TFAWS Passive Thermal Paper Session

Thermo-Radiative Cell – A New Waste Heat Recovery Technology for Space Power Applications

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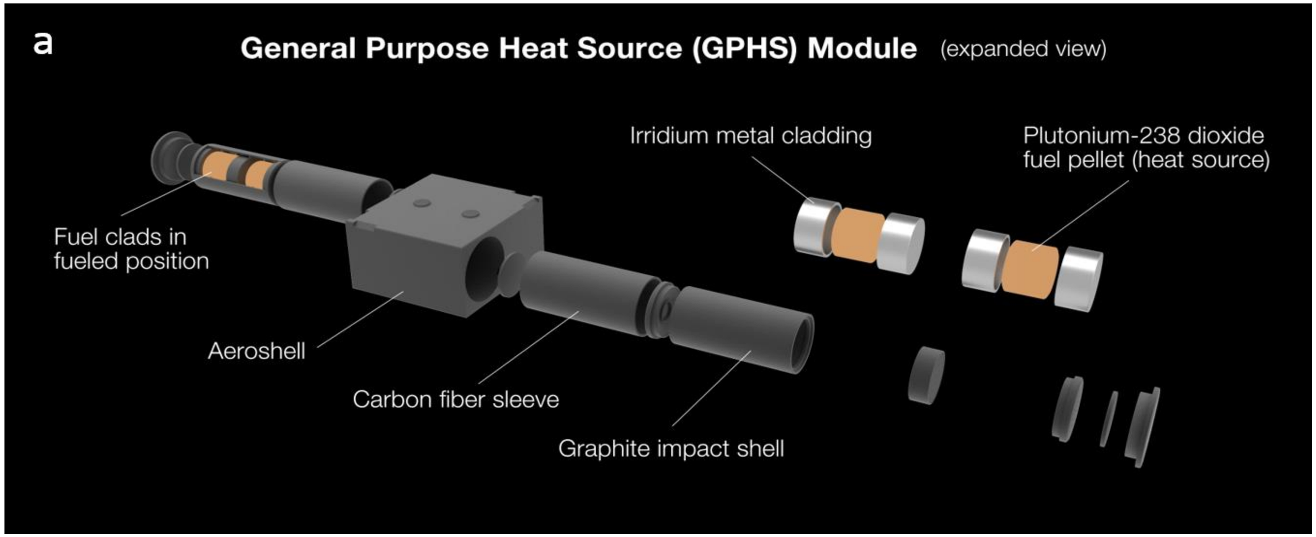
Outline

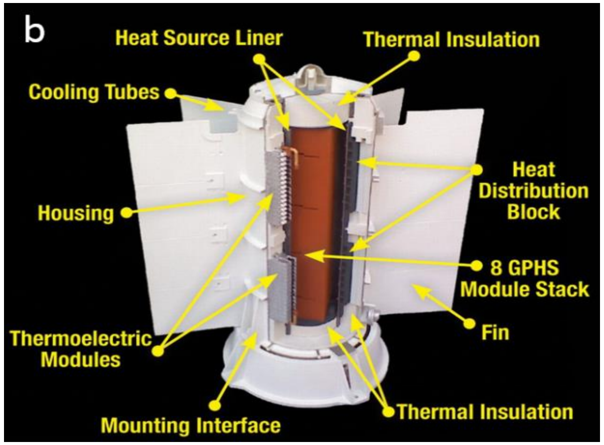
- Motivation
- Principle of thermo-radiative cell
- Analysis of thermo-radiative cell performance
- Benefits to radioisotope power systems (RPS)
  - ❑ Integrated with dynamic RPS
  - ❑ Integrated with thermoelectric RPS
- Proof-of-concept demonstration
  - ❑ ON/OFF response demonstration
  - ❑ Current-voltage characteristics
- Summary and future work

Space Radioisotope Power Systems

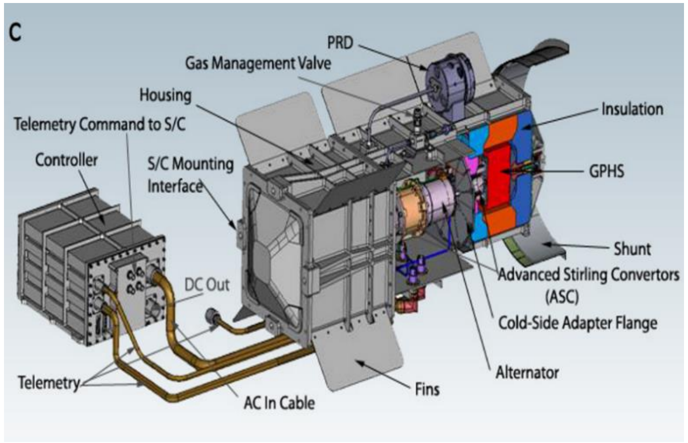


Current stockpile of Pu-238 is only enough for 3 nuclear batteries.

$\eta = 6\sim8\%$



Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)



Advanced Stirling Converter

$\eta = 25\sim30\%$

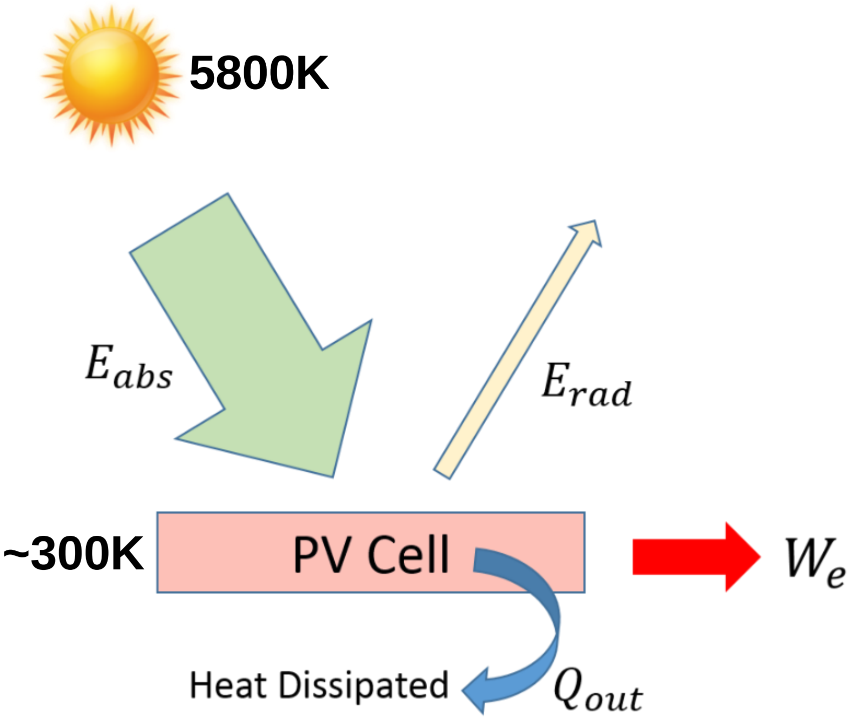
Images courtesy of NASA.gov

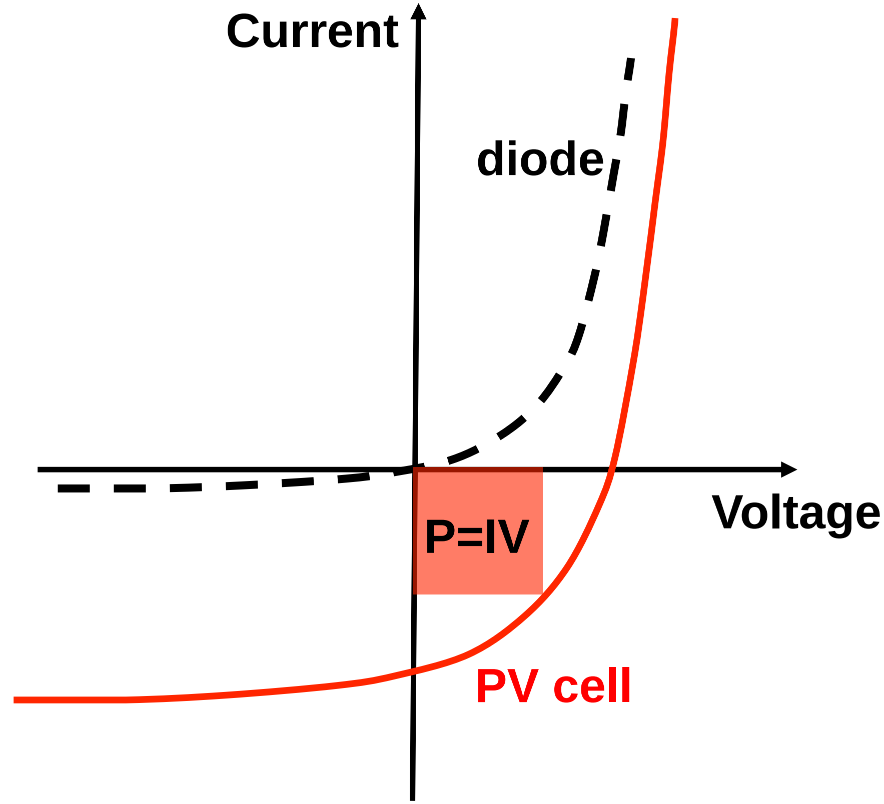
How to efficiently utilize the space waste heat ?

- Low-grade waste heat is difficult to utilize for terrestrial applications.
- In deep space, the extremely cold universe (at 3 K) could provide a robust heat sink.
- The communication between the heat source and heat sink is radiation.

Thermo-Radiative Cell

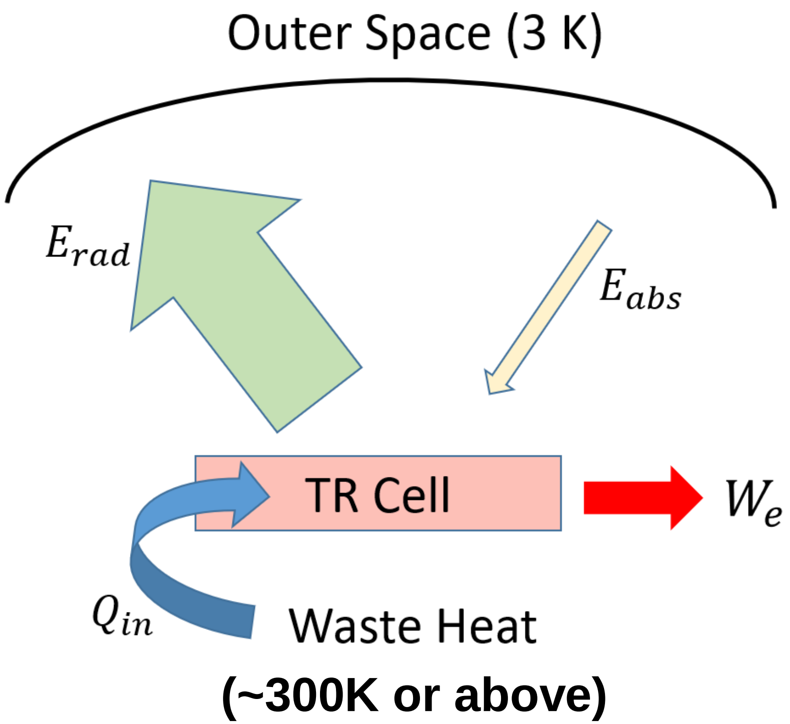
Photovoltaic (PV) Cell

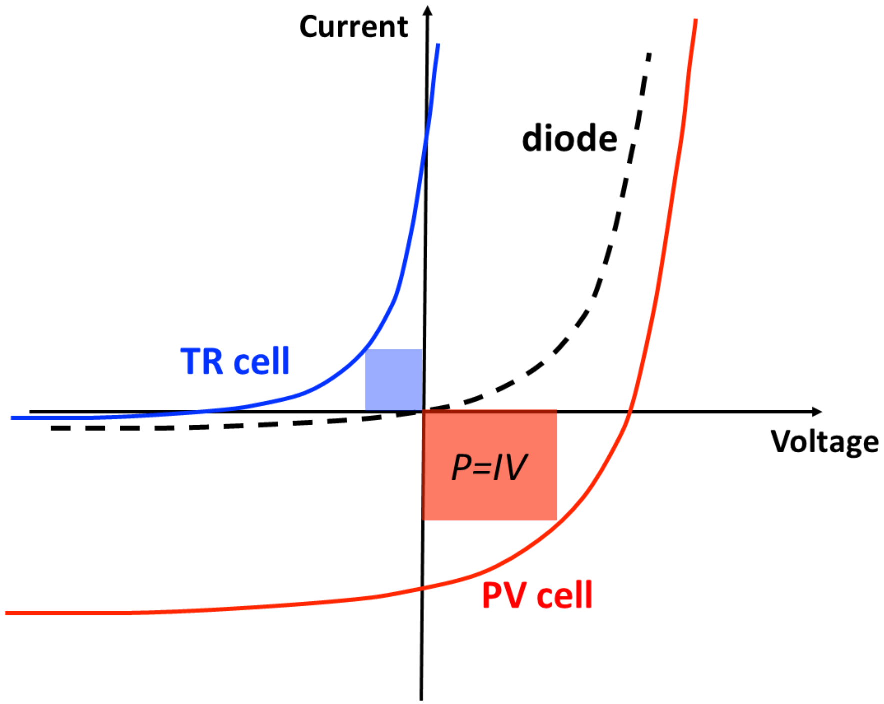




- PV cell at ~300 K faces to the sun at ~5800 K
- Net photon flux: from environment to PV cell

Thermo-Radiative (TR) Cell

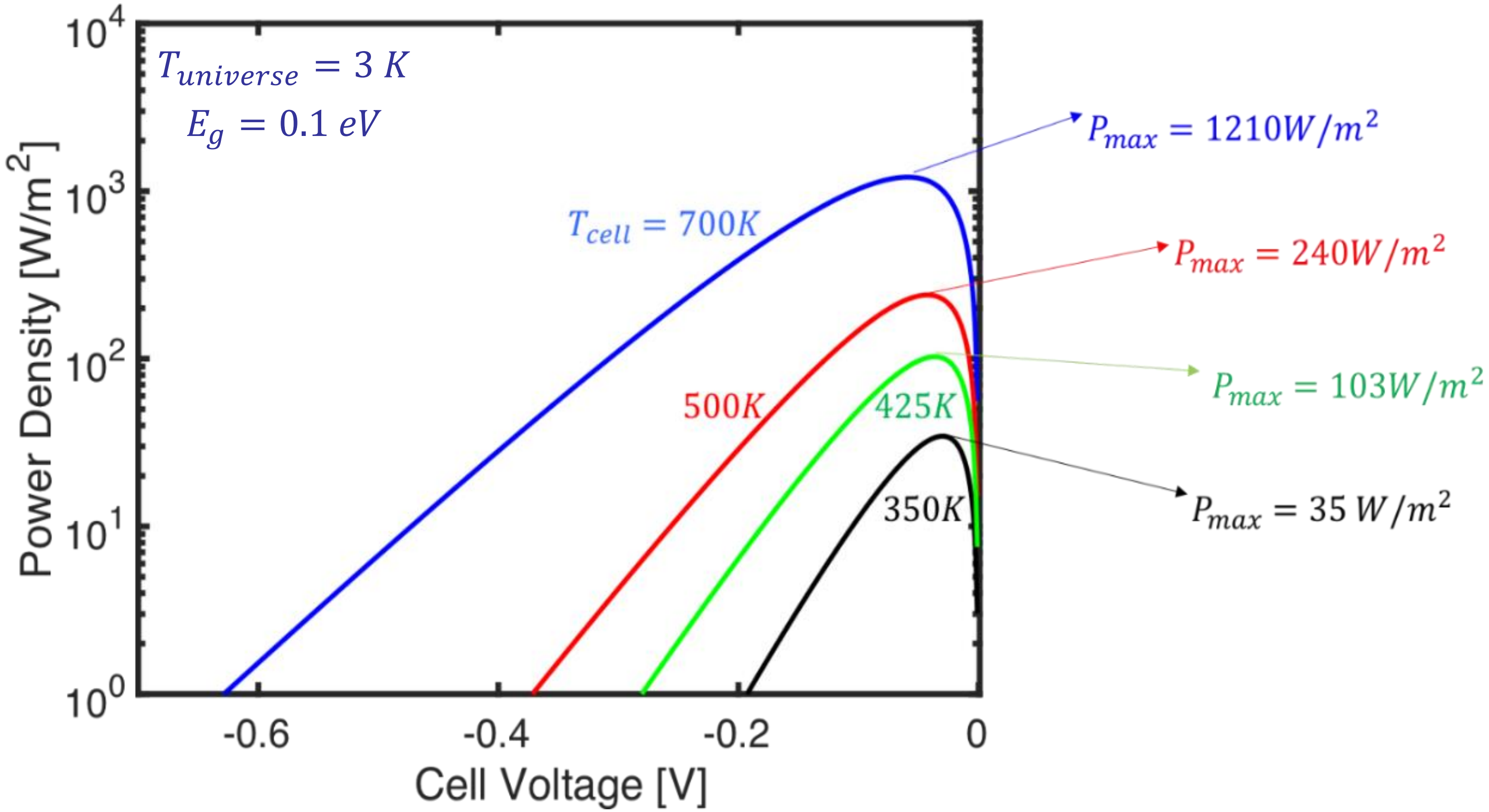




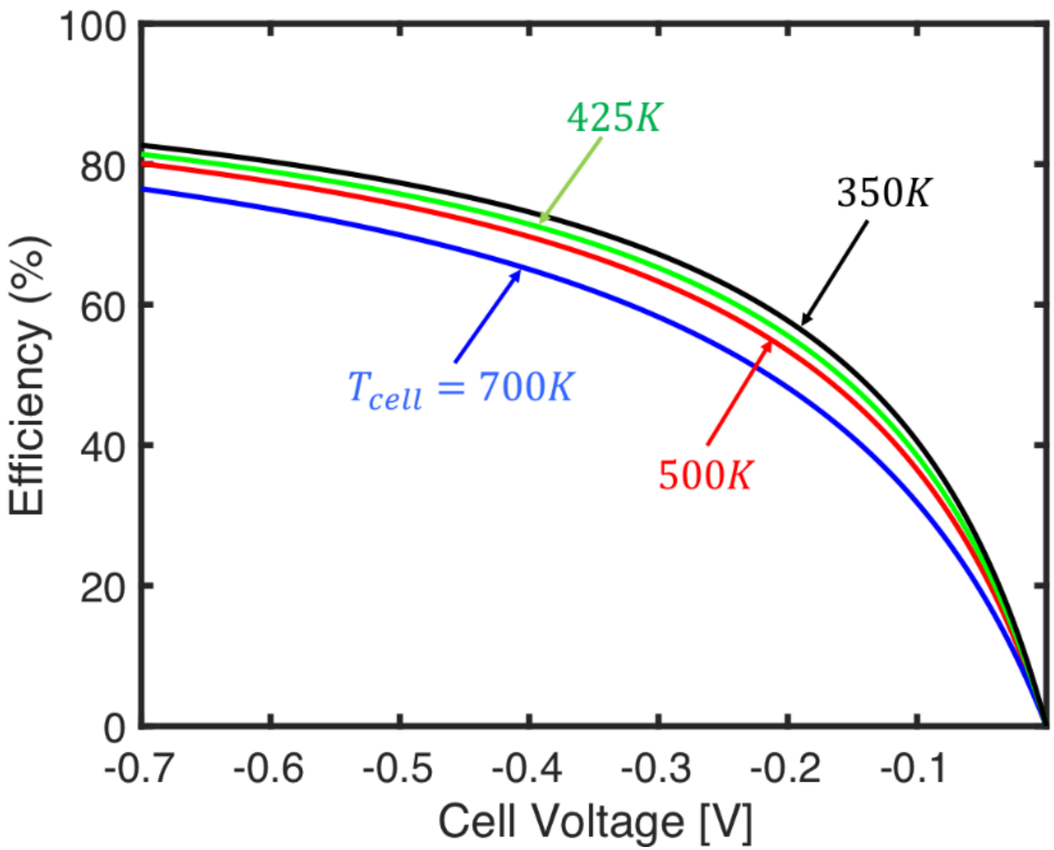
- Thermo-radiative cell concept was proposed by R. Strandberg (*JAP*, 2015)
- Net photon flux: from TR cell to environment
- Generated current and voltage directions in TR cell are opposite to the PV cell
- TR cell is anticipated to have better performance at high temperature

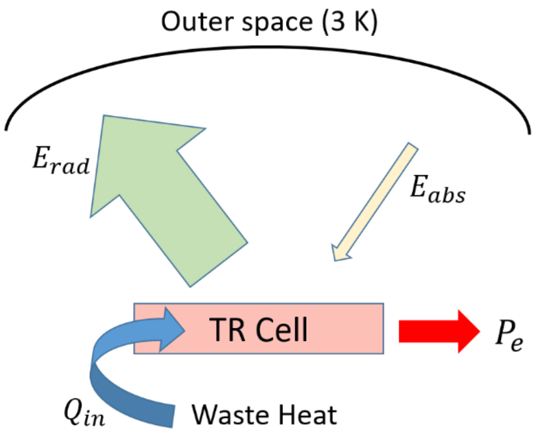
TR Cell Performance – Power Density

$$P_e = IV = eV\left(\frac{2\pi}{h^3c^2}\right)\left[\int_{E_g}^{\infty} \frac{\varepsilon^2}{exp\left(\frac{\varepsilon}{k_B T_a}\right) - 1} d\varepsilon - \int_{E_g}^{\infty} \frac{\varepsilon^2}{exp\left(\frac{\varepsilon - qV}{k_B T_c}\right) - 1} d\varepsilon\right]$$



TR Cell Performance - Efficiency





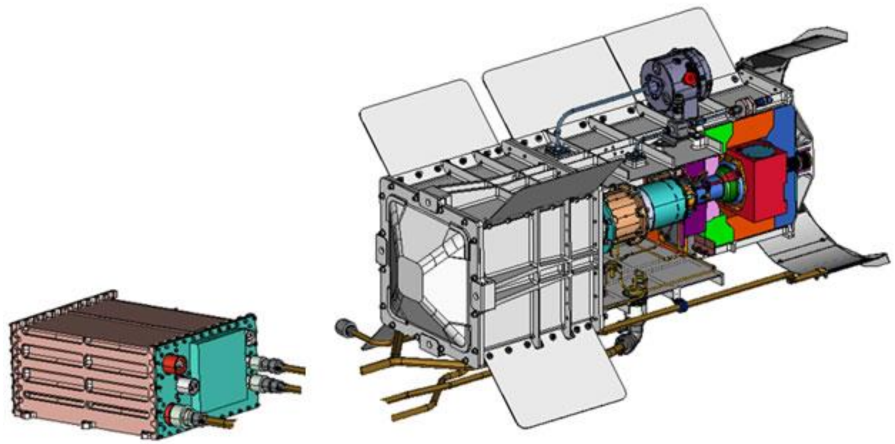
$$\eta = \frac{P_e}{Q_{in}} = \frac{P_e}{P_e + \dot{E}_{rad} - \dot{E}_{abs}}$$

$$\dot{E}_{rad} = \frac{2\pi}{h^3 c^2} \int_{E_g}^{\infty} \frac{\varepsilon^3}{exp\left(\frac{\varepsilon - qV}{k_B T_c}\right) - 1} d\varepsilon$$

$$\dot{E}_{abs} = \frac{2\pi}{h^3 c^2} \int_{E_g}^{\infty} \frac{\varepsilon^3}{exp\left(\frac{\varepsilon}{k_B T_a}\right) - 1} d\varepsilon$$

The predicted efficiency at peak power is about 18%, ~3X of MMRTG. It could be much higher at lower power output.

Integrated with a Dynamic RPS



Stirling RPS Dimension:
76cm X 46cm X 39cm

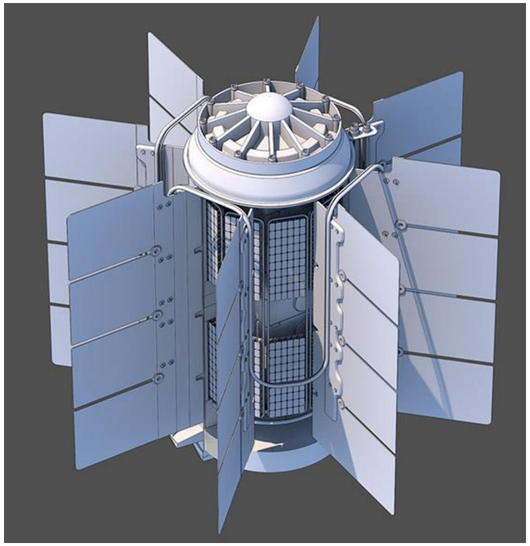
	Stirling RPS
Hot Side	850℃
Cold Side	130℃
Efficiency	28%
Two GPHS	2*250 W
Electrical Power Output	140 W
Mass of Pu-238	1.2 kg

If TR cells were attached on the radiator of a dynamic (e.g., Stirling) RPS, assuming the average cell temperature is ~75℃, under ideal situation this:

- Provides additional electrical power 45W by TR cells integration.
- Increases the system efficiency from 28% to 37%.
- Has negligible temperature increase at the RPS cold side.

Integrated with a Thermoelectric RPS

Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)
Mass = 43 kg, Diam = 64 cm, Length = 66 cm



MMRTG

$$T_{hot} = 530°C$$

$$T_{cold} = 200°C$$

$$m_{Pu-238} = 3.5kg$$

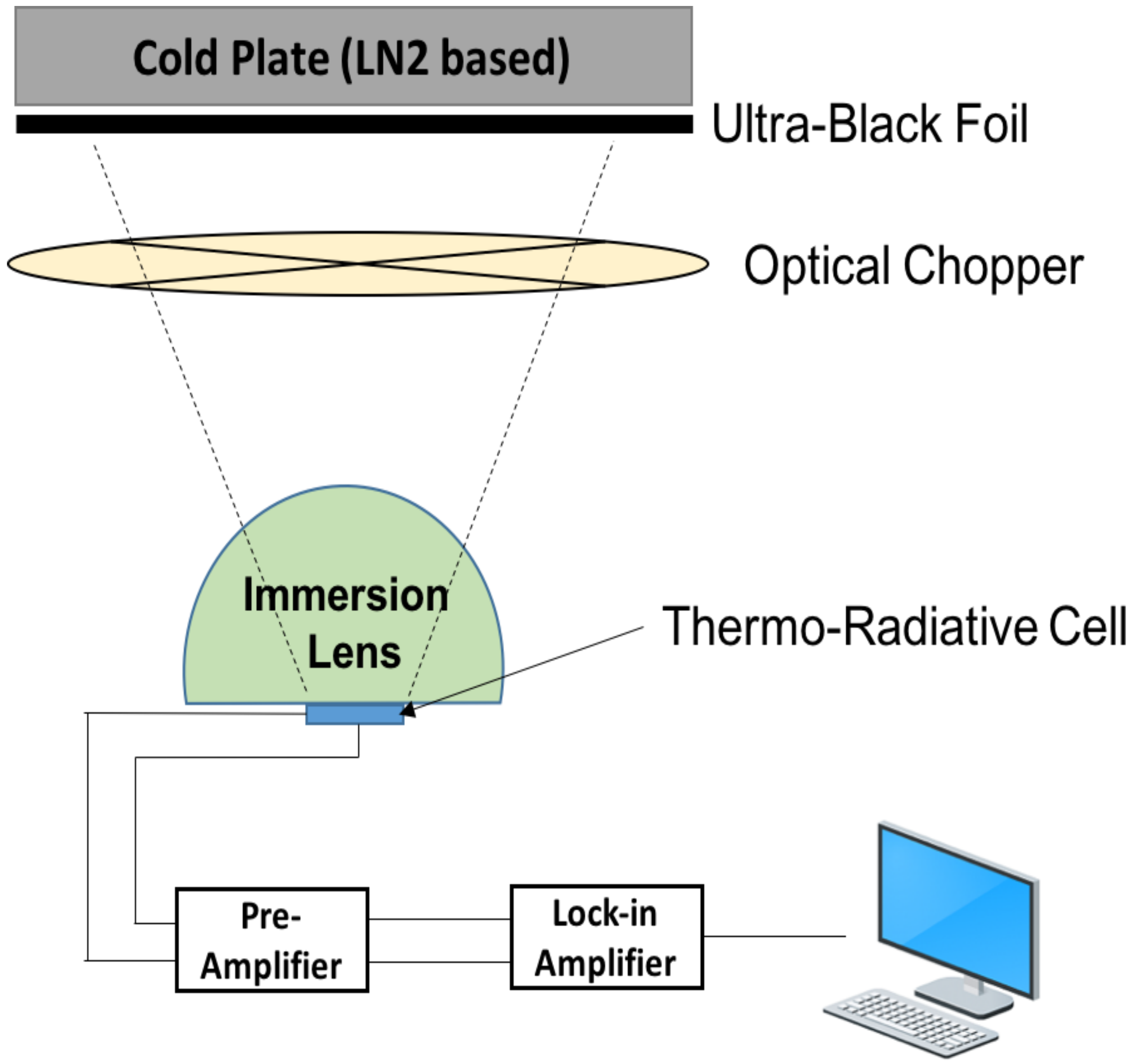
$$\eta = 6\%$$

$$P = 110W_e$$

If we add TR cells on MMRTG fins, assuming the cell temperature is ~175°C, under ideal situation it could:

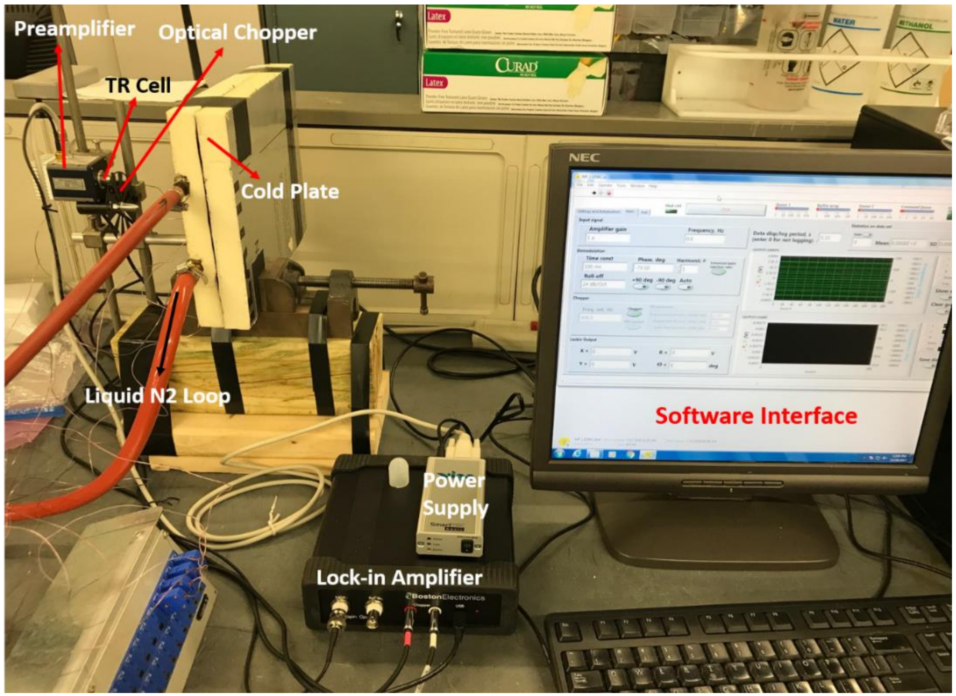
- Provide additional electrical power ~110W.
- Boost the system efficiency from 6% to 12%, while the future e-MMRGT goal is 8%.
- Or it could reduce the Pu-238 weight by more than 50% if still sustain the 110W output.

Schematic Design for the TR Cell Concept Demonstration



Experimental Setup for Proof-of-Concept Demonstration

Complete system setup without chamber



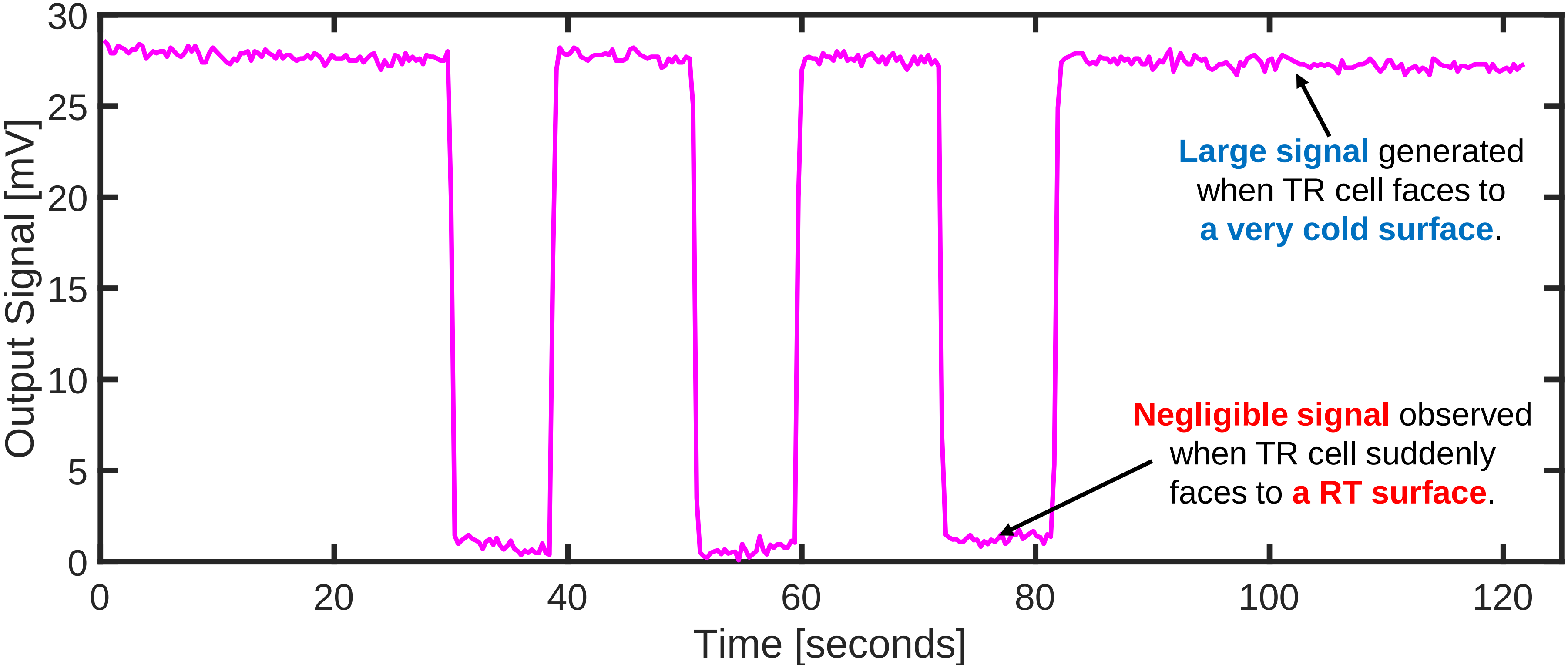
Side View
(within chamber)

Thermo-radiative cell

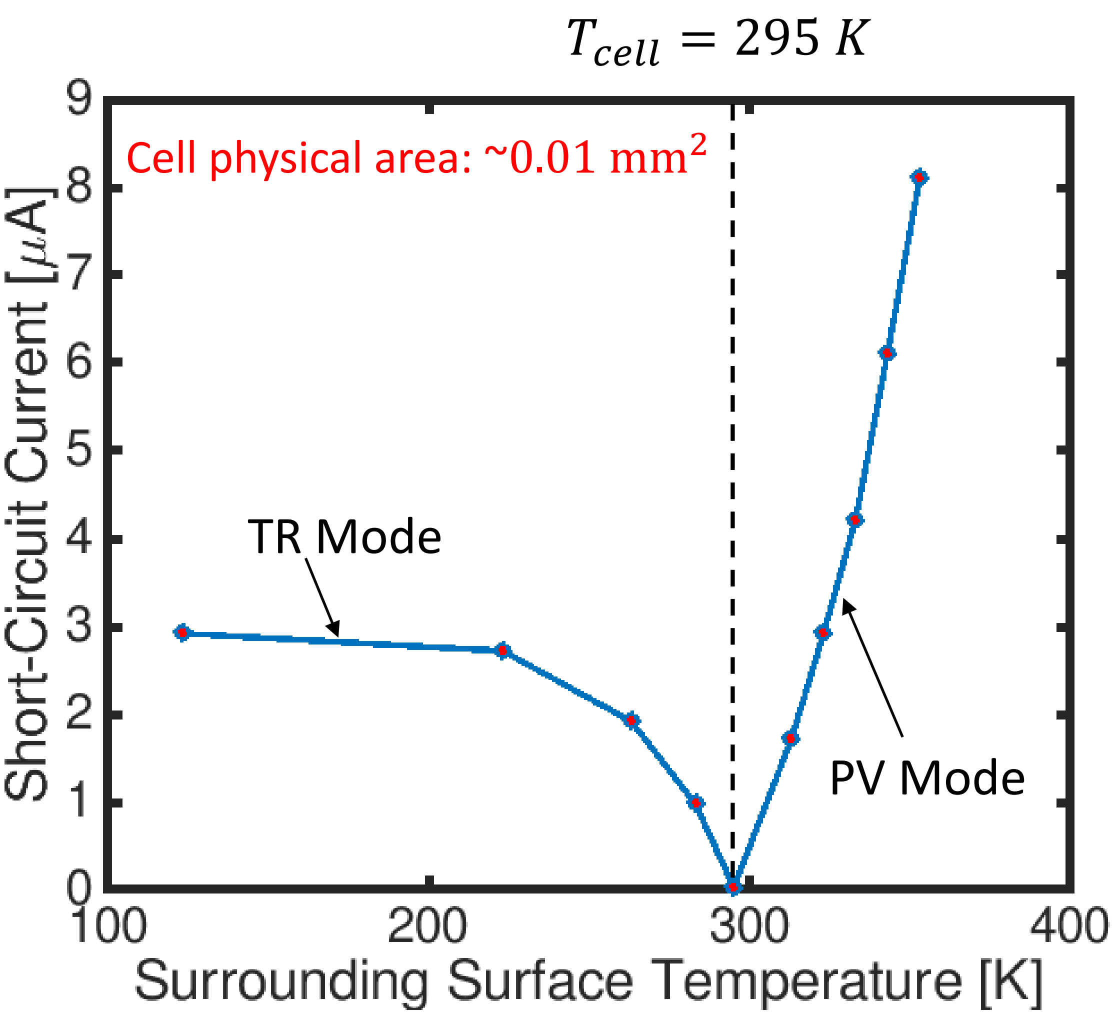
During the tests, the cell (HgCdTe) is placed in a home-built chamber, which is flowed with dry nitrogen to reduce the humidity in the chamber.

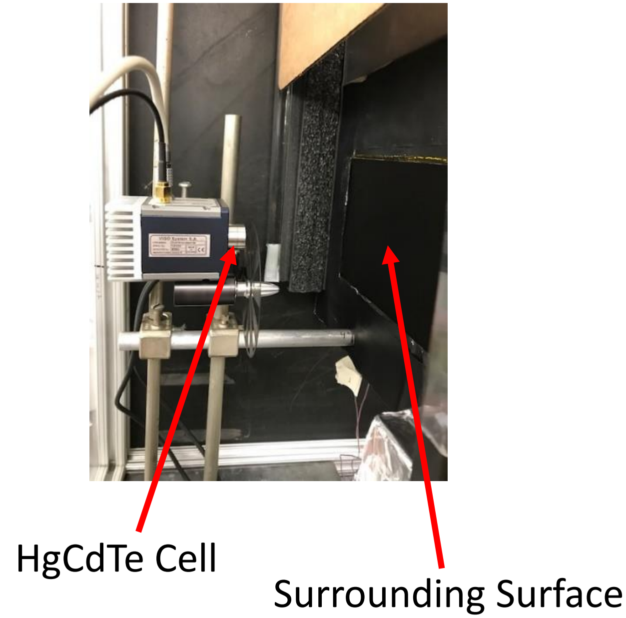
Experimental Results (ON/OFF Response)

An example measurement at -50 ℃



- The cell is kept at room temperature (RT = 295 K)
- The cold plate surface is change from RT to -150 ℃ (TR mode) & from RT to 80 ℃ (PV mode)
- Output signal increases from 0.3 mV to 29.2 mV (TR mode) & from 0.3 mV to 81.1 mV (PV mode)

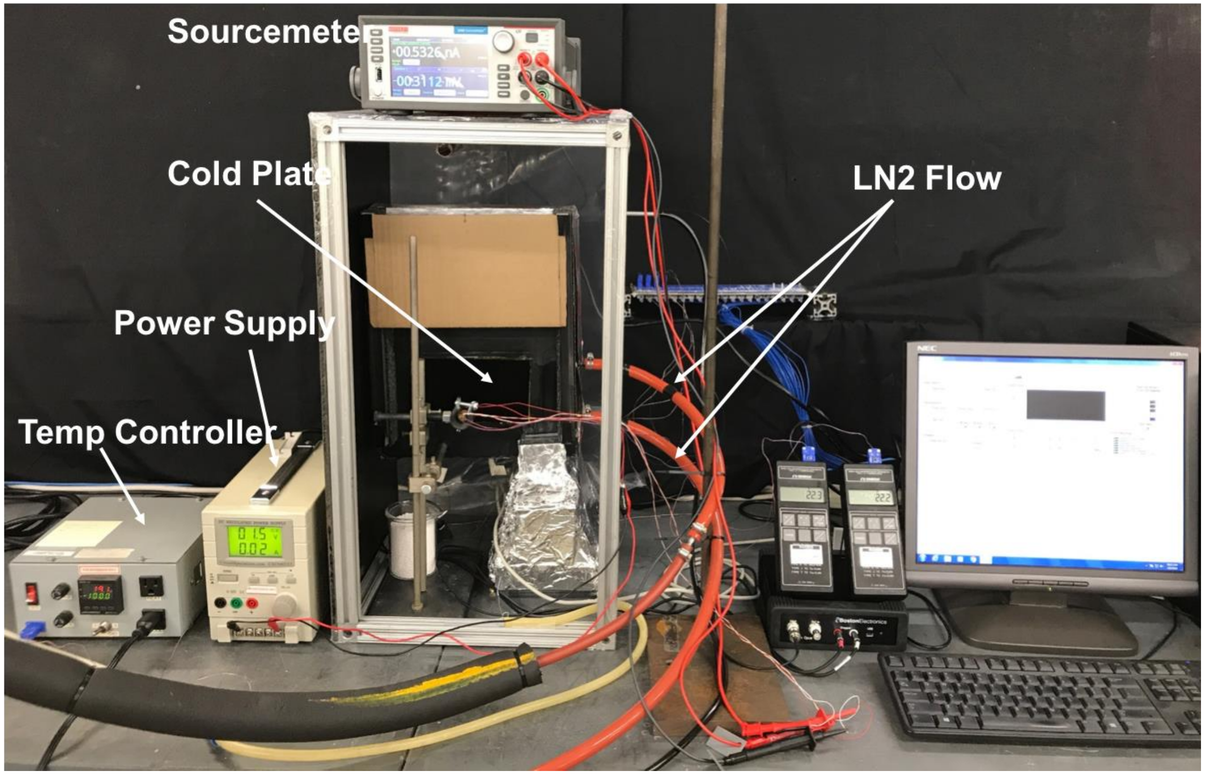


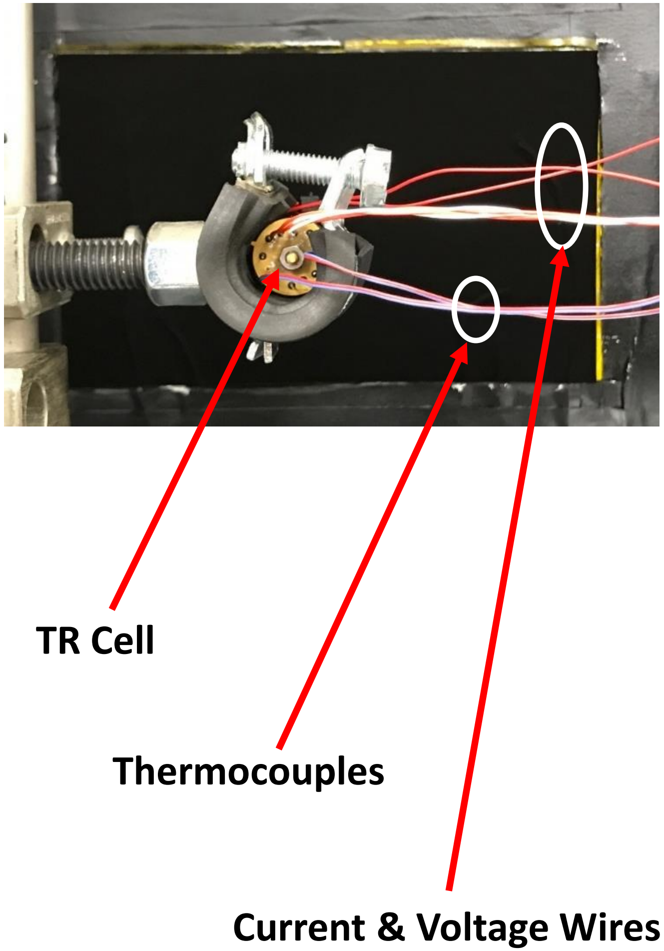


When $T_{surr} < T_{cell}$, it works as Thermo-Radiative cell

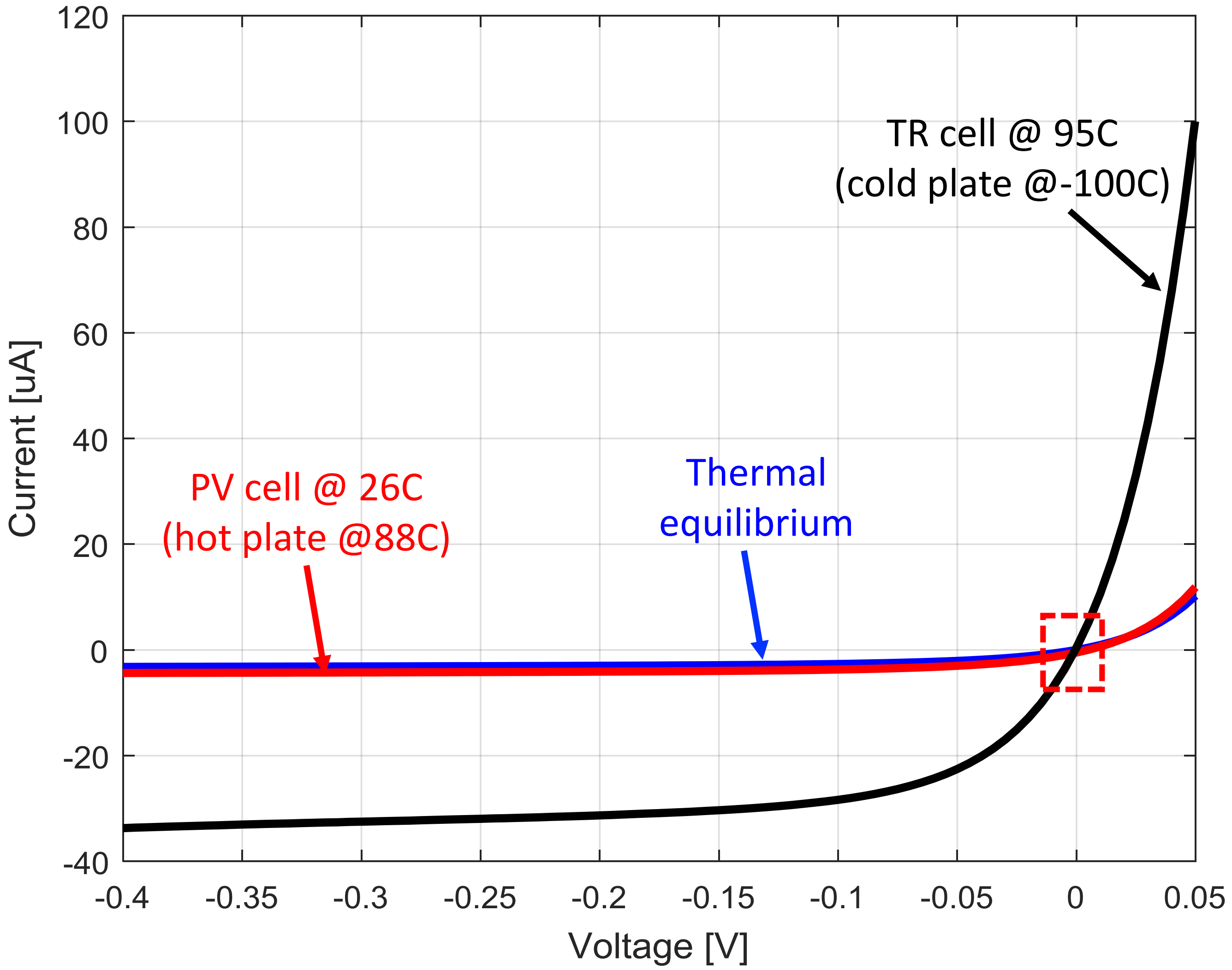
When $T_{surr} > T_{cell}$, it works as Photo-Voltaic cell

I-V Characteristics Measurements

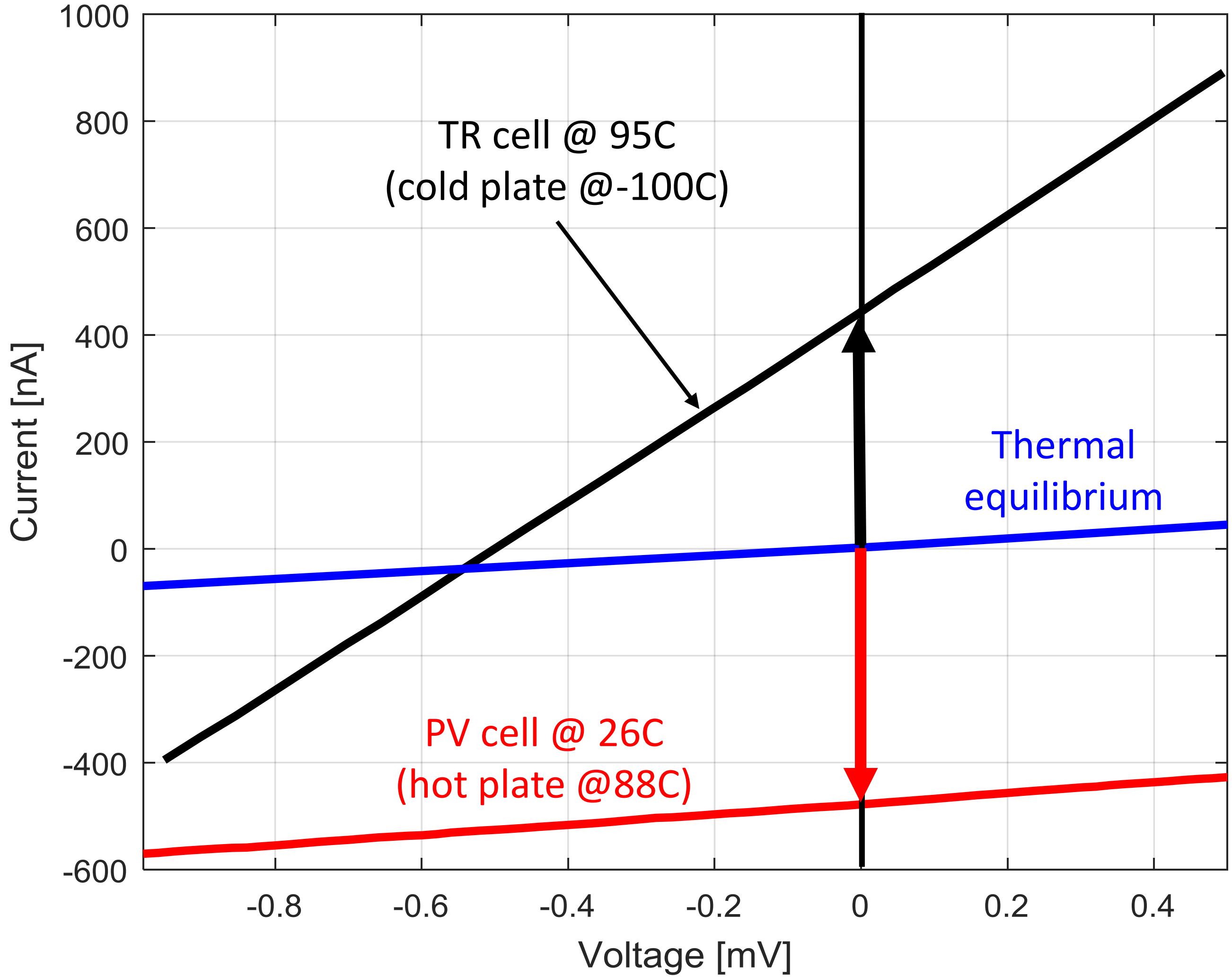




I-V Measurement Results



I-V Measurement Results



Summary and Future Plan

- Our theoretical analysis showed that thermo-radiative cell as a new waste heat recovery technology is extremely suitable for space power applications.
- Combining thermo-radiative cells with RPS could significantly mitigate the stress on the short supply of Pu-238 radioisotope fuel.
- We successfully validated the thermo-radiative cell concept via ON/OFF response demonstration and I-V measurement.
- Plan to fabricate a thermo-radiative cell prototype using 1-watt radioisotope heating unit.

Acknowledgements

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- We would like to thank Wayne Wong of NASA Glenn and Jean-Pierre Fleurial of NASA JPL for their helpful comments and suggestions on integrating TR cells with NASA spacecraft.

- Phil Martin was the laboratory technician who helped on the system setup.

Questions ?

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