ADVANCED COOLING TECHNOLOGIES

The Thermal Management Experts | www.1-ACT.com

ACT Technologies for Radioisotope Power Systems

May, 2018

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Agenda

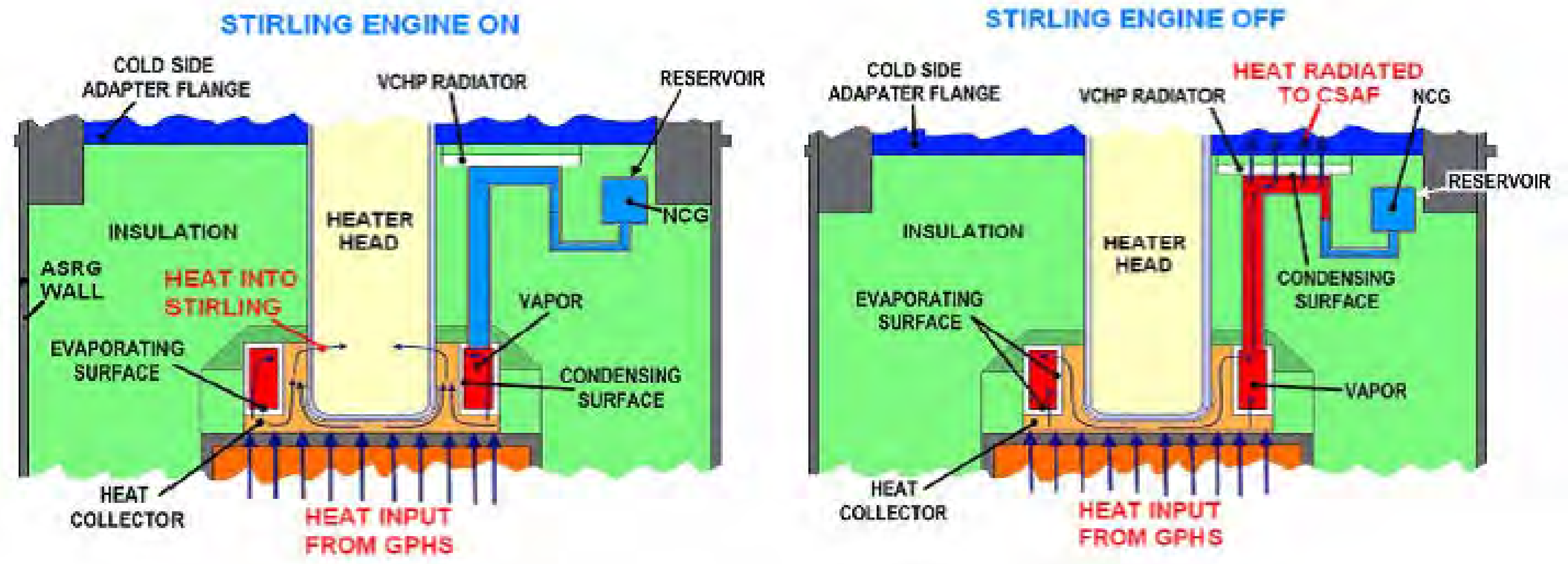
- Alkali Metal Heat Pipes for Radioisotope Systems
- Water Heat Pipes for Radioisotope and Fission Systems
- Waste Heat Recovery by Thermo-Radiative Cell for Radioisotope Applications

Alkali Metal Heat Pipes for Radioisotope Systems

- On a previous Phase II program, ACT developed a Variable Conductance Heat Pipe (VCHP) for Radioisotope Systems
  - Allows convertors to be shut down while loading the GPHS bricks
  - Allows convertors to be shut down to eliminate vibration and electrical interference during scientific measurements
  - Can also be used to reduce hot shoe mass
  - Could be used with other radioisotopes, for shorter term missions
- Have not demonstrated ability to withstand high accelerations
  - 20 g for 1 minute, 5 g for days
- ACT believes that it will be easy to modify for 5 g
- 20 g may not be a problem, due to the thermal capacitance of the system

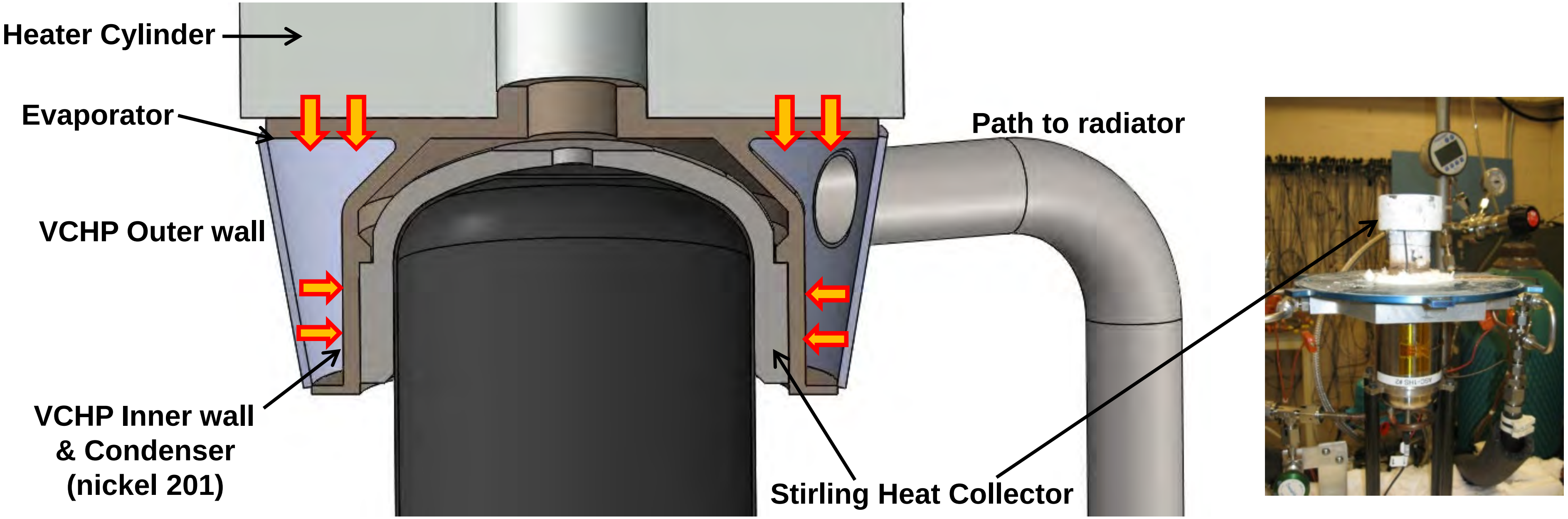
ASRG Backup Cooling Concept

- Normal operation with the Stirling On and VCHP attached is shown in the left picture
  - VCHP transfers heat from the GPHS to the Stirling heater head
- When the Stirling is turned off the VCHP passively rejects the continuous heat generated by the GPHS (right picture) via the radiator
  - VCHP passively rejects this heat to the Cold Side Adaptor Flange (CSAF) with a small increase in the working fluid vapor temperature



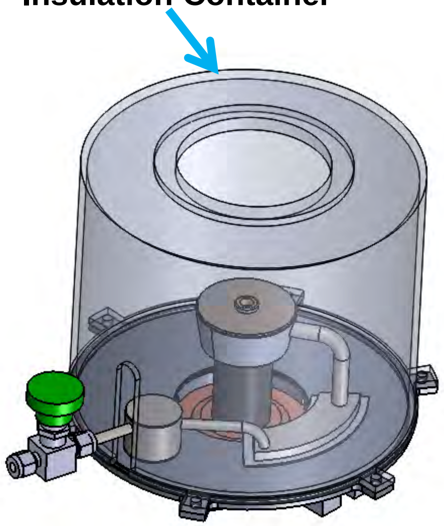
VCHP Prototype Introduction

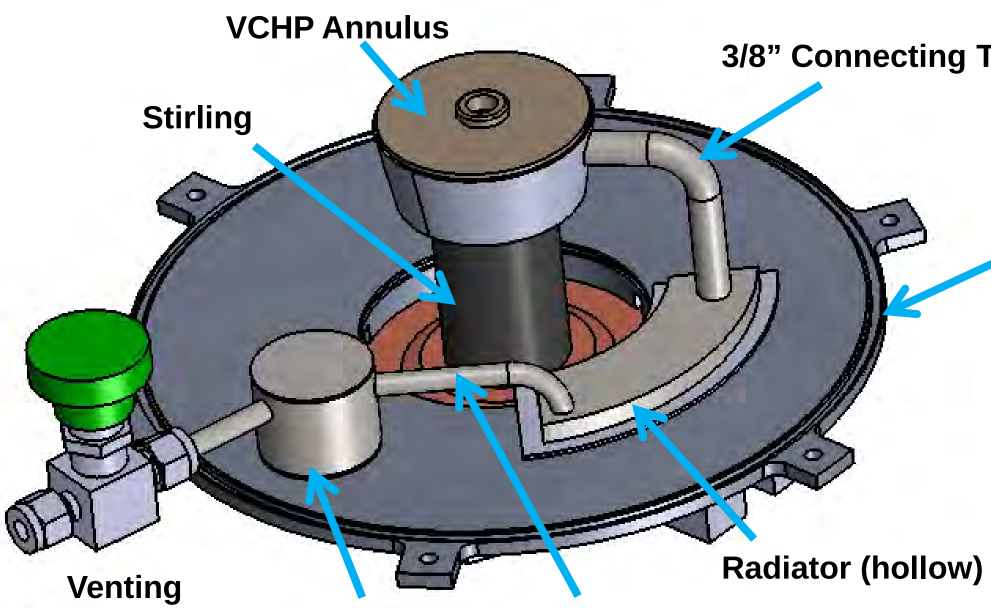
- VCHP annulus slides over the Stirling heat collector
- VCHP transfers heat from the heated cylinder to the Stirling heat collector during normal operation
  - Nominal heat path is shown, the top of the VCHP is the evaporator and the inner wall is the condenser
  - When the Stirling is off the heat /sodium vapor will go down the 3/8” tube on the right to the radiator that rejects to the CSAF assembly

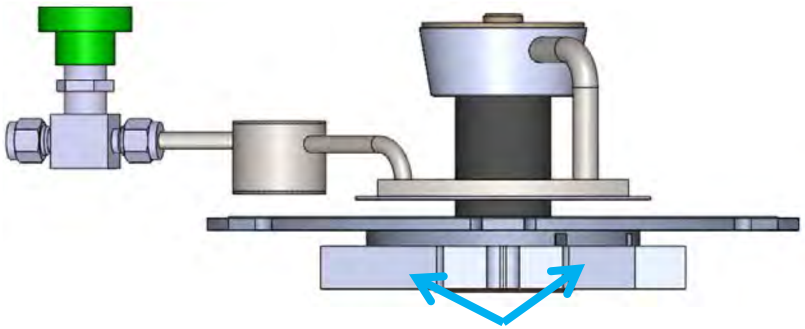


VCHP Layout with Stirling

- VCHP layout shown with the Stirling and CSAF assembly
- VCHP consists of the annulus, 3/8” connecting tube, radiator, ¼” connecting tube and the reservoir
  - All components except the valve are inside of the insulation container (flight ready hardware would not require a valve)





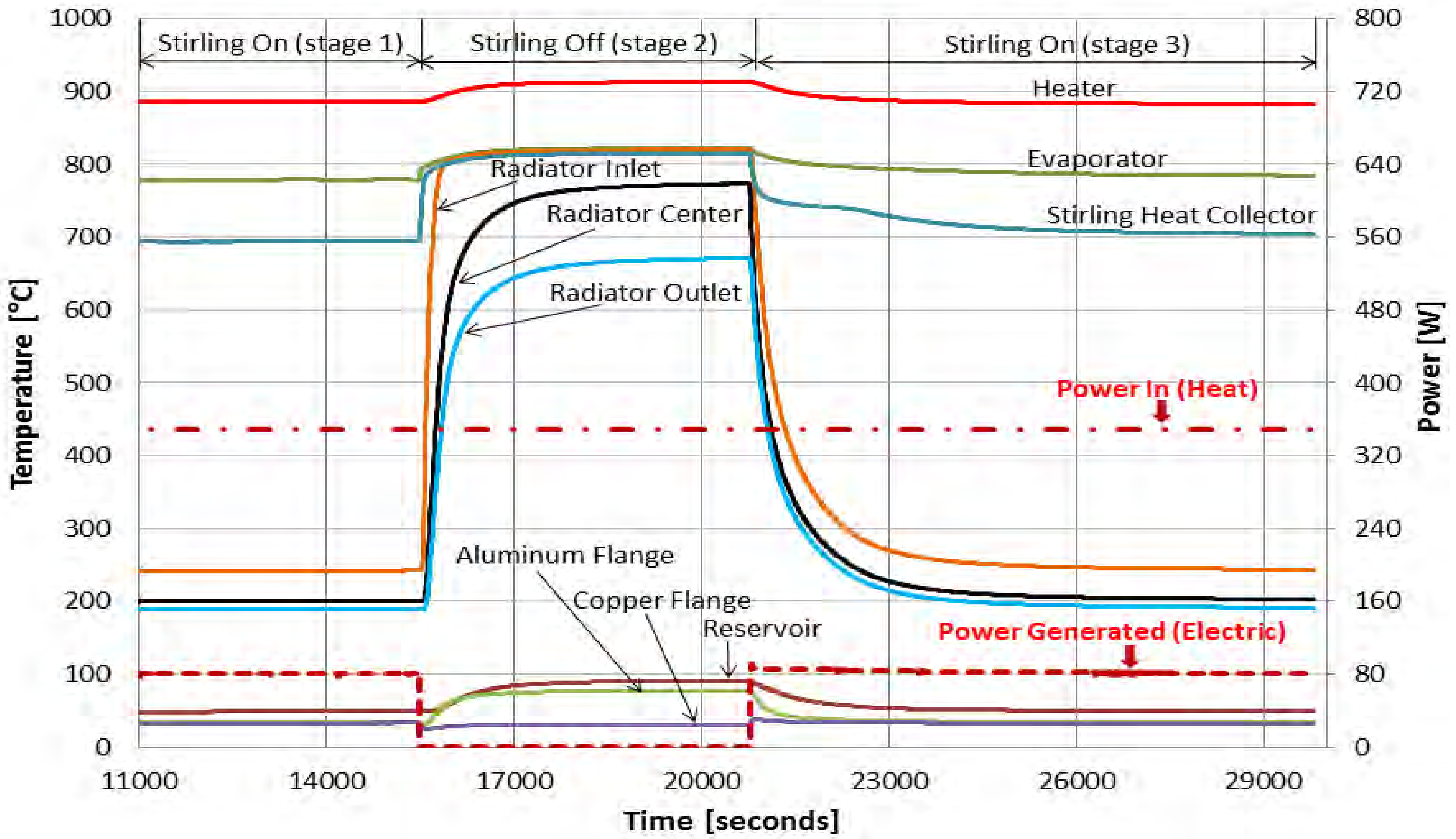


VCHP Mass

- The mass of the VCHP as built (minus the weight of the valve)
  - 0.79 lbs (358 grams)
    - Includes the VCHP body, screen & sodium weight
    - Valve weight is not included as flight ready hardware would be sealed and not required the valve
- VCHP is semi mass optimized to reduce risks during the program
  - Further weight optimization is possible
    - Reduce structural FOS
      - Currently 2+
    - Use superalloys with high strength at high temperatures to reduce wall thickness
    - Thinner two-phase radiator
    - Spherical reservoir

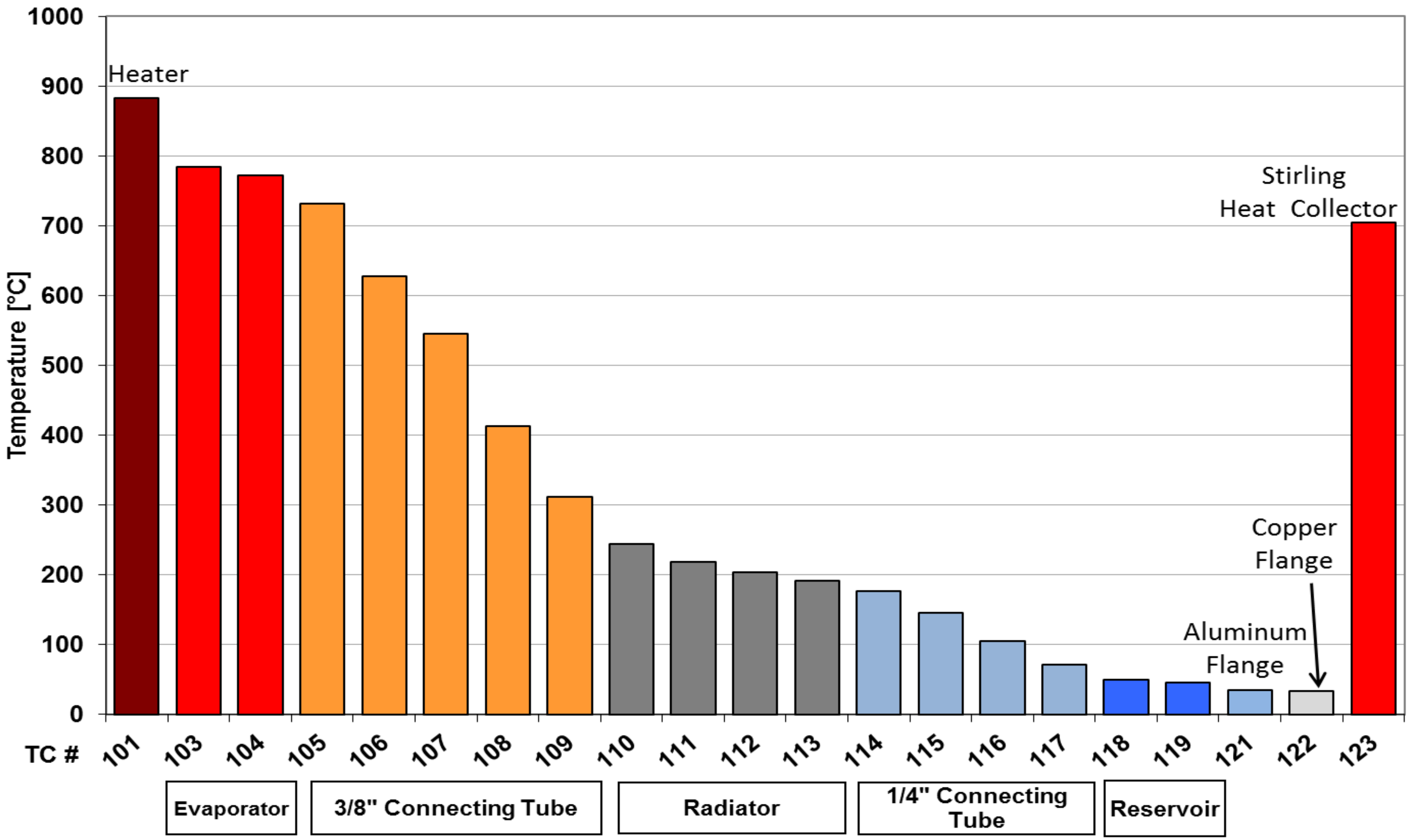
Transient Test Results with VCHP & Stirling Convertor

- Stirling convertor starts on and is cycled off to demonstrate how the VCHP is passively activated and able to bypass the heat directly to the CSAF assembly
  - The Stirling convertor was turned off between 15500 s and 21000
  - The radiator temperature increases to reject the heat directly to the CSAF assembly
  - System recovers well
  - Only parameter modified during testing is turning on or off the Stirling simulator air cooling



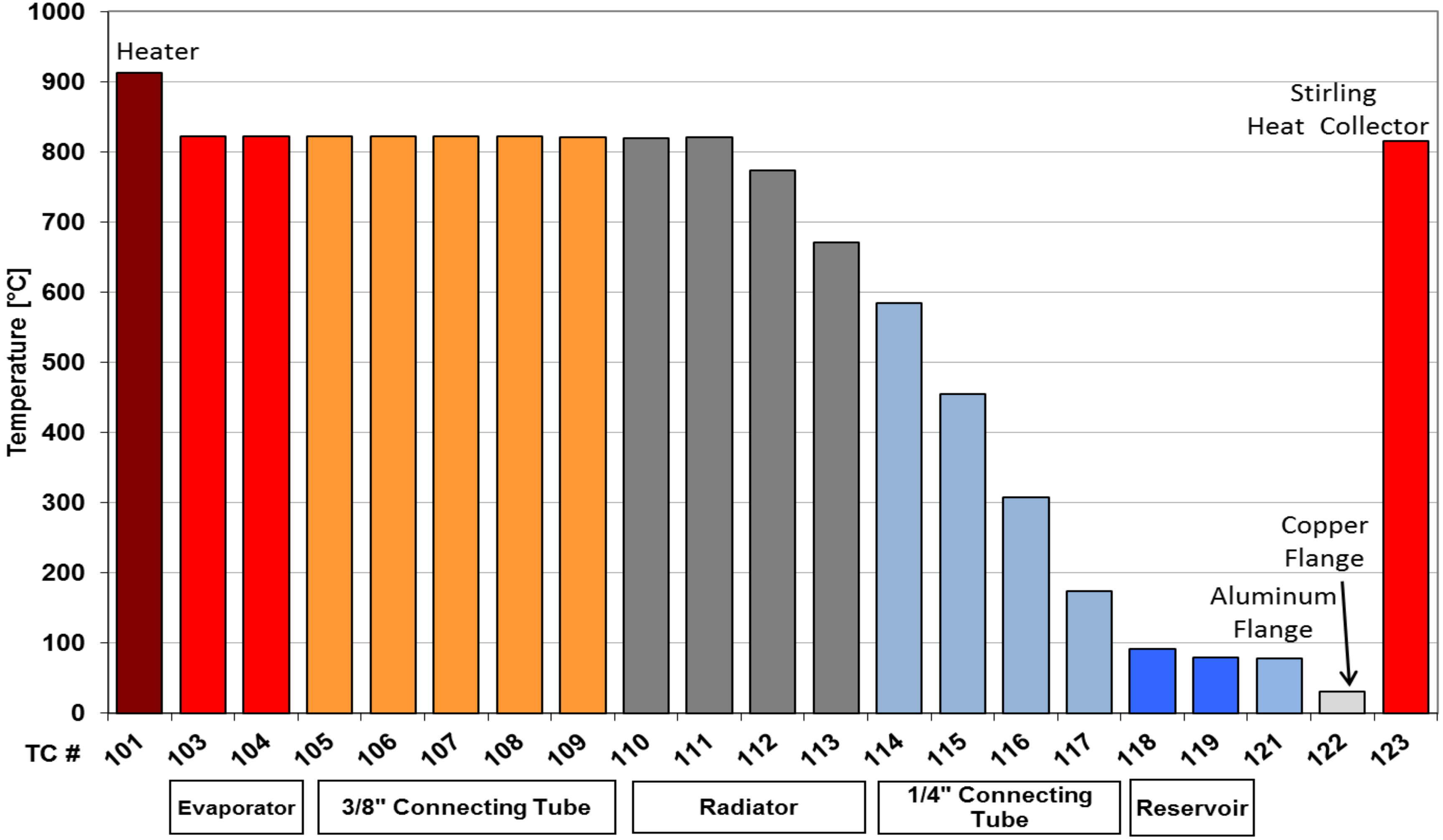
Steady State Results with Stirling Convertor On

- Temperature profile of the VHCP and hardware is shown for steady state conditions with the Stirling simulator On
- NCG front is at the inlet of the evaporator, visible by the sharp drop in temperature at TC 105
- Radiator temp. is significantly lower that the evaporator limiting the unwanted heat transfer through the radiator to the CSAF assembly



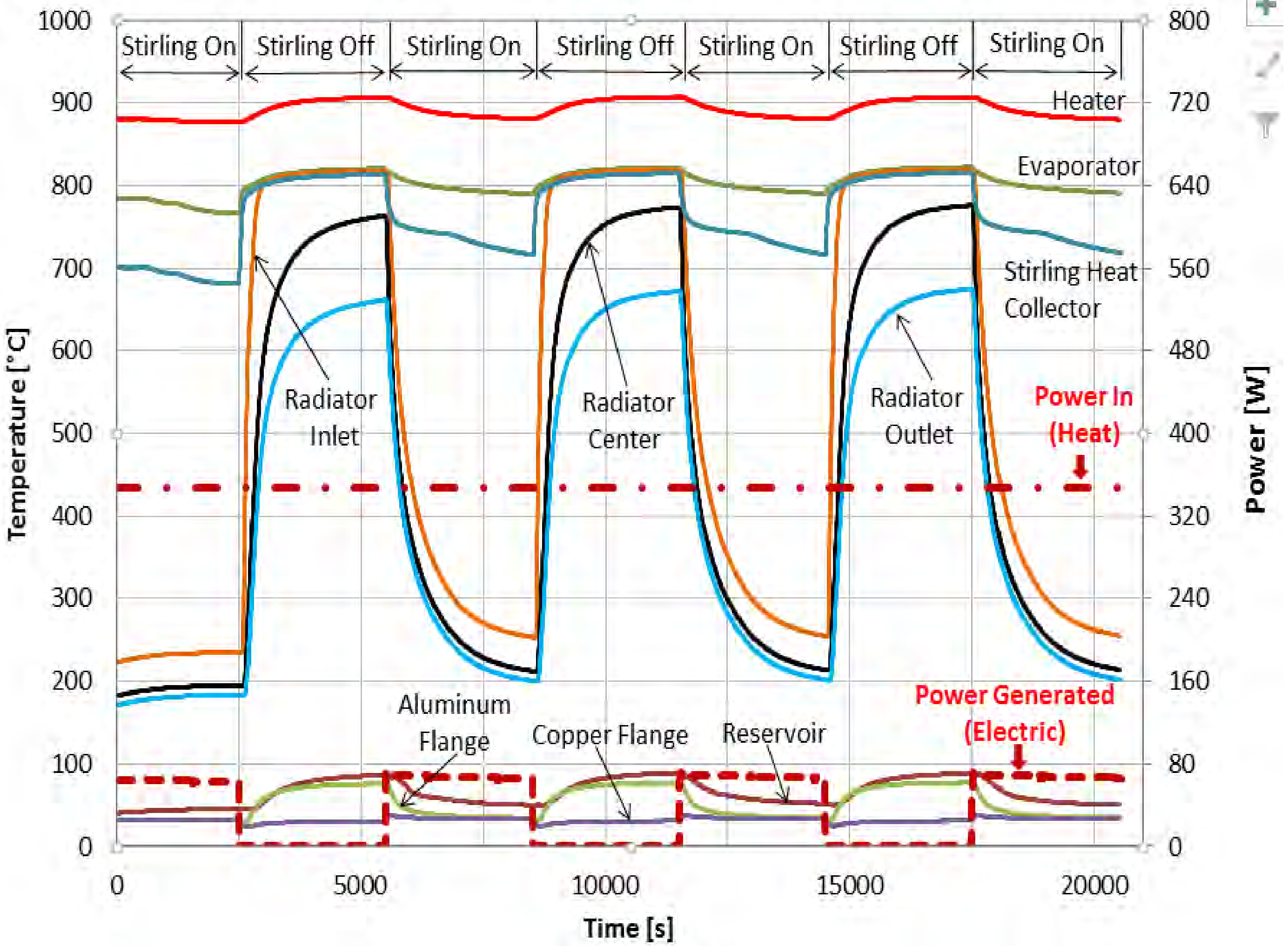
Steady State Results with Stirling Simulator Off

- Temperature profile of the VHCP and hardware is shown for steady state conditions with the Stirling simulator Off
- NCG front is in the radiator, visible by the sharp drop in temperature at TC 112
- Radiator is active rejecting the heat to the CSAF assembly



Transient Test Results with VCHP & Stirling Convertor

- Repeatability of the VCHP-Stirling behavior is shown.
  - Stirling engine was cycled off three times
  - ~5000s was the duration of one cycle
  - The radiator temperature increases to reject the heat directly to the CSAF assembly
  - System recovers well each time
  - Only parameter modified during testing is turning on or off the Stirling simulator air cooling



Agenda

- Alkali Metal Heat Pipes for Radioisotope Systems
- Water Heat Pipes for Radioisotope Systems
- Waste Heat Recovery by Thermo-Radiative Cell for Radioisotope Applications

Water Heat Pipes for Radioisotope Systems

- Al/Ammonia heat pipes are the standard microgravity heat pipe
  - Maximum operating temperature of 80°C
  - Not suitable for radioisotope systems
- Since 2003, ACT has been working with NASA GRC to develop higher temperature heat pipes and radiators for fission power applications
  - Titanium/Water and Monel/Water, operating at temperatures up to 270°C
  - Life tests at 270°C for 7 years successfully completed
  - Analysis by GRC showed no problems
  - >> 20 year life at radioisotope system operating temperatures
  - Water heat pipes now have flight heritage
  - Can survive thousands of freeze/thaw cycles

Water Heat Pipes for Radioisotope Systems

- Also have developed low-mass, high-performance radiators
  - Graphite Fiber Reinforced Composite GRFC (up to twice the thermal conductivity of aluminum)
  - Pipes to the right are gravity aided thermosyphons
- With a screen wick, can operate 25 cm against 1 g
  - Suitable length for a radioisotope system
- Can embed small heat pipes in plates to boost conductivity
  - 600 to 1200 W/m K for aluminum
- Could be used in radioisotope systems at higher g, if arrange so that some of the heat pipes are gravity aided.

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Thermo-Radiative Cell Overview

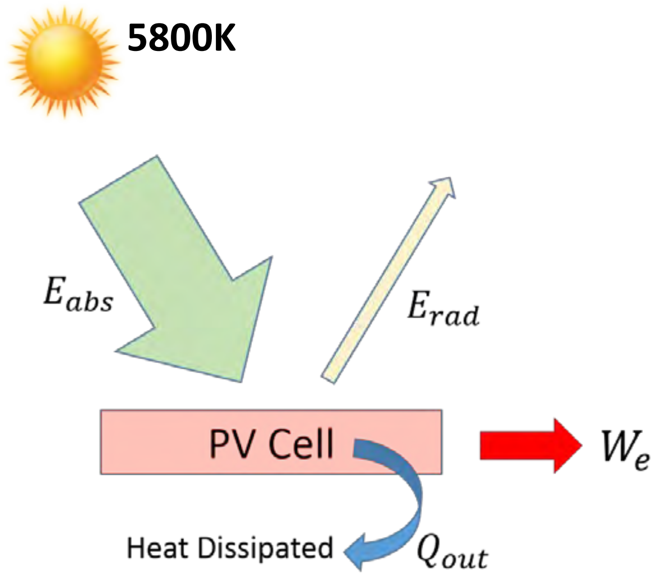
- We have developed a new concept for converting waste heat to electricity suitable for applications that radiate to deep space
- The technology works similar to a photovoltaic cell, but instead of generating electricity during photon absorption, electricity is generated during photon emission
- Modeling results to date show that you can get considerable additional power output without increasing the system weight and thermal resistance, when integrating TR cell and Hi-K plate in ASRG
- We have validated the concept and want to discuss the integration of system with Radioisotope Convertor experts

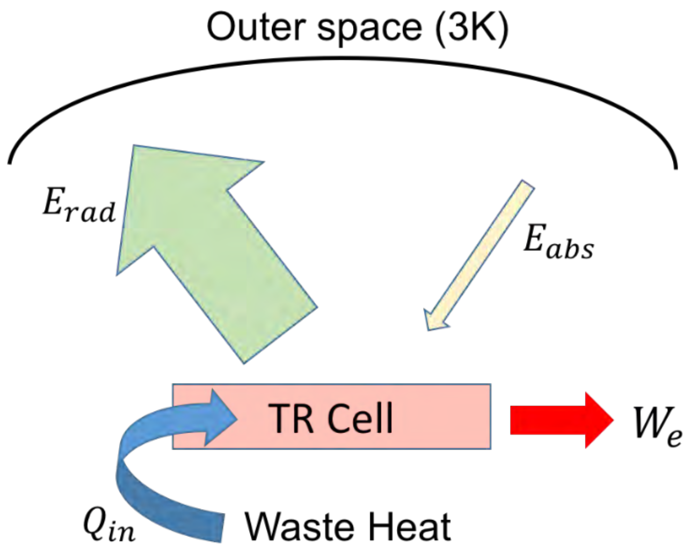
How to efficiently make use of the space waste heat?

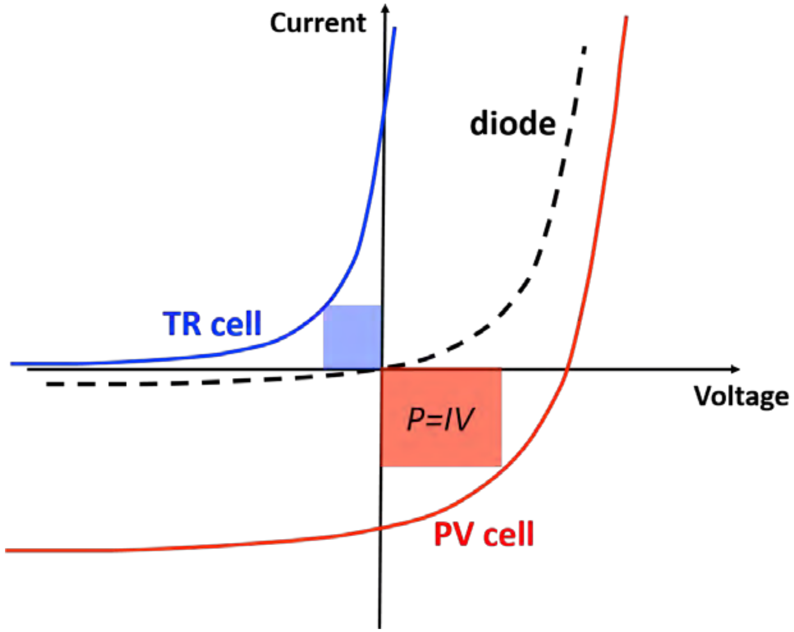
- Radioisotope Convertors: waste heat around 100-200°C.
- In space, dark universe (3K) could provide a robust heat sink.
- The communication between the heat source and heat sink is radiation.

Thermo-Radiative Cell

Thermo-Radiative (TR) Cell Concept

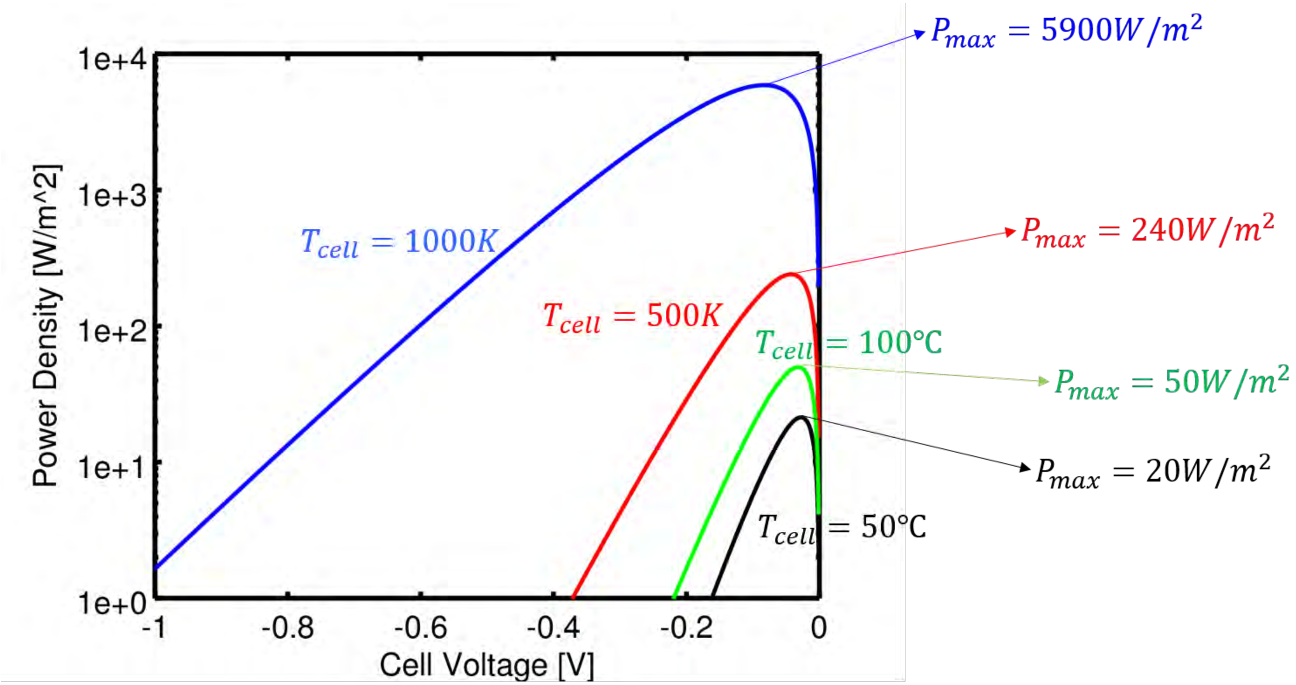




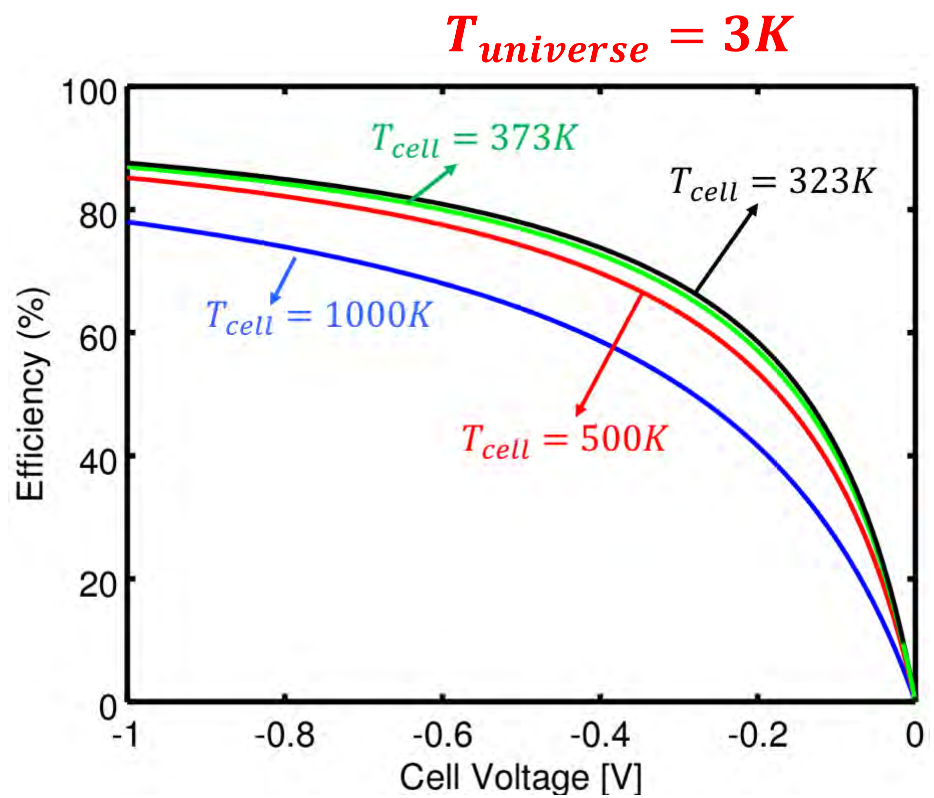


- Thermo-radiative cell was proposed by R. Strandberg (*JAP*, 2015)
- Net photon flux: from cell to environment (TR cell) *vs.* from environment to cell (PV cell)
- Generated current and voltage directions in TR cell are opposite to the PV cell
- TR cell is anticipated to have better performance at high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

Thermo-Radiative Cell Performance

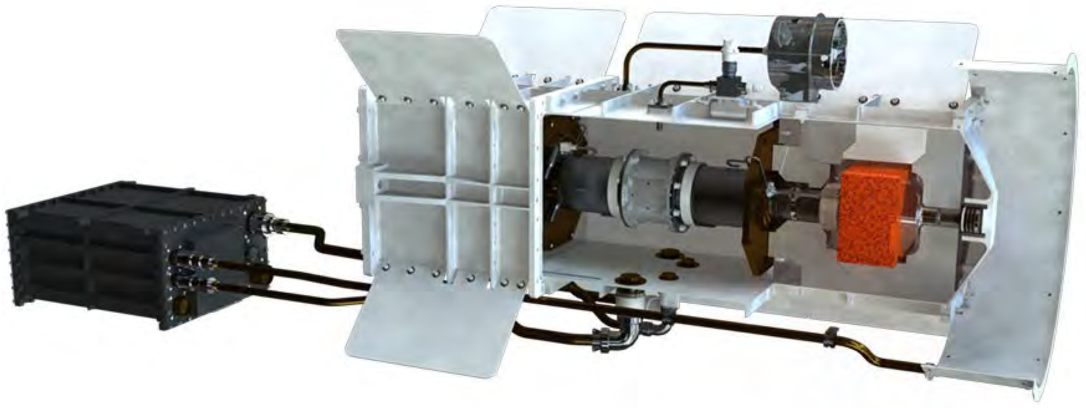


Cell bandgap 0.1eV

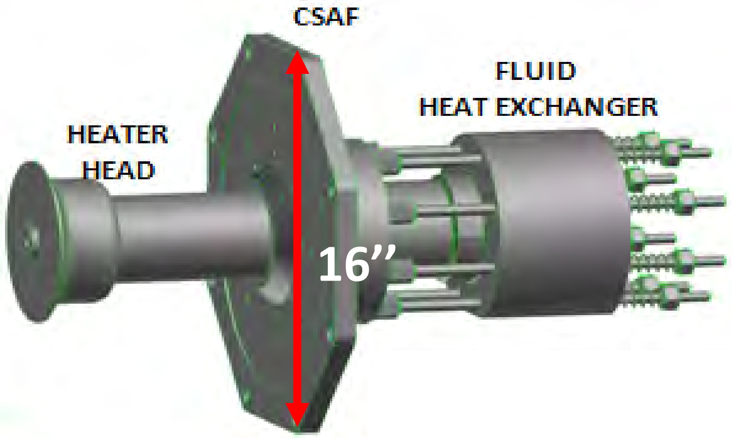


- The power density of TR cell increases rapidly with temperature.
- Predicted efficiency at peak power is 18%, almost 3X of MMRTG. Could be much higher at lower power output.

If Integrated with ASRG



ASRG Dimension: 76cm * 46cm * 39cm



- Waste heat is conducted from CSAF to the Beryllium housing.
- Current CSAF is made of Copper (TC=400 W/mK)
- Thickness of the CSAF is about ¼''
- Inner diameter: 4''
- CSAF height: 16''
- Four of the 8 edges is in contact with Beryllium housing.

** Some parameter values are based on estimation.*

Performance Improvements When Integrated with ASRG

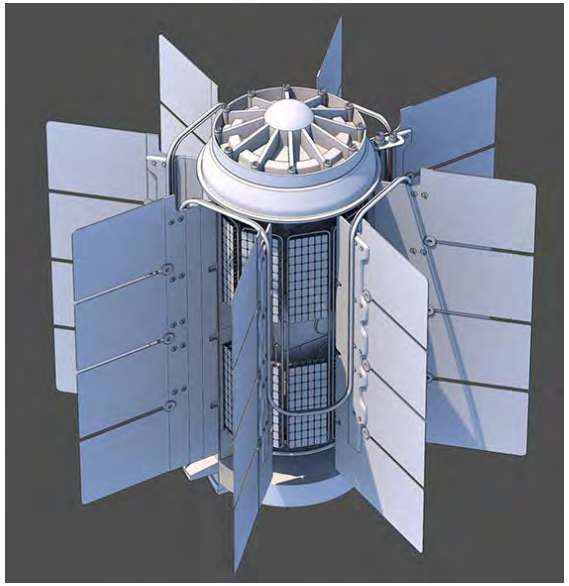
	Current ASRG
Hot Side	850℃
Cold Side	130℃
Efficiency	30%
Two GPHS	2*250 W
Each CSAF Dissipates	175 W
Edge of CSAF Temperature	113℃ (simulation)
CSAF R_{th}	0.097 $℃/W$
Beryllium Housing & Fins R_{th} (including radiation)	0.629 $℃/W$

- We could integrate the TR cell on top of the Beryllium housing, and replace the copper $(400W/mK)$ by Hi-K plate $(1200W/mK)$ to make the CSAF.
- The surface emissivity of TR cell can be fabricated to be ~0.85, similar to the Beryllium housing emissivity. No or negligible change on the radiation thermal resistance.
- Using Hi-K plate to make CSAF can reduce R_{th}^{CSAF} from 0.097 $℃/W$ to 0.032 $℃/W$. The total thickness of TR cell is 1/4" (including TIM layer). The addition of conduction resistance by TR cell (~10W/mK)is much smaller than the reduction of CASF resistance by Hi-K plate.

Conclusion: 1) Cold side temperature of ASRG will even be decreased if we use Hi-K plate to make CSAF.
2) The weight increase by TR cell will be offset by weight reduction of using Hi-K plate.
3) And ASRG system will get additional 45W power output by TR cell integration

Performance Improvements When Combined with MMRTG

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



MMRTG

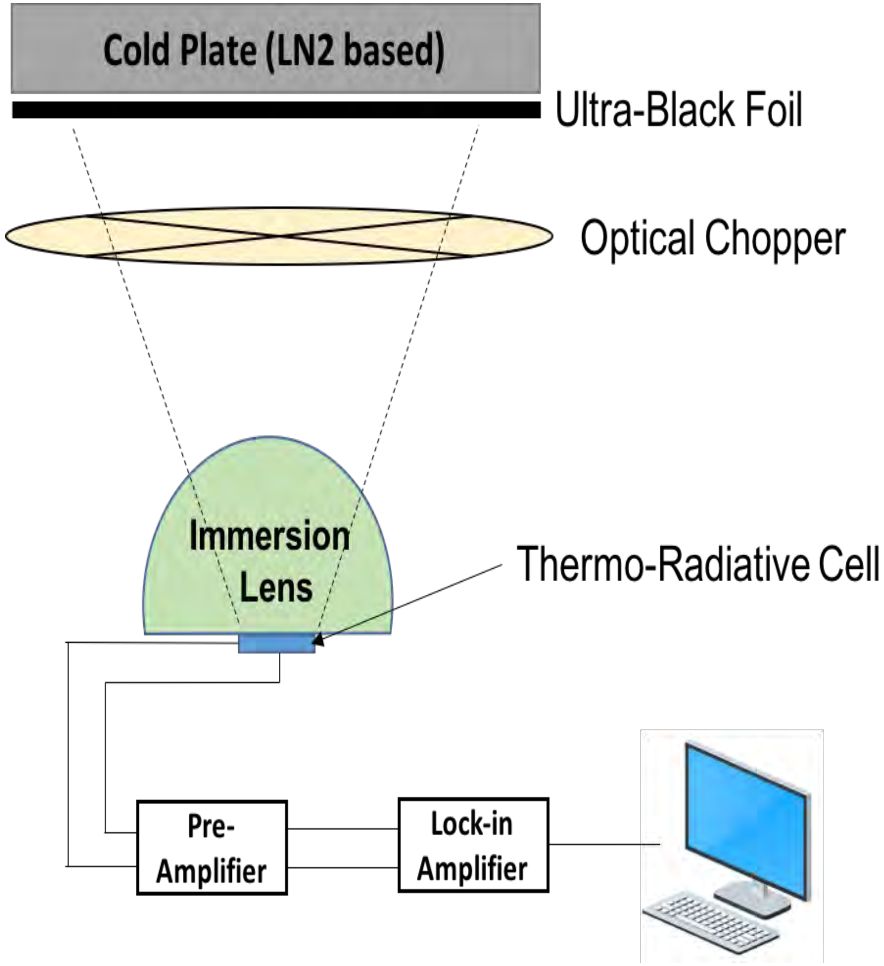
$$T_{hot} = 530°C$$
$$T_{cold} = 200°C$$
$$m_{Pu-238} = 3.5kg$$
$$\eta = 6\%$$
$$P = 110W_e$$

If integrate TR cells with MMRTG fins, assuming the cell temperature is ~450K, under ideal situation:

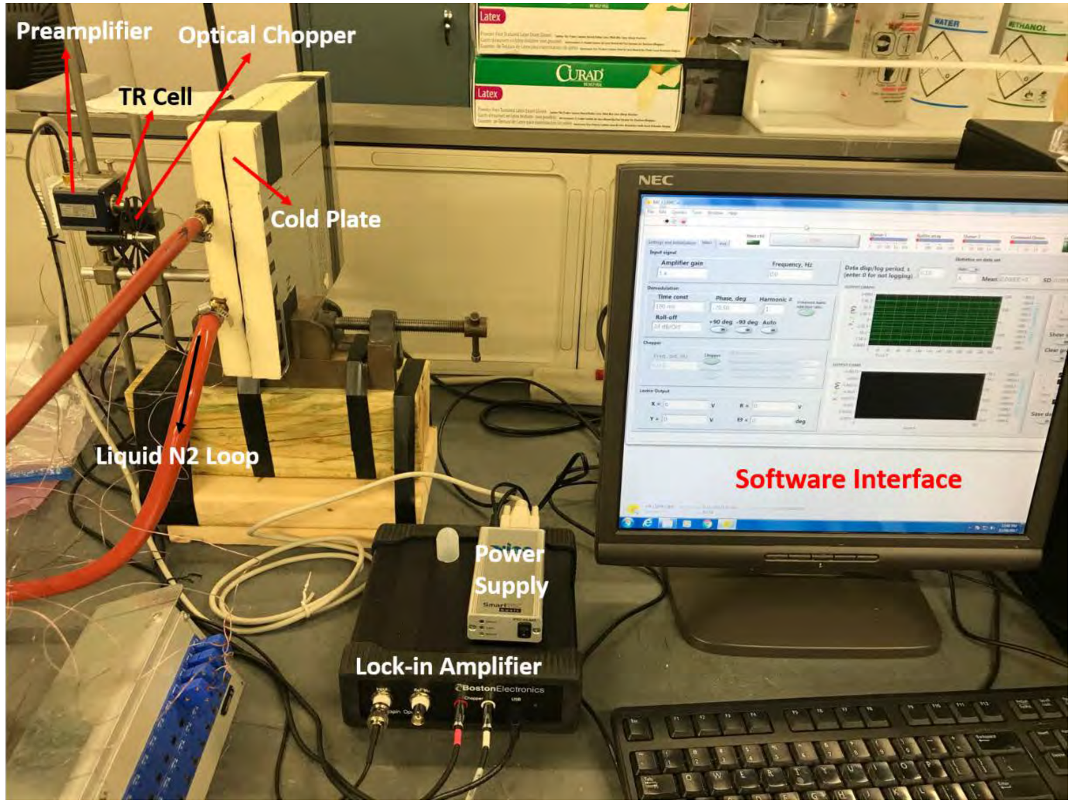
- It could provide additional electrical power ~110W.
- It could boost the system efficiency from 6% to 12%, while the future e-MMRGT goal is 8%.
- Or it could reduce the Pu-238 weight by more than 50% if still sustain the 110W output.

It could also be integrated with mW-class Radioisotope Heating Unit (mW-RHU).

Proof-of-Concept Demonstration



Whole system setup without chamber



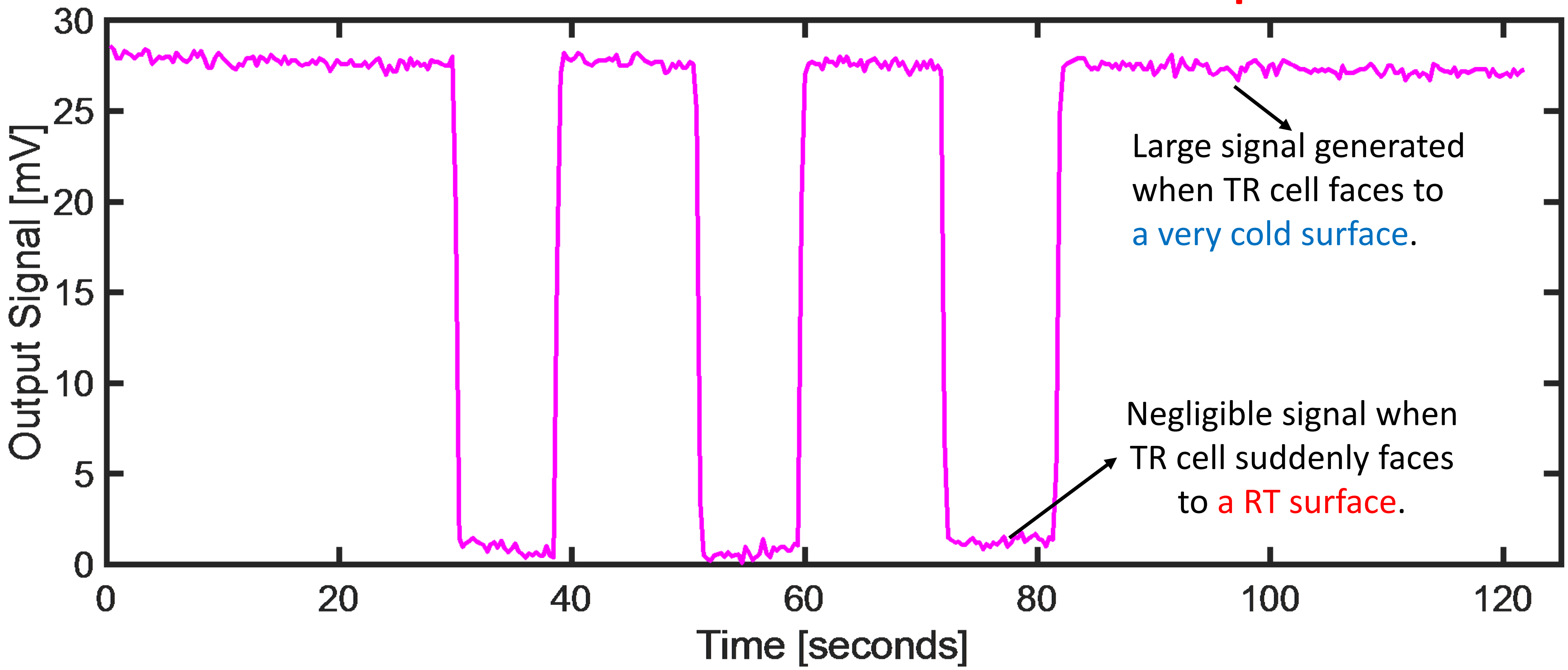
Side View (within chamber)

Thermoradiative cell

During the tests, the cell (HgCdTe) is placed in a chamber, which has a low flow of dry nitrogen to reduce the humidity in the chamber.

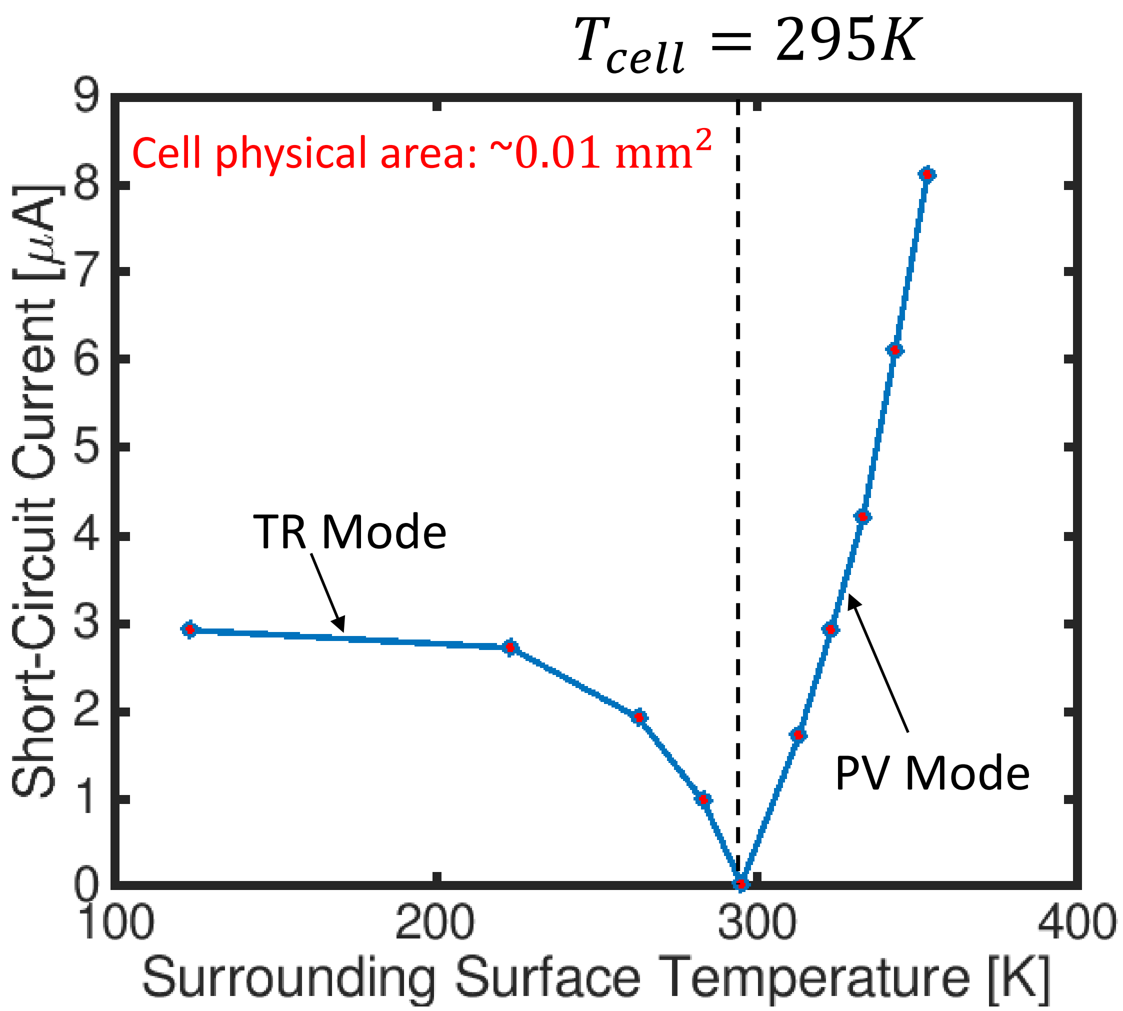
Experimental Results (ON/OFF Response)

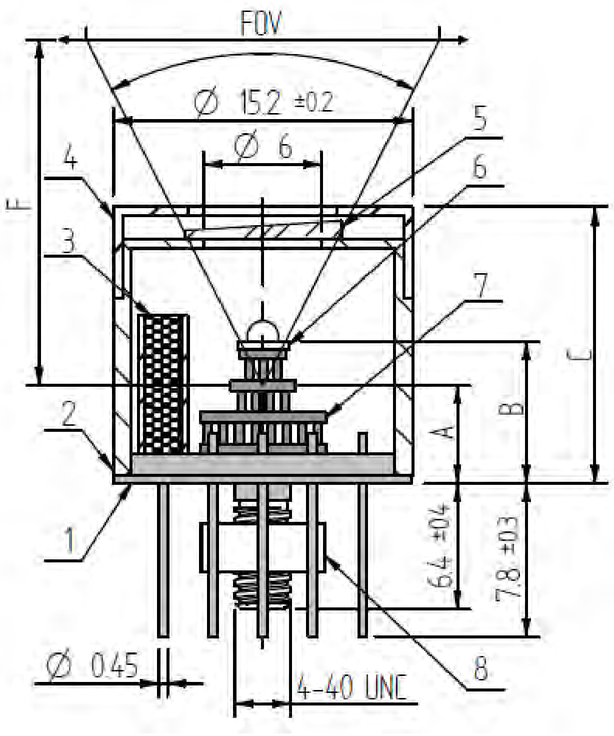
Example measurement at -50℃



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

Measured Photocurrent in the Cell

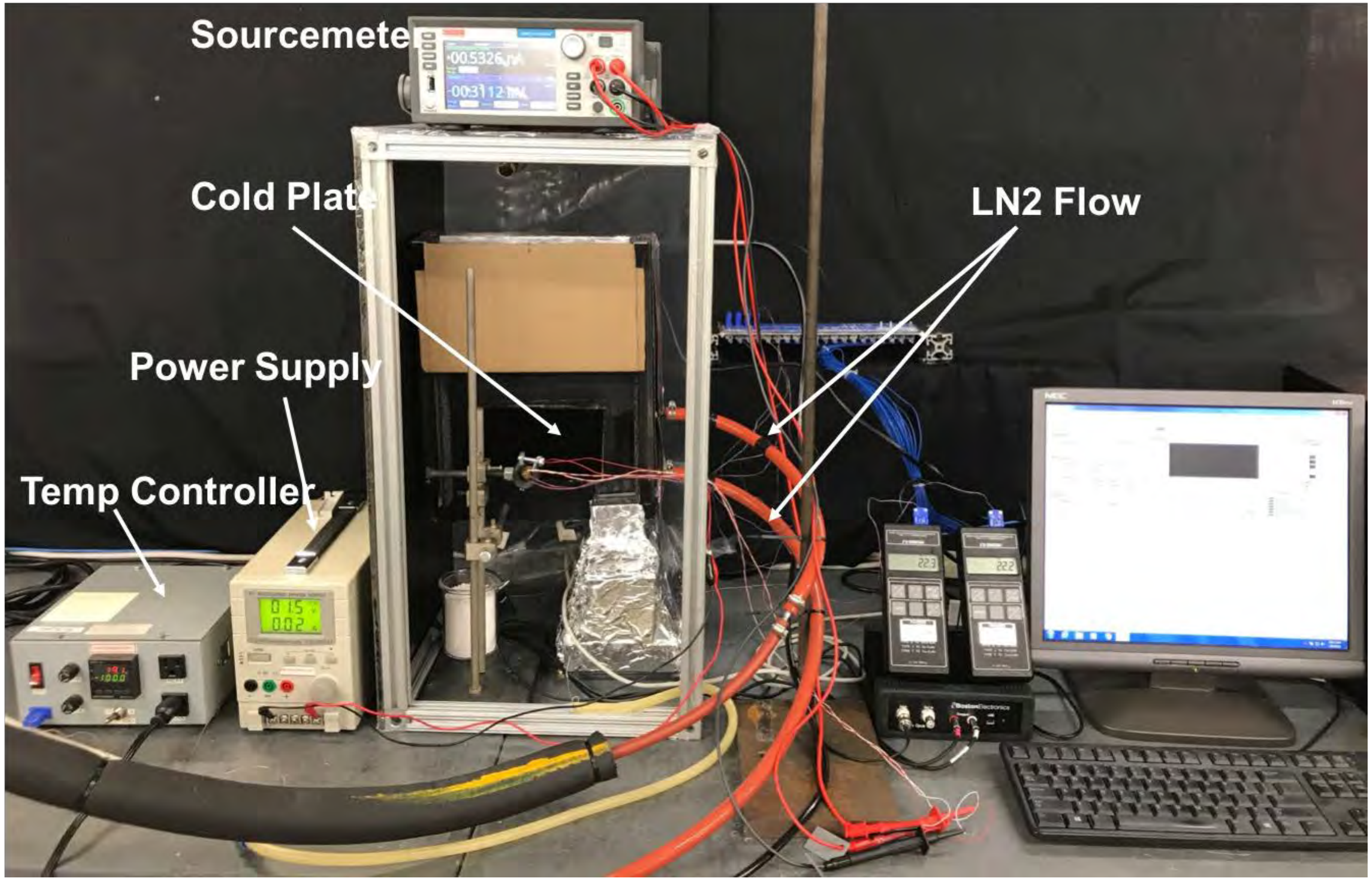


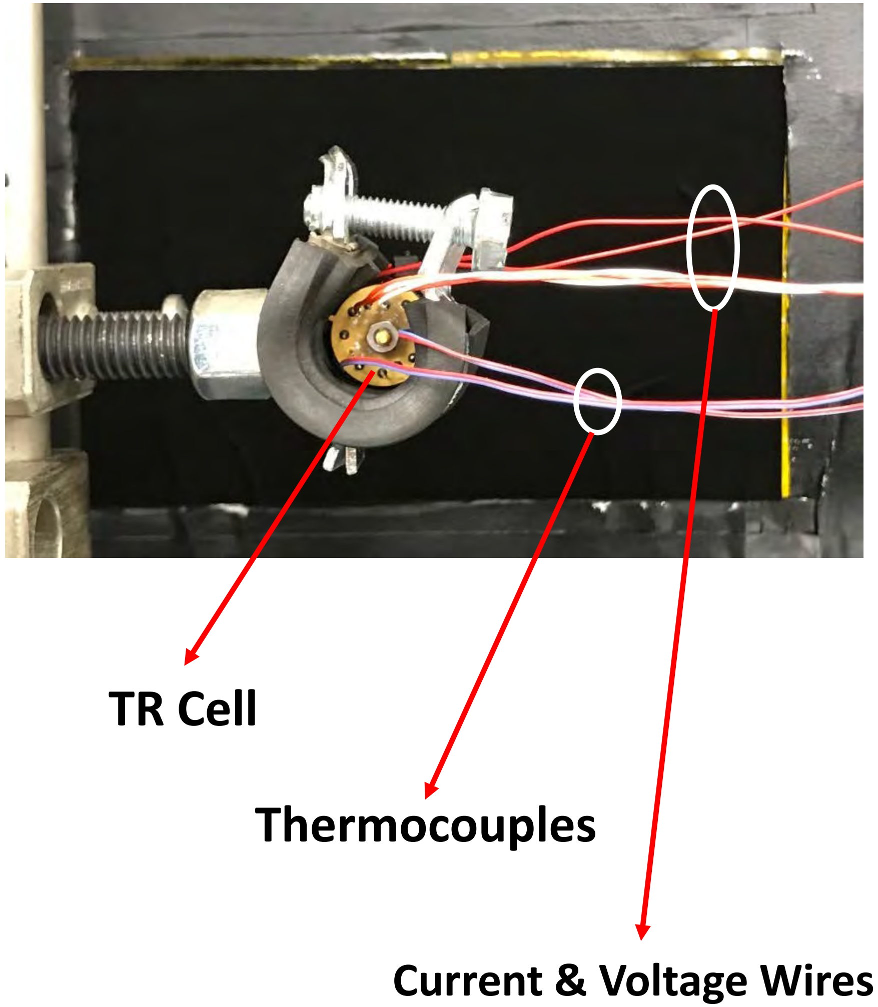


When $T_{surr} < T_{cell}$, it works as
Thermo-Radiative cell

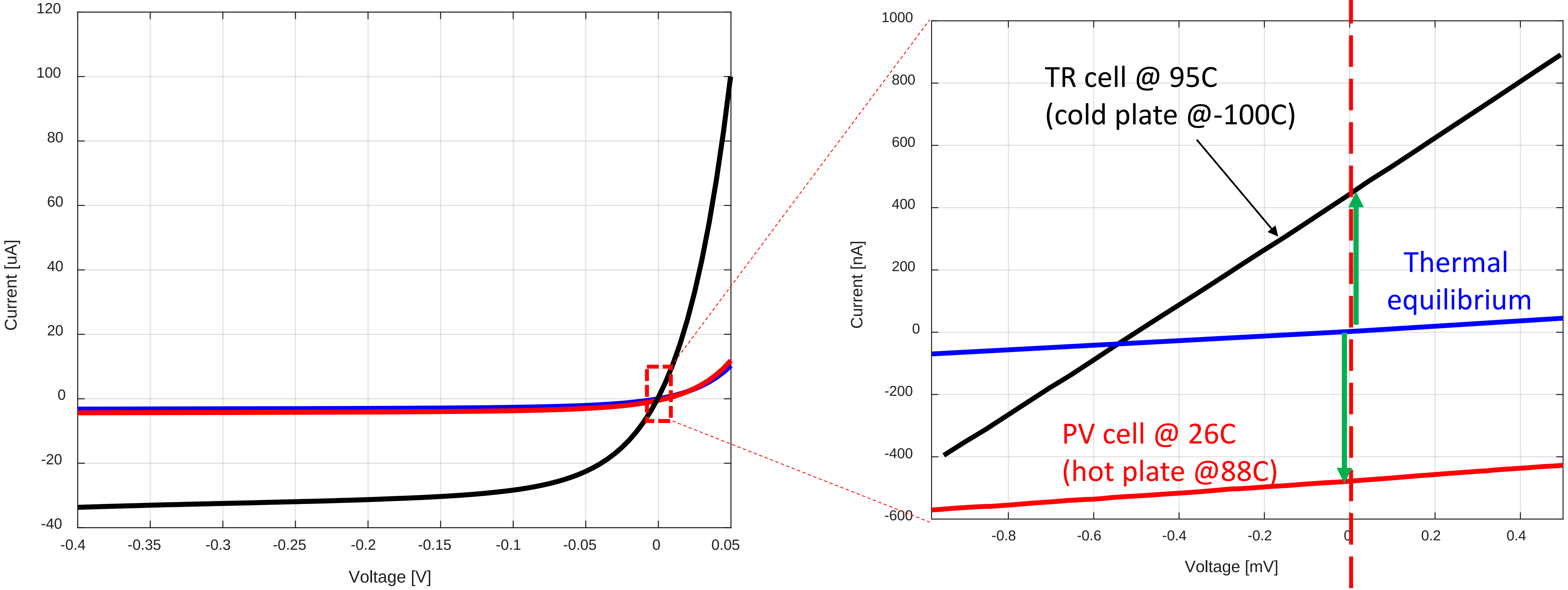
When $T_{surr} > T_{cell}$, it works as
Photo-Voltaic cell

I-V Characteristics Measurements





I-V Measurement Results



The TR cell short-circuit current is around 450nA, much smaller than previous 3μA, due to the larger band gap of the cell.

Discussion

- We successfully demonstrated the validity of thermo-radiative cell concept via ON/OFF response & I-V measurement.
  - Currently at TRL 3
- Short circuit current increases from 60nA to $3\mu A$ when the bandgap of cell (ambient condition, $0.01\mathrm{mm}^2$) changes from 0.32eV to 0.21eV.
- $Hg_{1-x}Cd_xTe$ p-n junction is used in our demonstration. Bandgap can be tuned between 0-1.5eV, depending on x. However, material fabrication may be challenge.
- Plan to optimize the cell performance and fabricate a larger TR cell prototype (Ø.5”) if we get Phase II funding.
- Looking for support from NASA
  - No communications with COTR

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