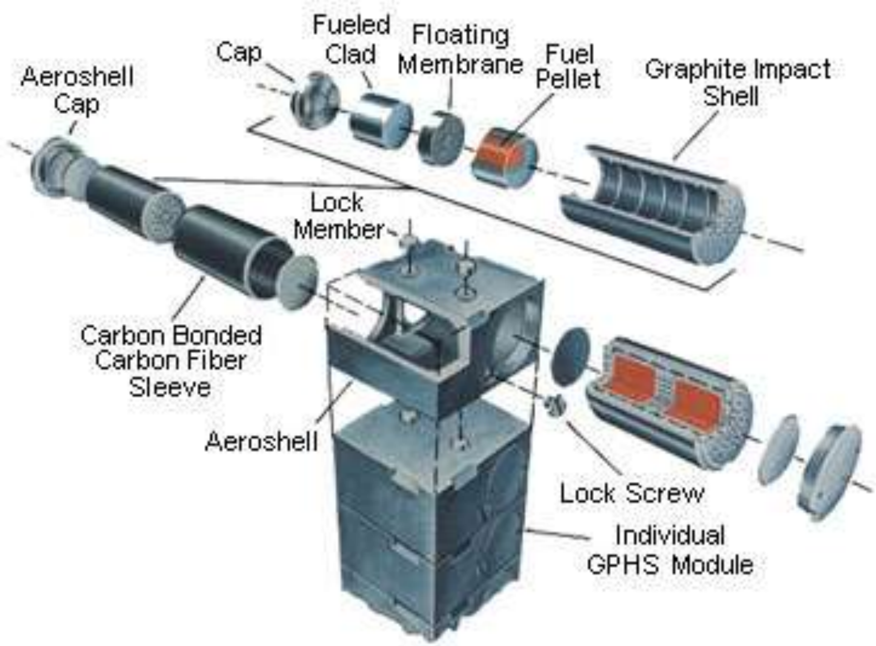
  ~600 g PuO_2 in 4 fueled clads

  ~4.8 kg PuO_2 in 8 modules
- Pellet Surface Temp: ~2700°F
- Fuel Clad Surface Temp: ~1600°F
- Module Surface Temp: ~1000°F



Current RPS Performance

- The specific masses of a RTG, MMRTG and ASRG are 198, 300 and 148 kg/kW$_e$ respectively
- The power density of the General Purpose Heat Source used in these units is 0.5 W/cm^3
- Thermo-electric conversion has low efficiency , i.e. 6-8%
- Stirling Engines have greater efficiency (~25 %) but have moving components.
- Max temperature (~1200 K) of GPHS is limited by grain growth in Ir cladding



General Purpose Heat Source (GPHS)

Comparison of MMRTG and GPHS-RTG

- MMRTG seal-welded for planetary surface mission
- Size and welding added new assembly challenges

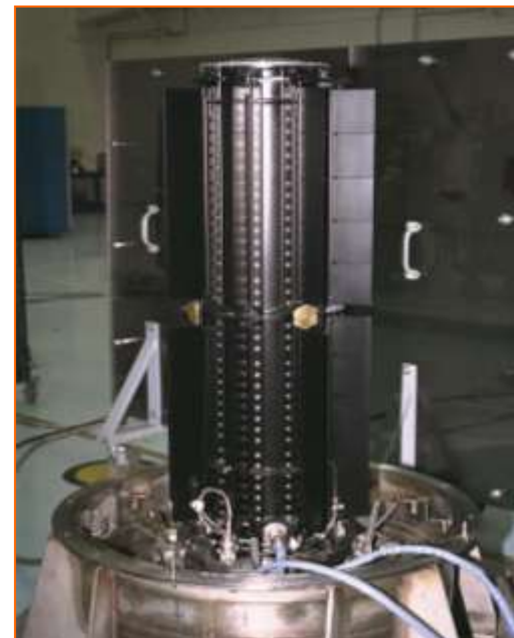
MMRTG

• MSL (1)	
• BOM Power (2009)	123 W_e
• Conversion Efficiency	~ 6.3%
• Modules	8
• Mass	97 lbs
• Length	2 ft
• Fin tip-to-tip diameter	2 ft
• Launch Window	Fall 2011

GPHS-RTG

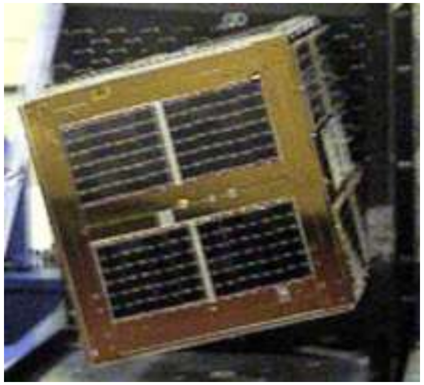
• Galileo (2), Ulysses (1),, Cassini (3) & Pluto New Horizons (1)	
• BOM Power (2006)	250 W_e
• Conversion Efficiency	~ 6.8%
• Modules	18
• Mass	127 lbs
• Length	4 ft
• Fin tip-to-tip diameter	1.5 ft
• Pluto New Horizons Launched	Jan 19, 2006

- GPHS-RTG utilizes active gas management system until after launch

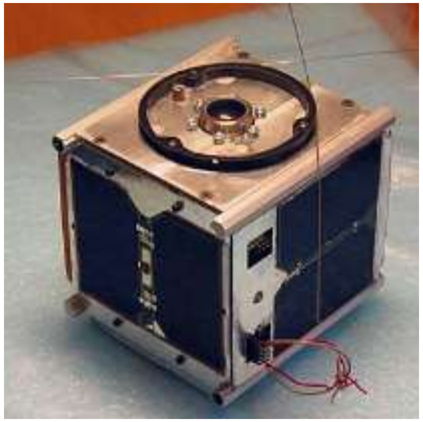


Growth in Nano & Micro Satellite Use

- Small satellites are increasing in use in near Earth space
  - *“Projections indicate a strong increase in nano/microsatellite launch demand, with an estimated range of 100 to 142 nano/microsatellites (1-50 kg) that will need launches globally in 2020 (versus 23 in 2011)”* *Space Works Commercial report November 2011*

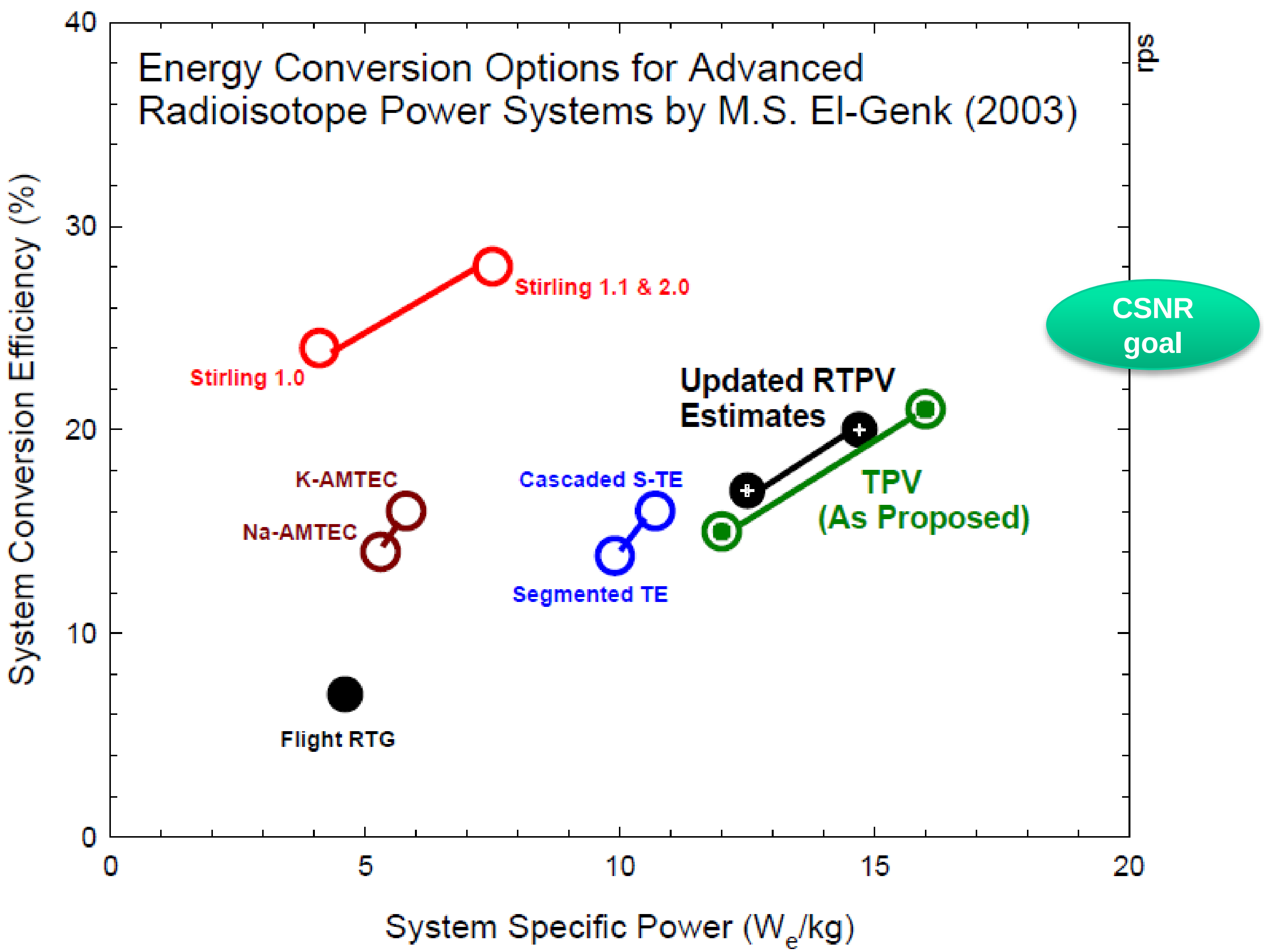


- The use of micro or nano satellites offers the potential for cheaper exploration of the solar system
- The smallest nuclear source available will be the ASRG at ~140 W_e with a mass of 22 kg.

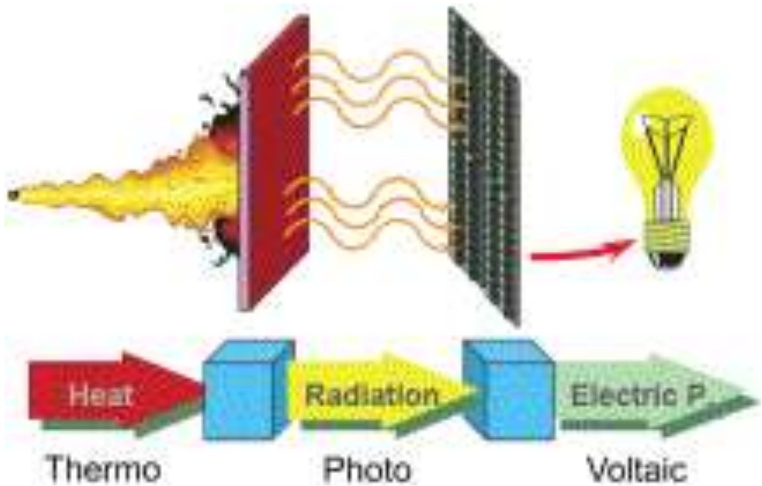


- No power source exists below the 100 W level to support small sat exploration beyond Mars orbit
- <u>Small sats could be applicable to Mars missions if a low mass, radioisotope power supply is developed</u>

Radioisotope Power Systems



Thermo-Photovoltaic Systems



- **Greatest efficiency achieved when wavelength of radiated heat is tuned to the band gap of the PV cells**
- **Scalable from ~50 mW_e to 500W_e power level**
- **Radioisotope fuelled RTPV systems have potential for 40-80 kg/kW_e.**

Alternative Method utilizes the CSNR tungsten encapsulation

- PuO2 dispersed in a tungsten matrix has a power density of 2.5 w/cm3 -- 5 times the power density of the GPHS
- Tungsten has an emissivity that is preferential to higher frequencies – couples well to PV cells
- Tungsten can easily operate at temperatures near 2000 K for long periods – potential efficiency of near 20%
- Tungsten can encapsulate alternative isotopes such as Americium-241 – allows source to be placed among instruments because of decrease in emitted gamma rays

RTPV potentially offers a x3 reduction in power source mass – to 50-70 kg/kWe

Universal Encapsulation - Common technology for reactor fuels and radioisotope sources

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The encapsulation of radioisotope materials and nuclear fuels in an inert carrier matrix addresses most of the issues for space power applications:

- Potential to address non-proliferation security requirements.
- The ability to survive re-entry into Earth's atmosphere and impact under accident conditions.
- Assembly & handling safety
- Reduction in material self interaction such as α-n reactions.
- Self-shielding properties.

Spark Plasma Sintering enables fabrication of tungsten parts at nearly full theoretical density

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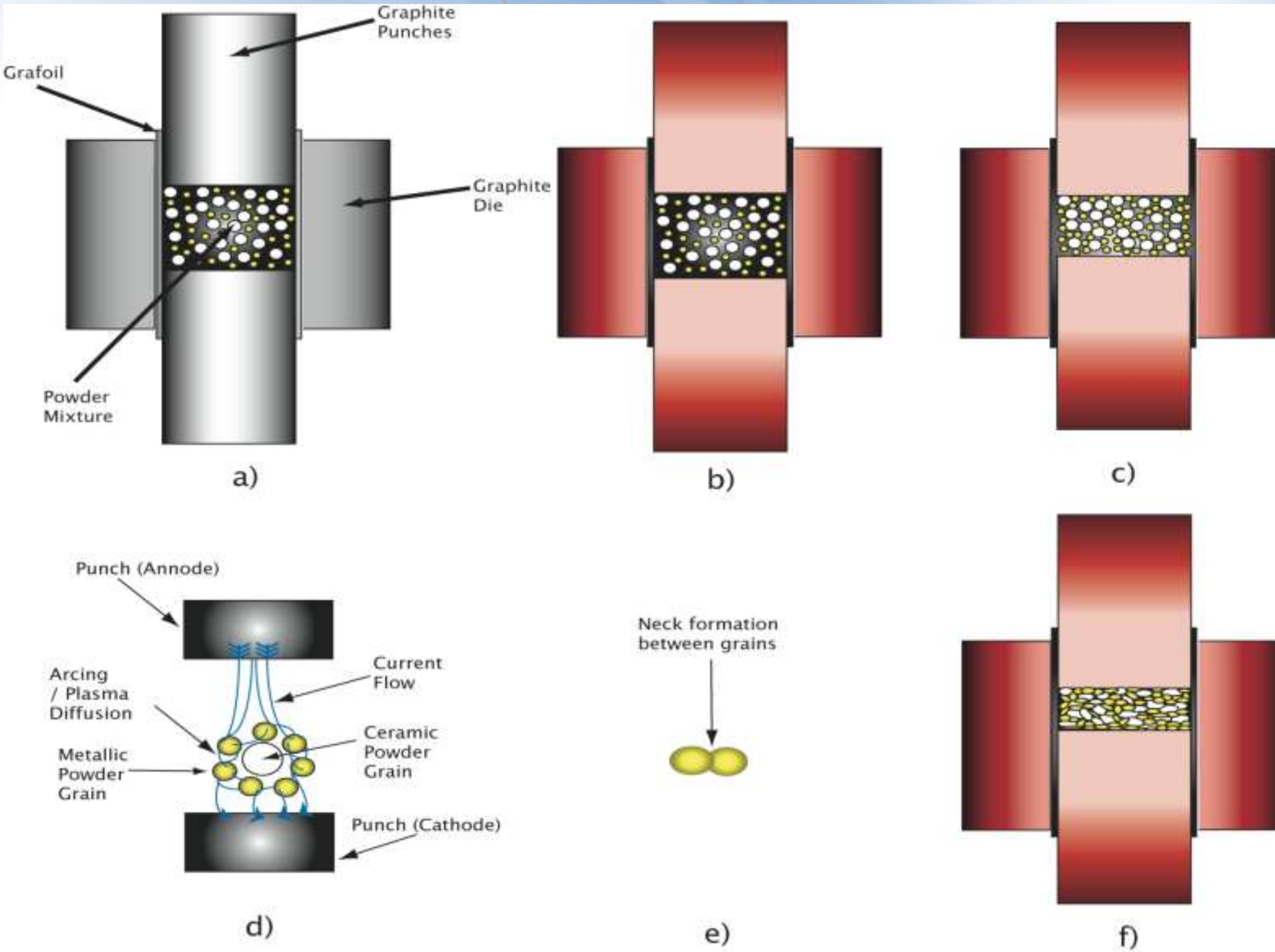
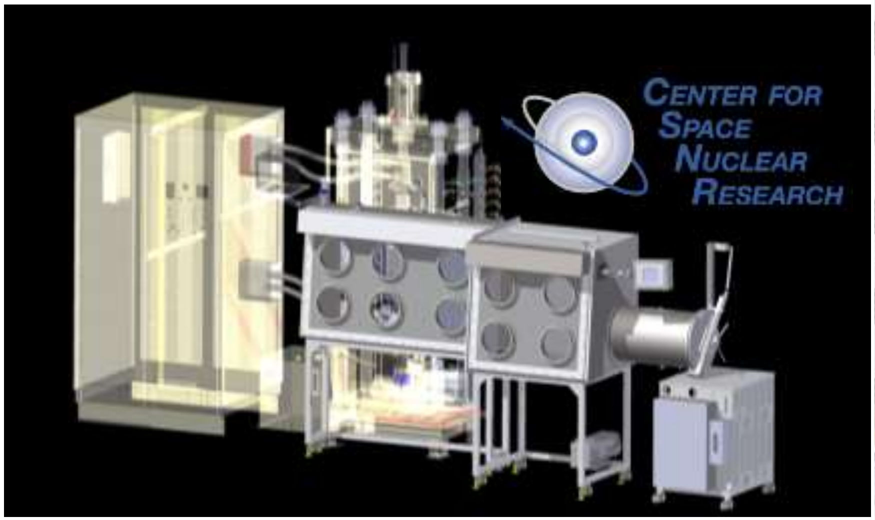
Spark Plasma Sintering of Cermets



RSPS facility Installation

- Furnace & 1st glovebox modules installed 2nd July 2012.
- 2nd glovebox modules installed 31st July 2012.

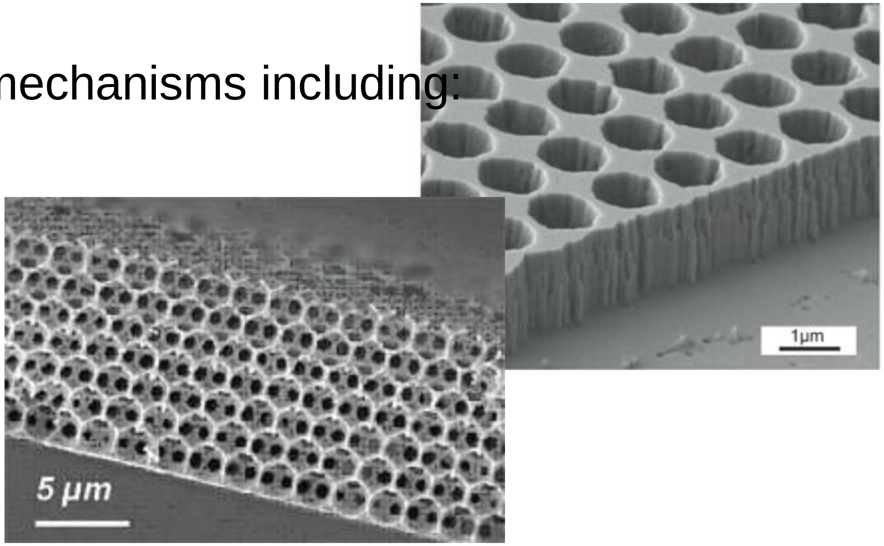


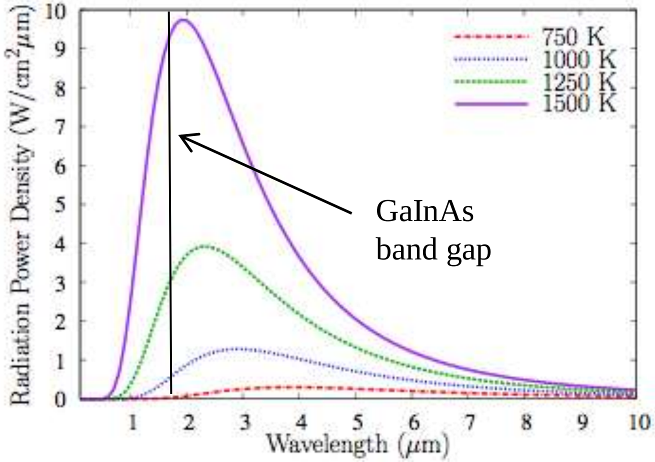
CSNR Development

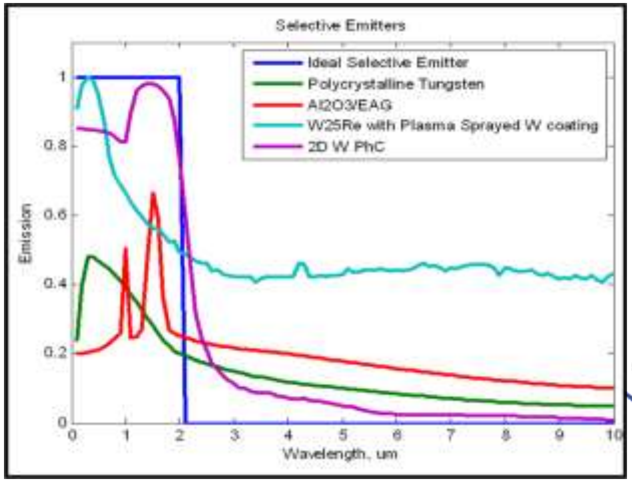
- **No moving parts**
  - No maintenance needed for life of mission
- Encapsulation method allows for modifiable source size, and smaller systems
- **Tungsten Cermets matrix shields harmful radiation**
  - Power sources can be housed among instruments
- Emitter material or coating can be part of Cermet fuel
- **Tungsten Cermets matrix can withstand very high temperature**
  - Temperature can be used to tune photonic emissions

Photovoltaic Optimization

- Surface nanostructures to manipulate grey body emission spectrum of heat source
- May rely upon the adoption of several mechanisms including:
  - Use of dopants such as Er_2O_3.
  - Photonic Crystals
  - Resonant cavities
- Optimal temperature for coupling of emitter to PV cell requires analysis of a variety of materials at different temperatures







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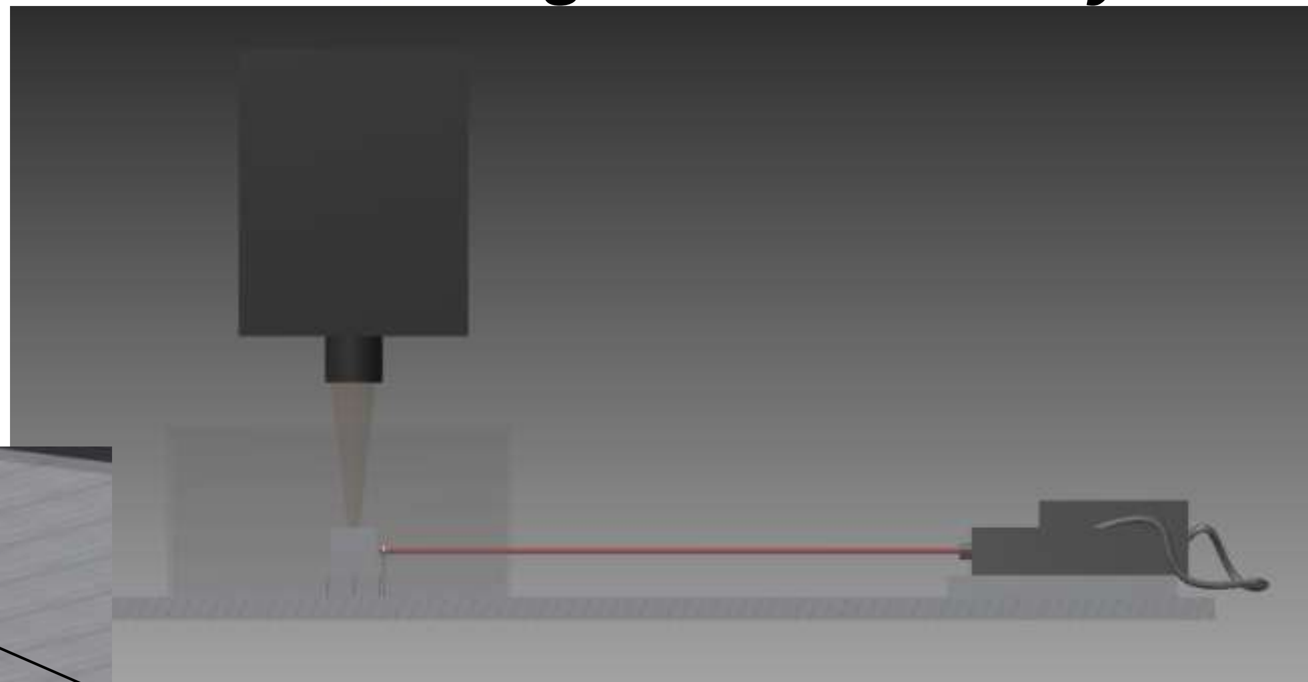
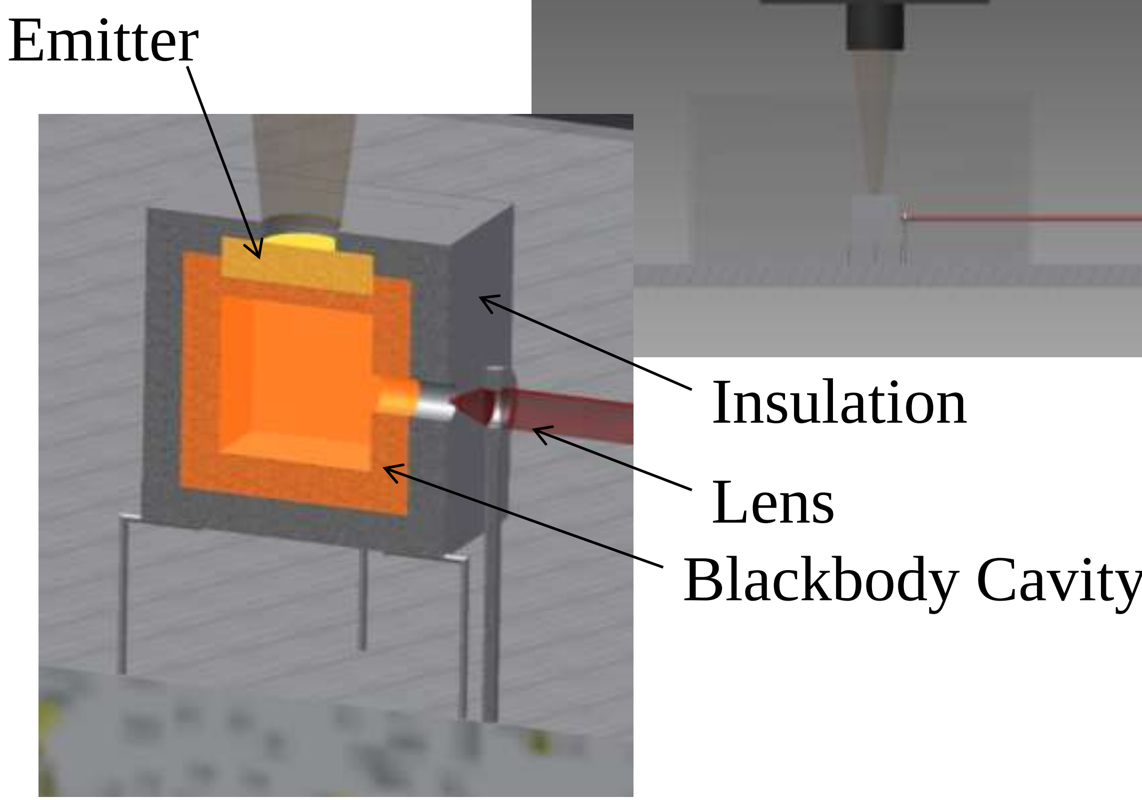
Spectral Emission / TPV Integral Test Facility



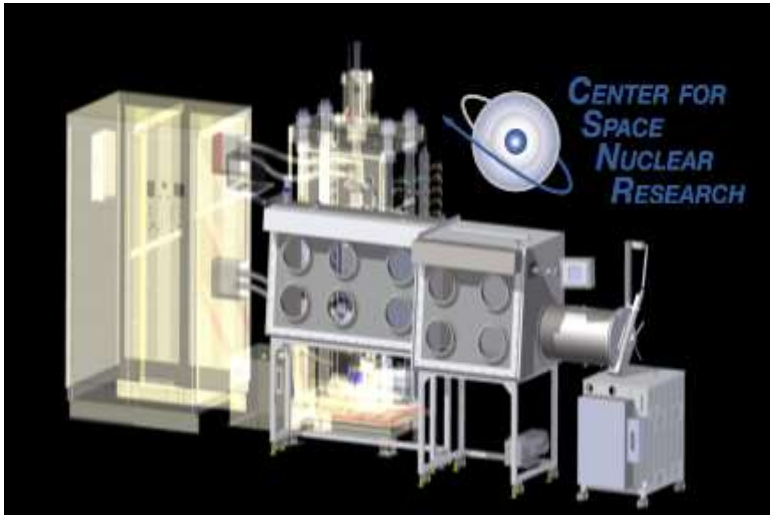


Option for Low Power Sources

- Power sources in the 5 - 20 We range entail additional issues and offer additional options
  - Requires small quantities of isotope – 62.5 g of Pu-238; 250 g Am-241 (for 5 We)
  - Am-241 is available at around 1 kg/yr commercially
  - Am-241 produces 59 kev gammas which are stopped readily by tungsten so the radiation field is very low
  - Thus, an Am-241 source could be placed in among the instruments and the waste heat used to heat the platform
  - Amounts of isotope are so low that launch approval may be easier, especially with the tungsten encapsulation

Path Forward

- Current effort is a 3 year project funded by INL discretionary funds at $200K/yr
- Final goals:
  - optimize the RTPV design between emitter and PV cell
  - Build an electrically heated prototype, i.e. fully functional and integrated unit except for radioisotope
- Future needs to produce final product
  - Duplicate current SPS furnace/glove box in controlled area on INL site
  - Perform accident scenario survivability tests

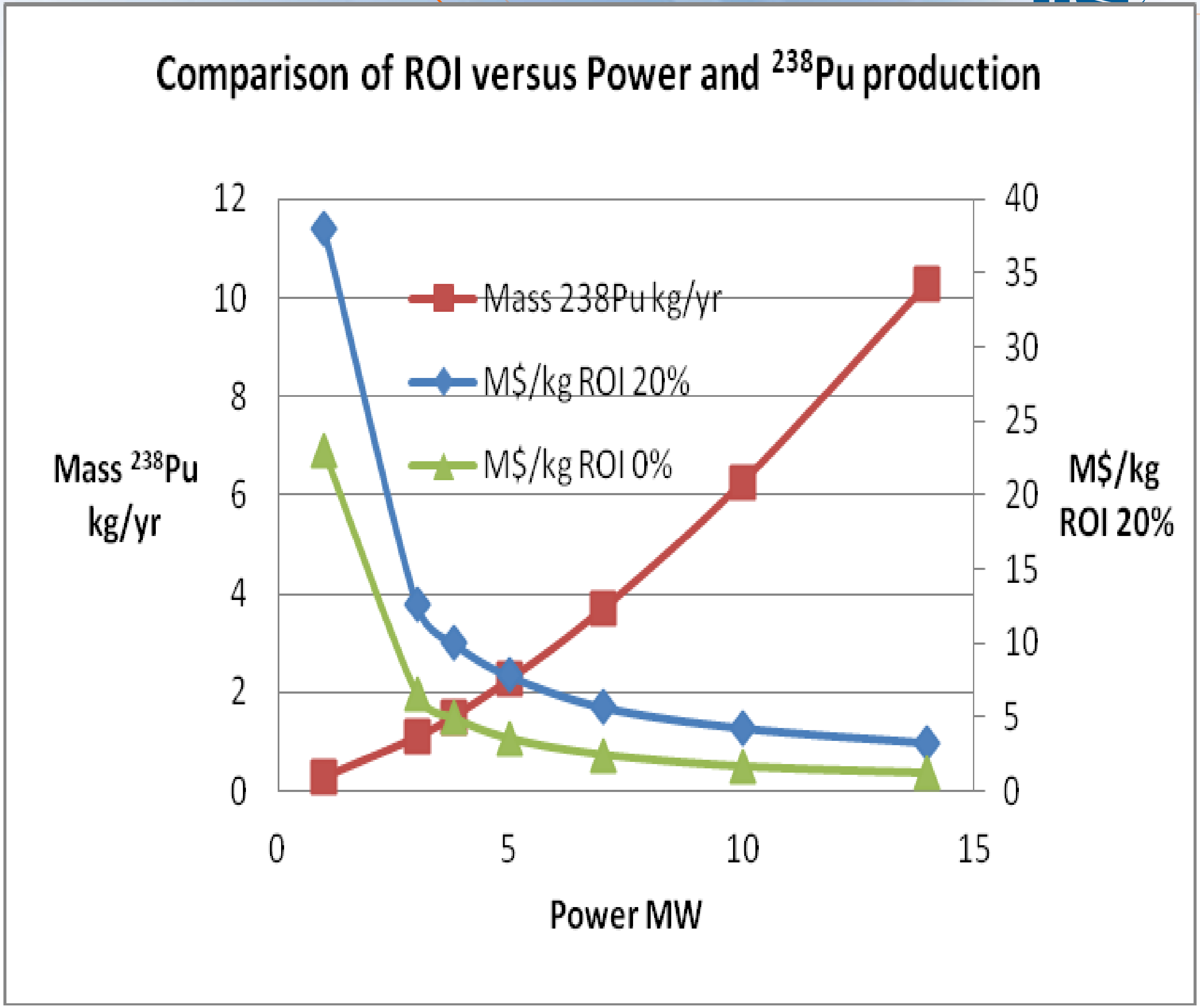


Summary

- Space exploration appears to be going in the direction of smaller, cheaper satellites but need radioisotope power sources for the outer planets
- RTPV devices can provide an efficient small-scale power system
  - No moving parts
  - Scalable depending on mission need
  - No dispersion on launch abort
- Tungsten Cermet enables the customization of isotopic power sources
  - Five times the power density of GPHS
  - Can hold a variety of different isotopes based on needs
  - Can be fabricated in a variety of shapes and sizes
  - Can emit in a selective spectrum
  - Has a higher maximum operation temperature

Estimated RPS source for 5 We– 400 g, "D cell" size

The CSNR is developing a photonic emission testing facility to tune emitters to optimal PV band gap ranges to create compact, robust, safe, long-lived power sources for hostile environments.



Comparison of ROI versus Power and 238Pu production
Mass 238Pu kg/yr
M$/kg ROI 20%
M$/kg ROI 0%
Mass 238Pu kg/yr
M$/kg ROI 20%
Power MW
0
2
4
6
8
10
12
0
5
10
15
20
25
30
35
40
0
5
10
15