Ultra High Temperature Thermionic Sensor

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NETL Crosscutting Research Review Meeting

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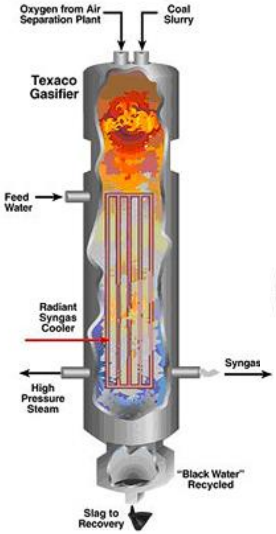
HEAT Sensor Project Goal

Harsh **E**nvironment **A**daptable **T**hermionics

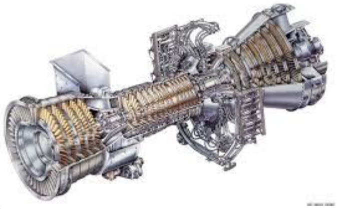
- **Develop sensors that measure process parameters**
  - Gasifiers -- harsh fuel, oxidizer and combustion product environment
  - High Temperature (750-1600 C)
  - High Pressure (up to 1000 psi)

- **Develop sensors that are wireless and self-powered**
  - Generate their own energy to operate and wirelessly transmit data
  - Avoids wires that may be a reliability or inconvenience concern

Source: GE Energy



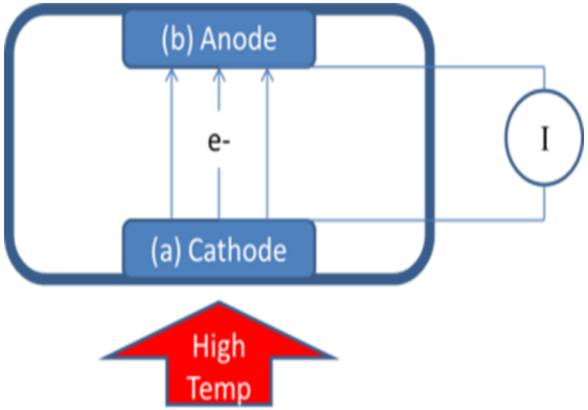
Source: GE Energy

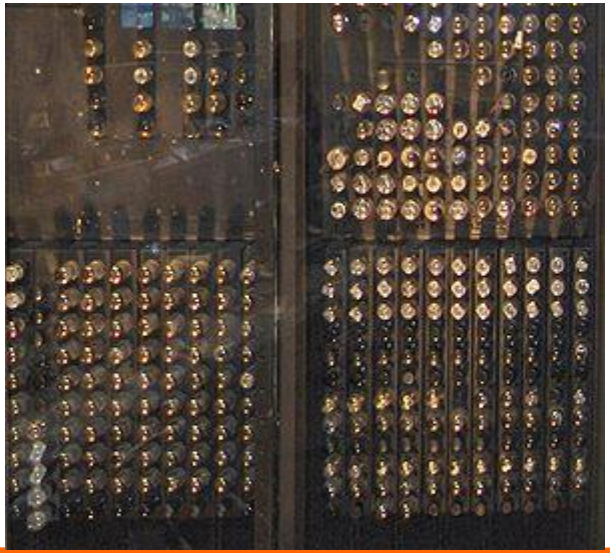


Thermocouple protection system for gasifiers (NETL website)

HEAT Sensor Project Concept

- Use Thermionic Materials as Sensors
  - Heat induced flow of electrons from a metal surface
  - Thermionic emissions occur at high temperature without need for external heater source
- Thermionic Technology
  - Diodes, Triodes, Tetrodes, etc…
  - Amplifier, Oscillators, Power Generation





The 1946 ENIAC computer used 17,468 vacuum tubes and consumed 150 kW of power

70-watt tube audio amplifier selling for US$2,680[31] in 2011, about 10 times the price of a comparable model using transistors.[32]

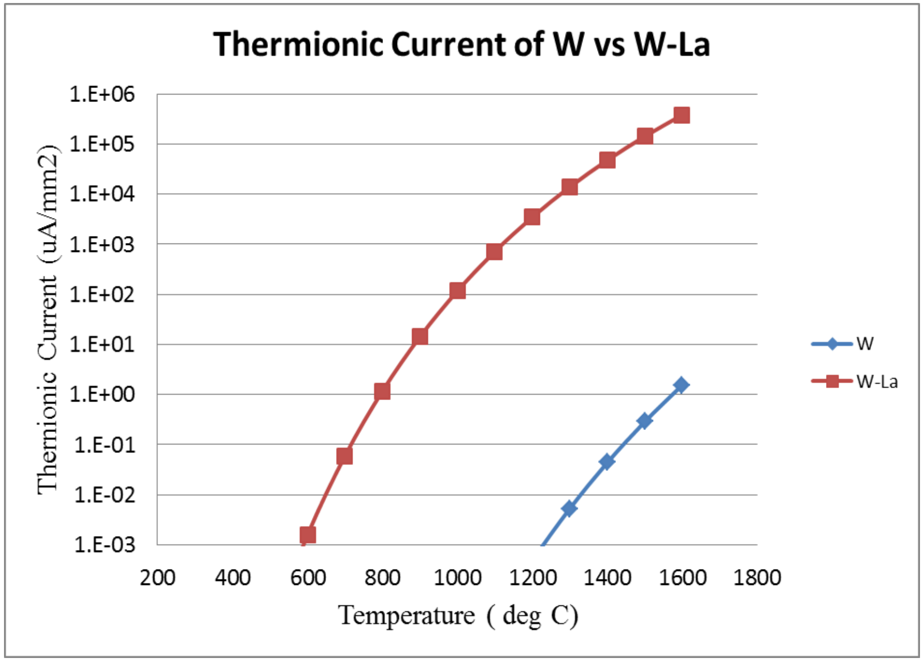
HEAT Sensor Project Plan

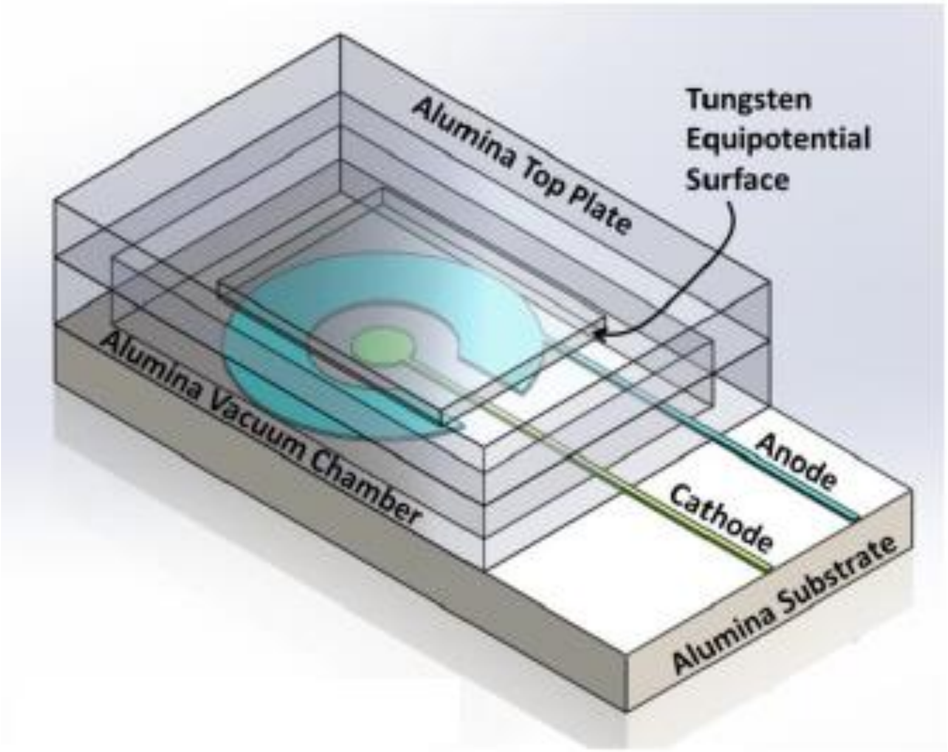
- Model and Pattern Thin Film Thermionic Layers
- Develop Experimental System
- Develop High Temperature Hermetic Package
  - Use High Temperature Co-Fired Ceramics (99.9% pure alumina)
  - Adhesive and Hermetic Sealant Development
- Thermionic Measurements
  - Temperature Sensor
  - Pressure Sensor
  - Circuits and Power Generation

Basic Temperature Sensor

Richardson's Law

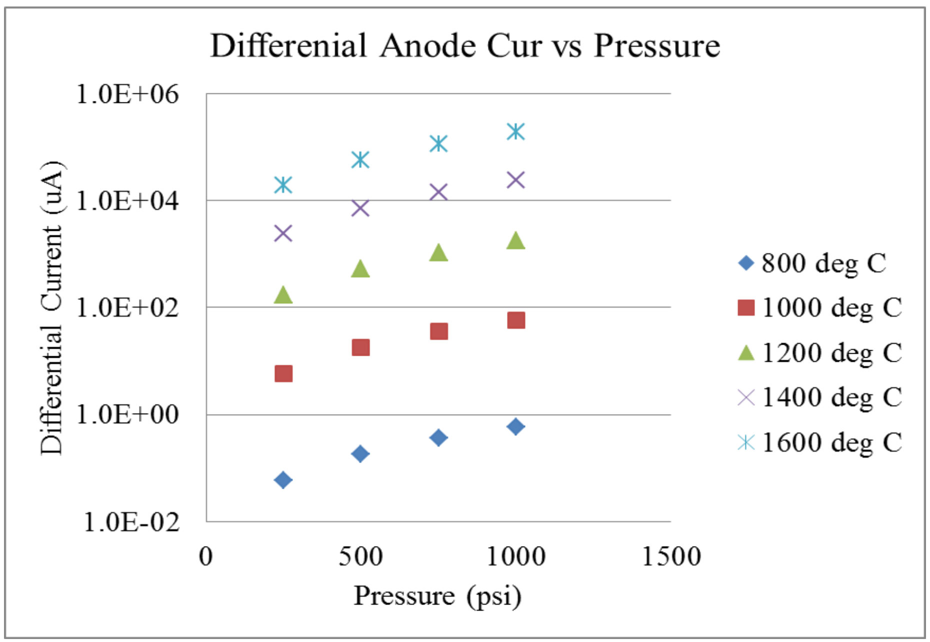
$$J = A_G T^2 e^{\frac{-W}{kT}}$$

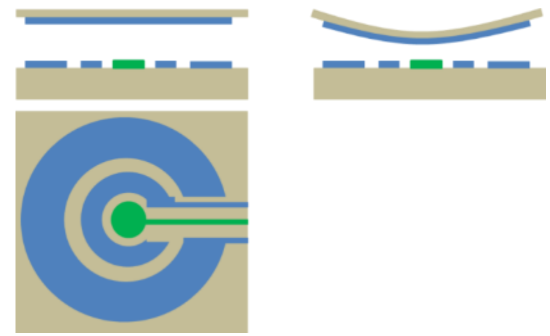


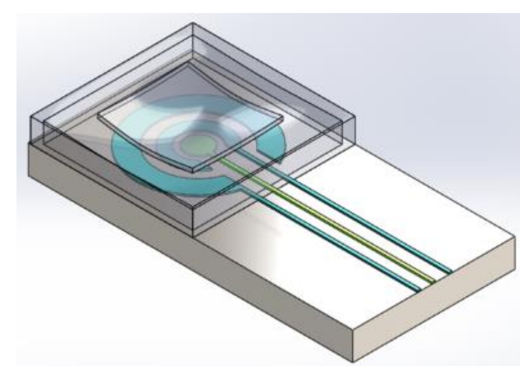


Pressure Sensor

Simulation

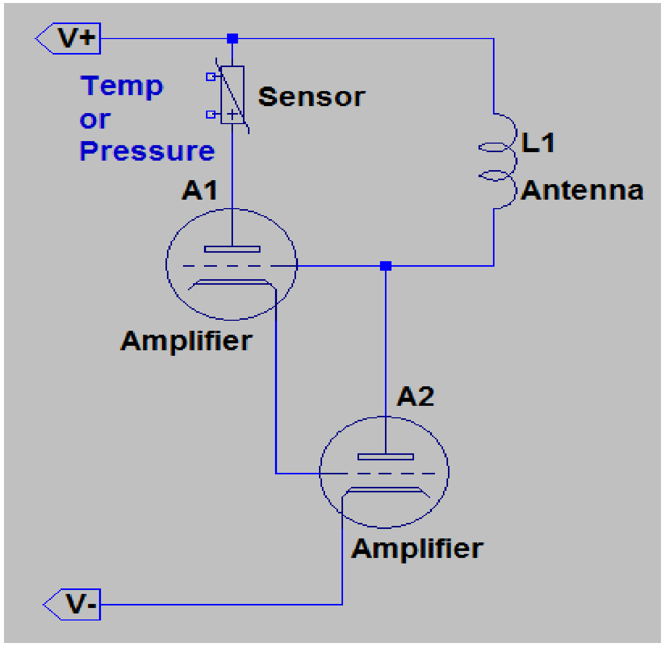




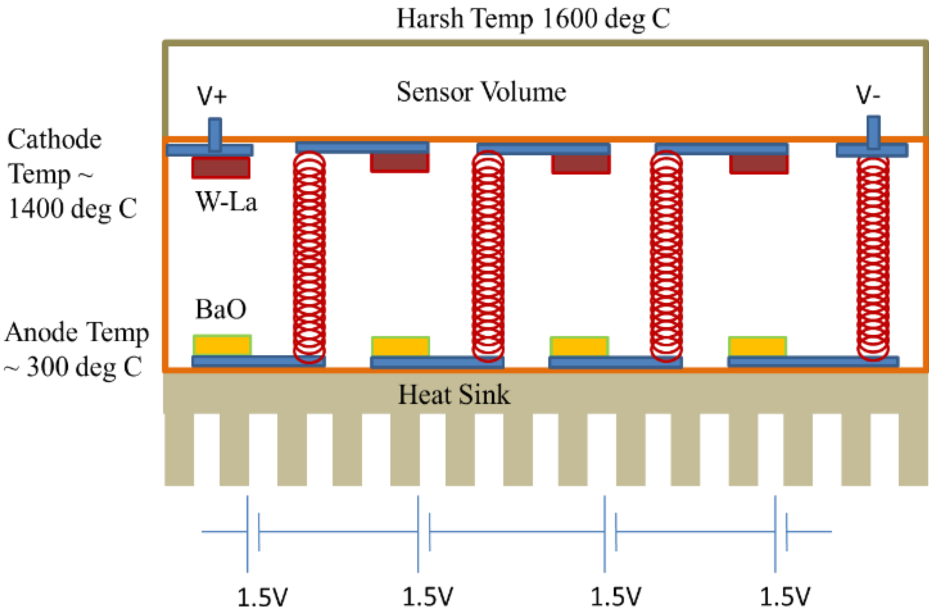


Autonomous Power & Wireless Transmission

Wireless Transmission Circuit Example



Power Generation Concept



50 mA/mm2 max current

Vacuum Tubes vs HEATS Platform

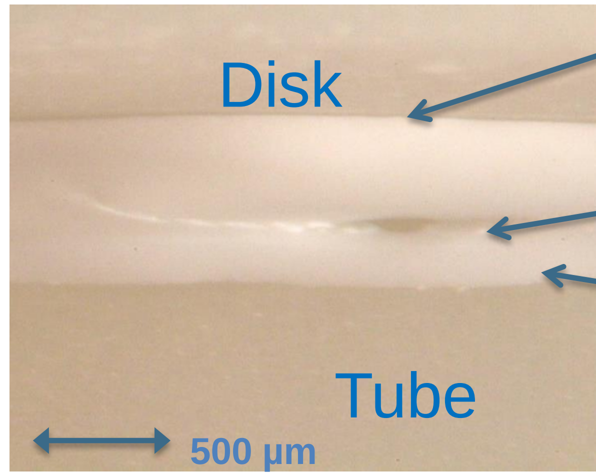
Characteristics	Vacuum Tubes	HEATS Platform
Operating vacuum level	Similar	Similar
Package hermetic sealing temperature	<300 C	> 1300 C
Package operating temperature	<300 C	> 1300 C
Package dimensions	~ cm	~ mm

Hermetic Seal Development

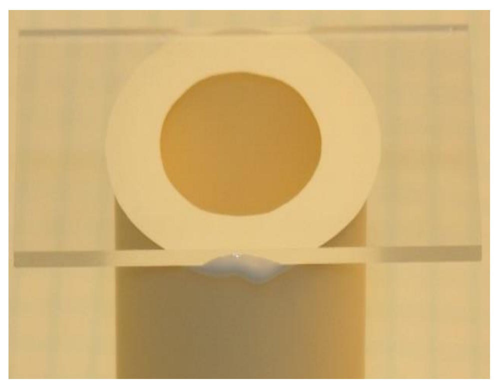
- Encouraging initial results using Alumina Paste
  - Fired @ 1350C
  - <3.4e-4 mbar base pressure
  - Our target is <1e-4 mbar
- Planned Improvements
  - Explore application method and firing procedure
  - Seal area and structure modification
  - Decrease paste particle size
  - Add CTE matched high temperature glass filler

Hermetic Seal Development

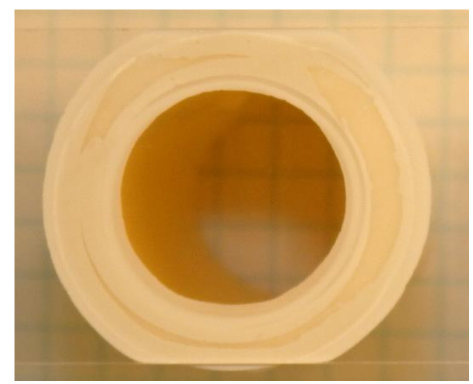
- Important parameters
  - CTE match (thin glue line)
  - Need melting component to fill in pores (sealing temperature)
  - Surface wettability during curing (additives and surface preparation)
  - Structural thermal stability of substrates
- Secondary importance
  - Paste particle size
  - Drying temperature



Paste, fired at 1500°C.



Sample after sealing but before any drying

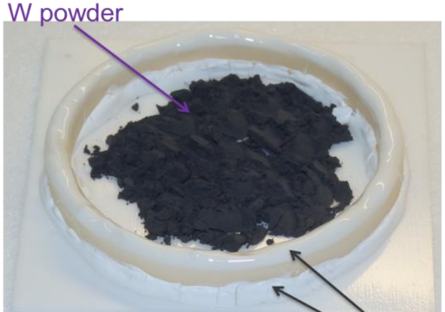


Sample after drying (<300 C bake)
Delamination is clearly visible

Hermeticity Testing

- Multiple paste formulations tested by measuring Tungsten oxidation weight gain
  - Package tungsten powder using sealing paste
  - Bake in air for set period of time
- Failed paste formulations showed oxidation of W (yellow) and volume expansion
- Promising paste formulation showed minimal mass gain at prolonged 1200C temperature soaks
  - 1.463 gr W initially
  - 7 mg gain after 130 hrs
  - ~ 1 e-5 bar cc/s ; Spec -- < 1e-7 bar cc/s
- 1mm thick HTCC plates had some curvature after curing

W powder

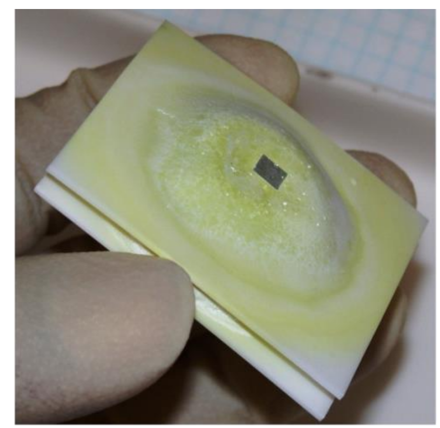


Sample 20140819-C, ready to apply lid.

On hotplate, after applied lid
(this paste flakes off when dry)

Fired @ 1600°C in N_2
(darkened in reducing environment)

Used PARC paste 20140731 for sealing.

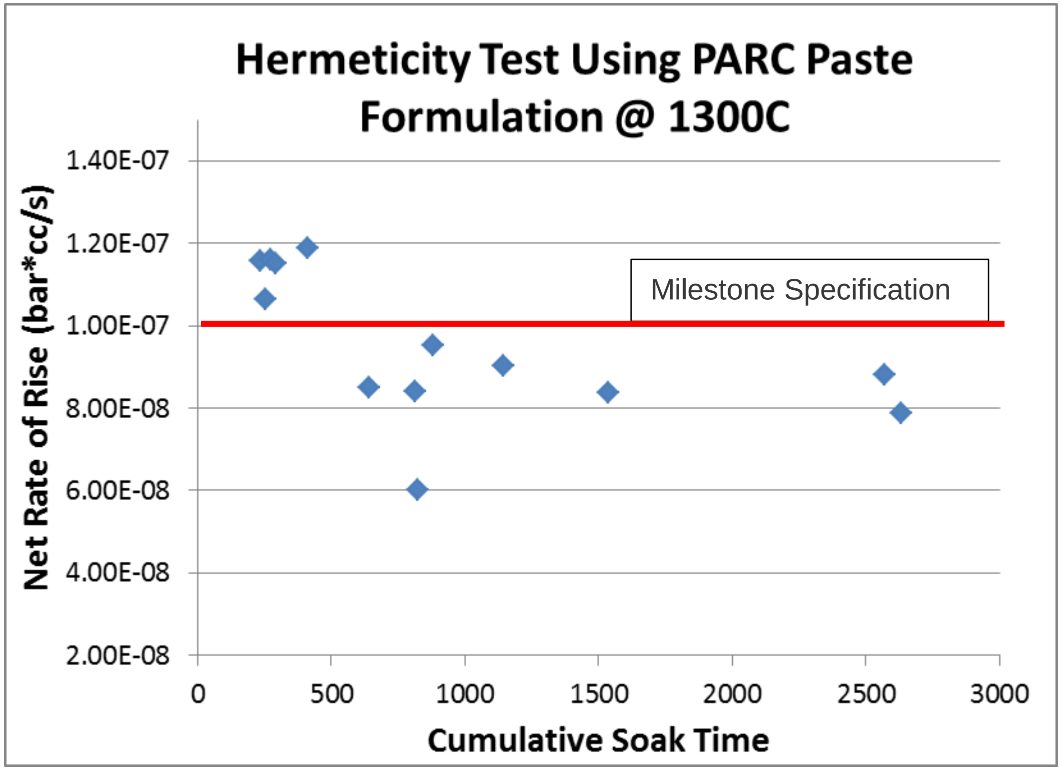


Re-fired for 30 hours in air at 1200°C

Tungsten oxidation → bad seal

Hermeticity Testing

- Used single layer alumina plate to minimize plate curvature during curing
- Soaked for over 2500 hrs at 1300C.
- Cycled to room temperature 3x and repeatedly cycled between 1000C to 1300C.
- Outgassing was further reduced by an high temperature cycle of 1400C.



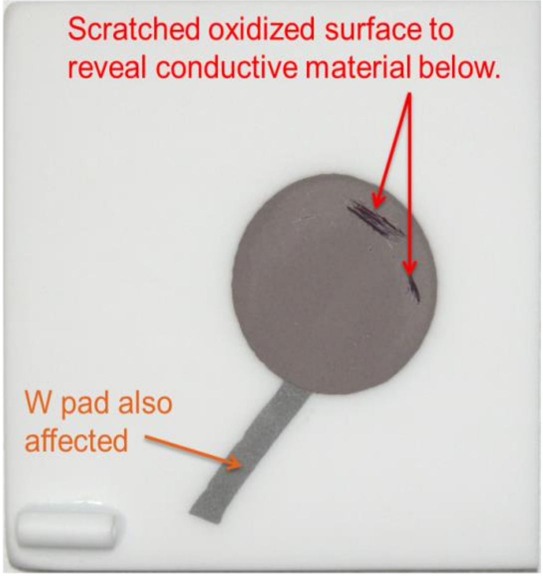
Firing in furnace #2


After firing, can see that some of sealant material flowed

Sample 20140910-A

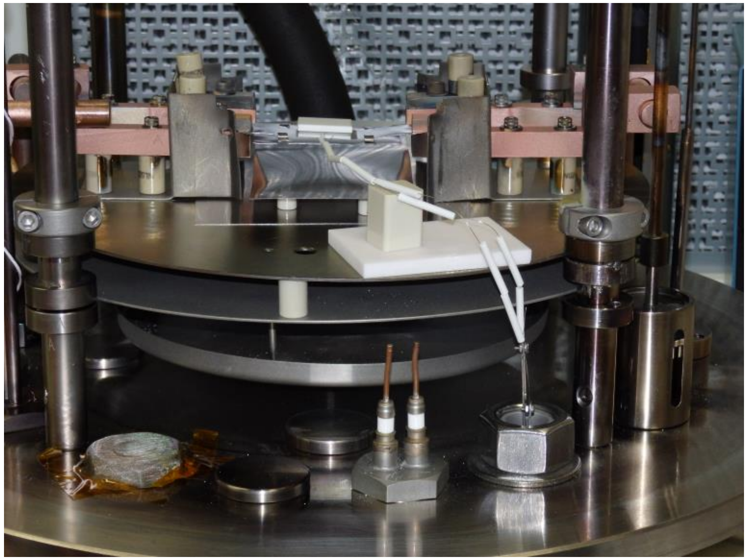
Thermionic Oxygen Poisoning

- Thermionic material oxidized
- Determined background vacuum in MTI tube furnace was too high
  - Getters did not prevent oxidation
  - Reduced current emissions observed
- Could not hermetically seal a package without oxidation of the thermionic material



New Test Apparatus

- Converted bell jar evaporator for thermionic testing
- Background pressure – 1e-7 mbar vs 1e-4 mbar for MTI furnace
- Temperature control up to 1300C for now (will test to 1600C in future)



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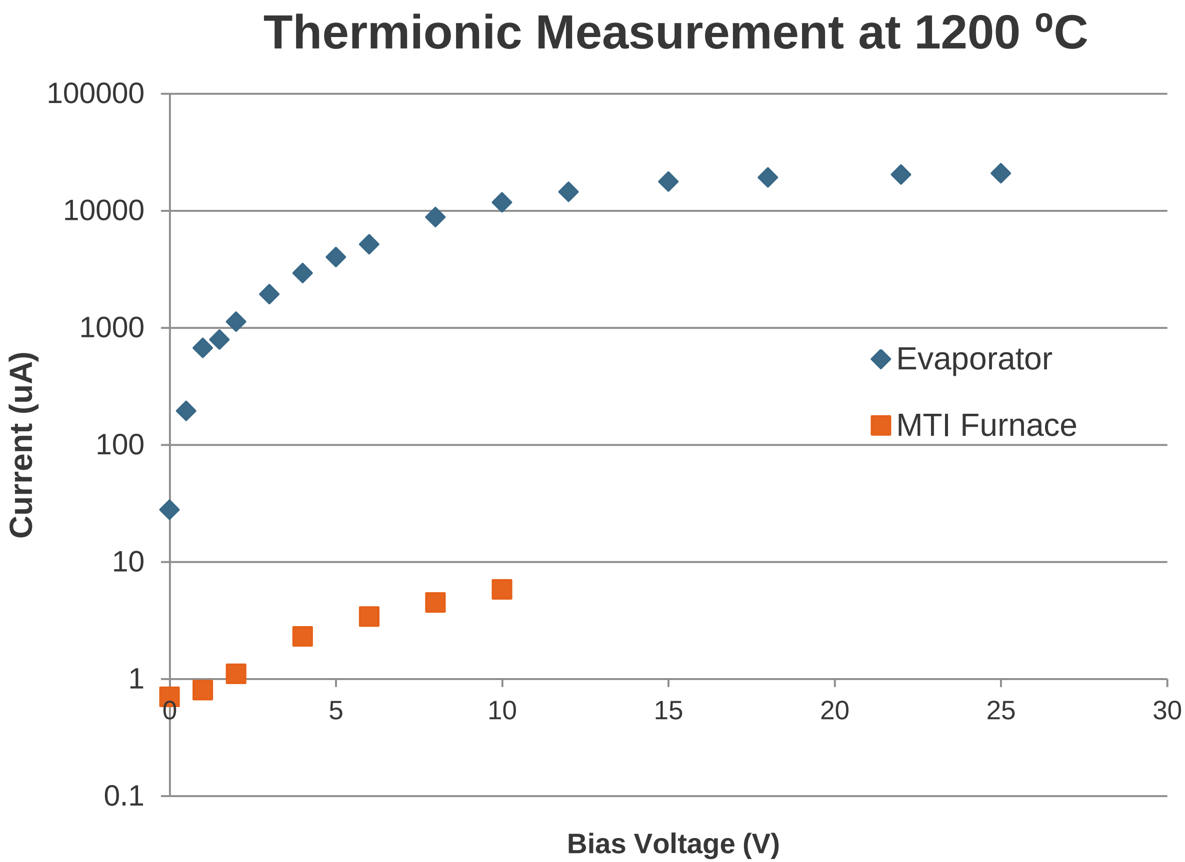
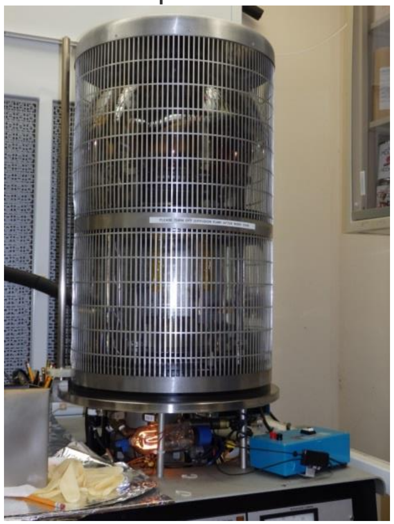
Data



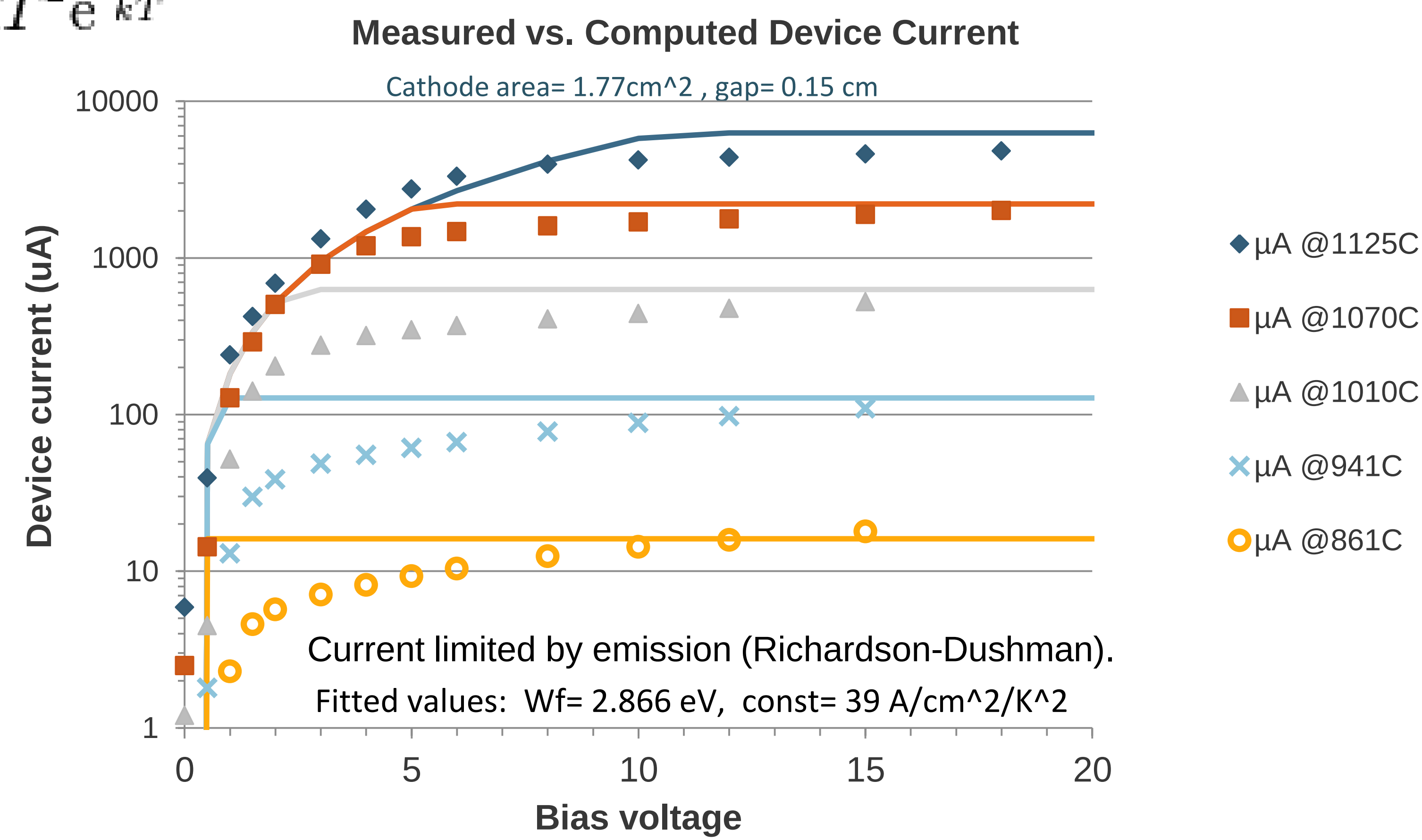
Evaporator



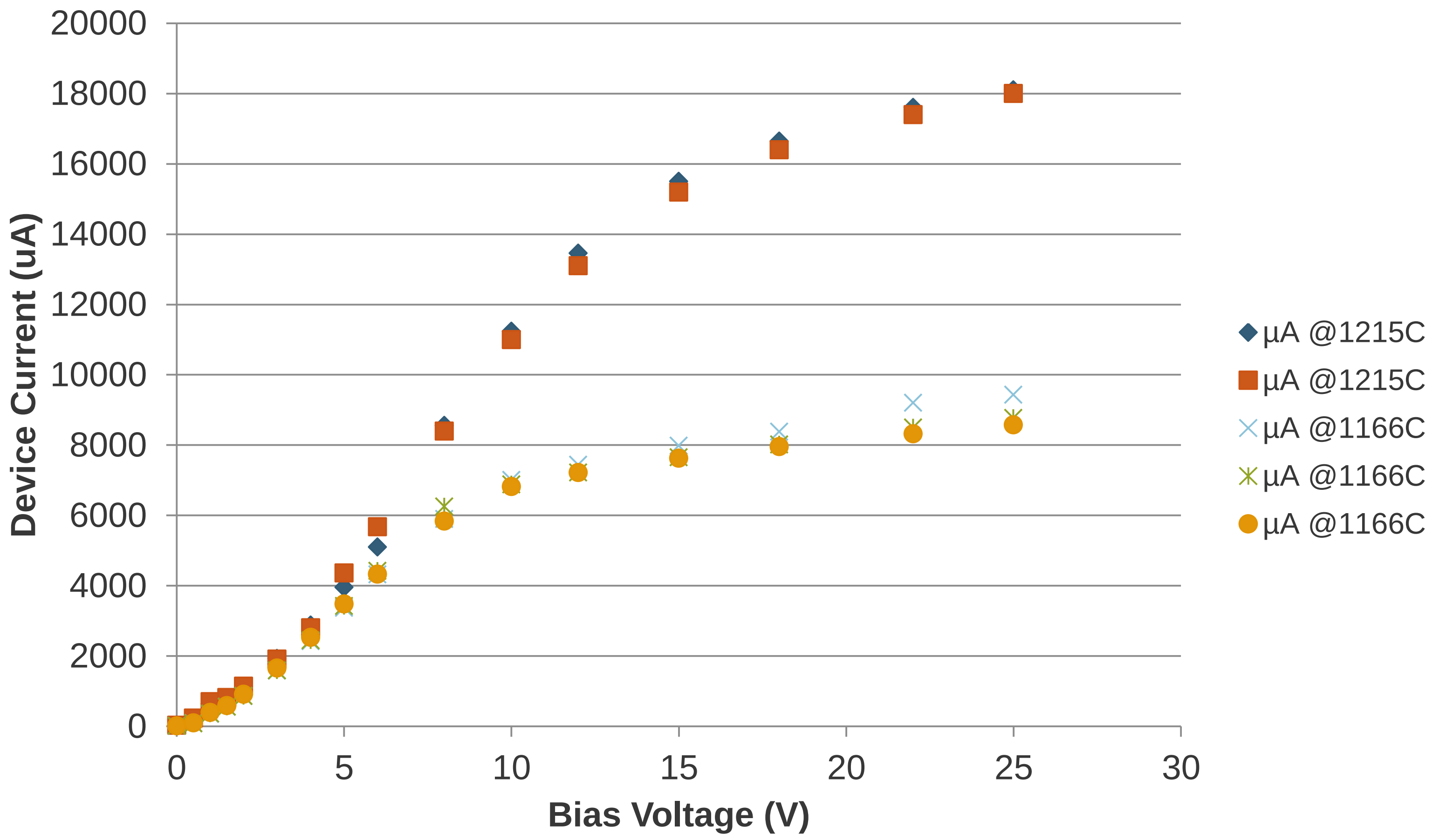
MTI Furnace

Data – Theory vs Actual

$$J = A_G T^2 e^{\frac{-W}{kT}}$$



Repeatibility



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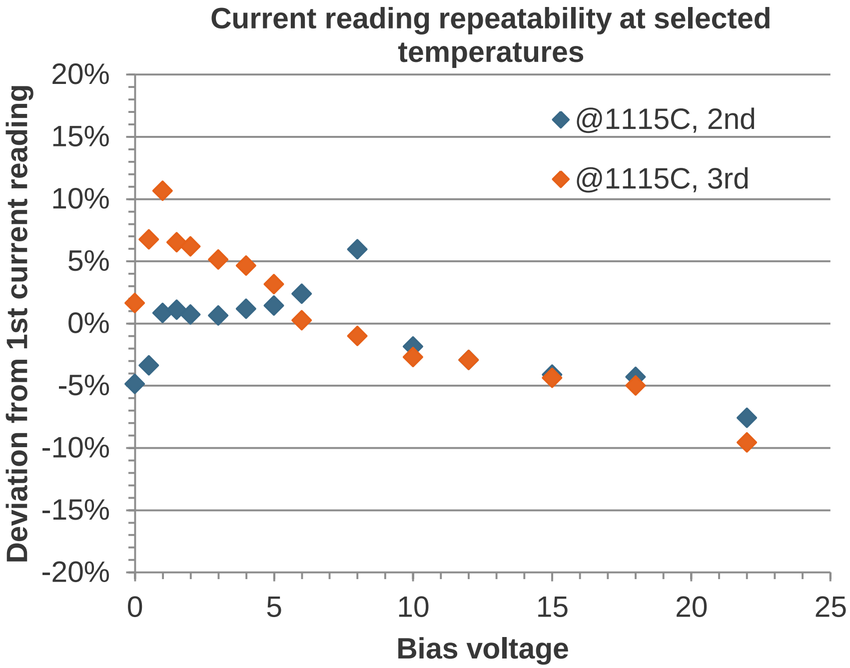
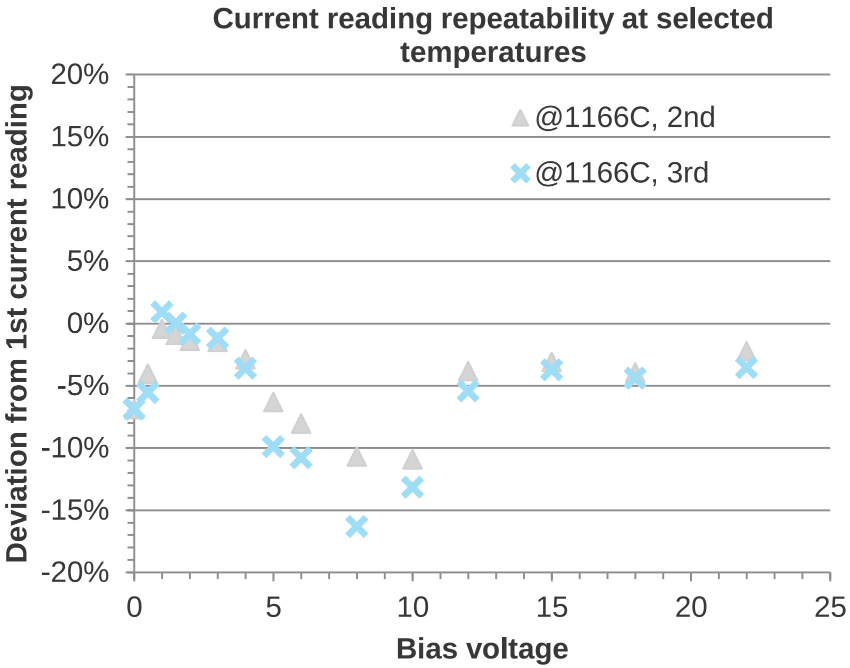
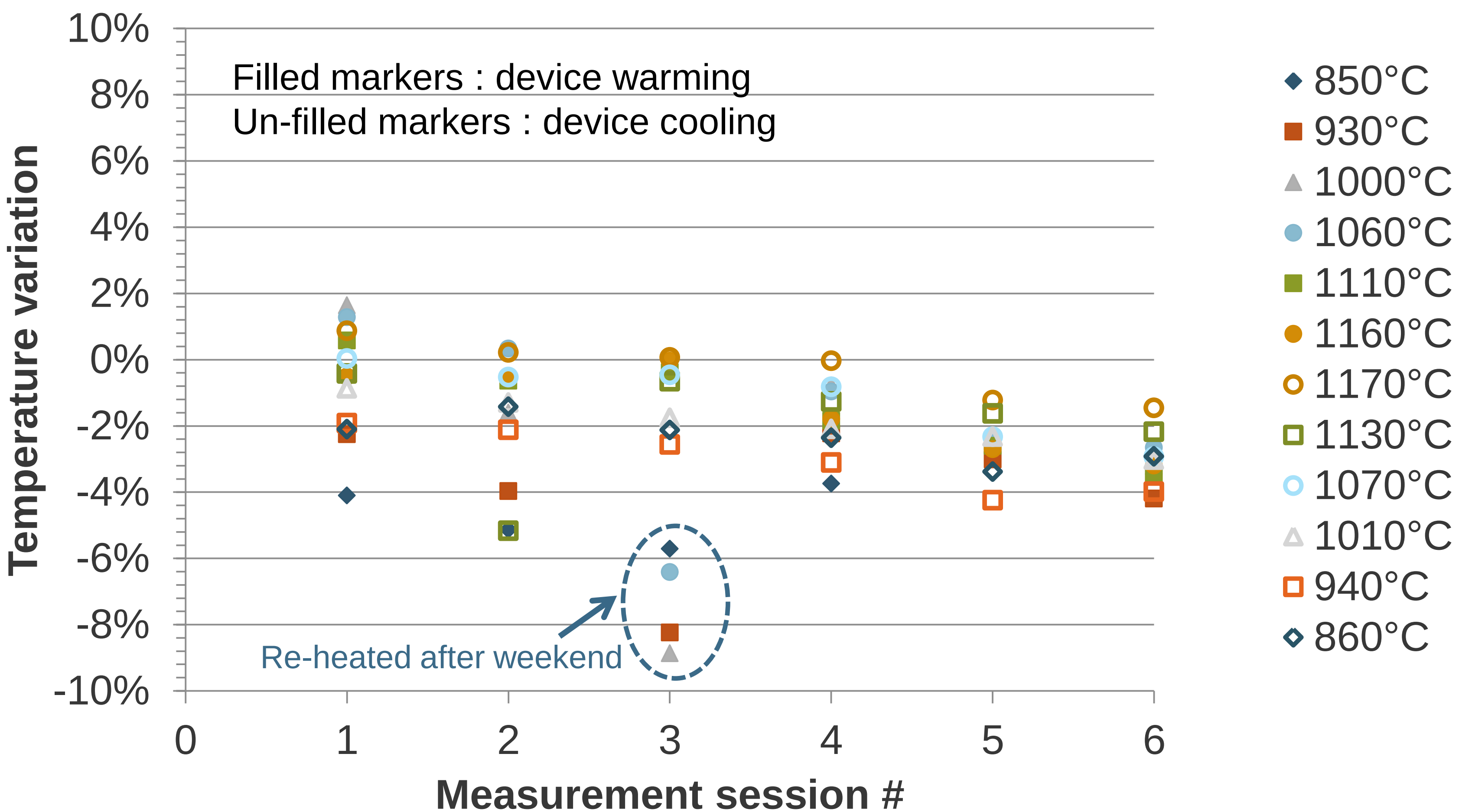




Temperature Measurement



Key Milestones

	Device Interconnect	Device Vacuum	Thermionic Material
Milestone 3 **Hermetic Seal @ Temp**	None	None	None
Milestone 4 **Temperature Sensor**	Zirconia wire	Active pumping	La
Milestone 6 **Pressure Sensor**	Zirconia wire	Active pumping	La
Milestone 9a **Self powered and wireless**	Zirconia wire	Active pumping	La, BaO
Milestone 9b **Self powered and wireless**	None	Self-contained vacuum with getter	La, BaO