TFAWS Passive Thermal Paper Session

Consolidation of a Sodium Heat Pipe and Stirling Engine for Fission Surface Power

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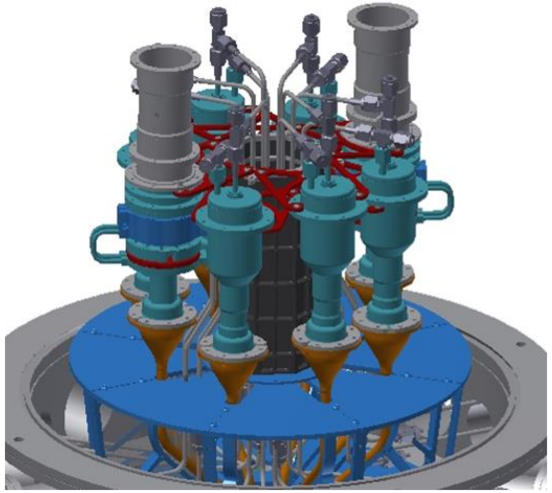
Outline

- Background/Purpose
- Consolidated Heat Pipe (CHP) design
- Test Setup
- Test Matrix
- Results
- Conclusion/Forward Work
- References
- Questions

Background

- The Kilopower Reactor Using Stirling TechnologY (KRUSTY) Test[1]
  - First fission reactor test for space application in over 50 years
  - Collaboration between NASA and the U.S. Department of Energy (DOE)
  - Built and tested at the Nevada National Security Site (NNSS) in 2018
  - Highly Enriched Uranium (HEU) provided thermal power to Stirling engines
  - An array of 2 Stirling engines and 6 thermal simulators
  - Heat Pipes were used to couple the reactor to the Stirling engines



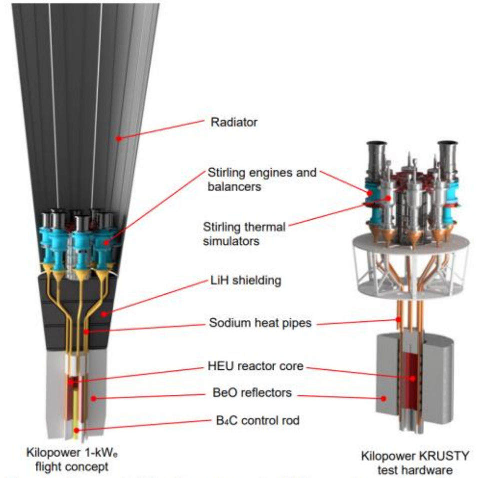


Figure 1.—Kilopower 1-kW$_e$ nuclear power system flight concept comparison with Kilopower Reactor Using Stirling TechnologY (KRUSTY) nuclear test hardware. HEU, highly enriched uranium.

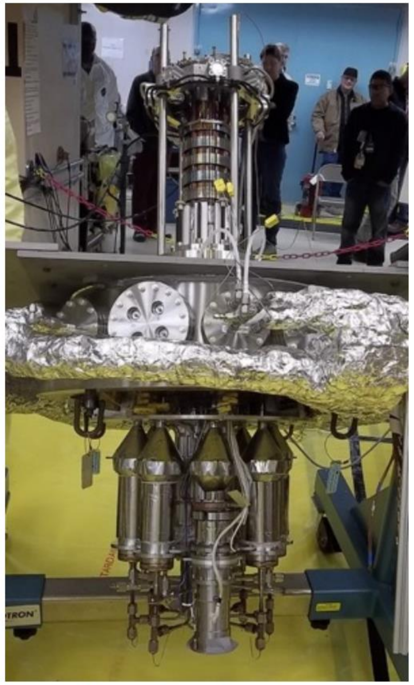
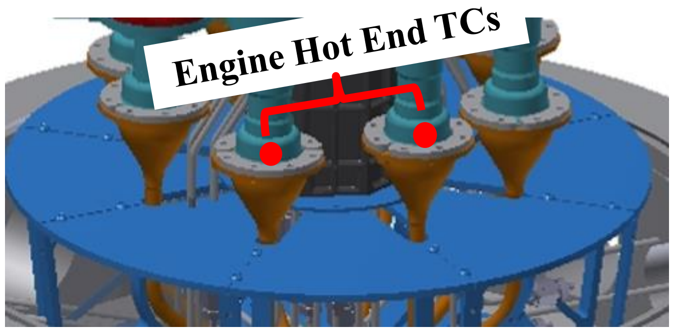


Figure 3.—Kilopower Reactor Using Stirling TechnologY test hardware assembled inside vacuum chamber service collar and positioned upside down with Stirling engines and simulators (lower) connected to highly enriched uranium core (upper) via sodium heat pipes.

20180007389.pdf (nasa.gov)

- KRUSTY Heat Pipes[1]
  - Bolted/clamped to the "hot end" of the Stirling engine
  - ΔT is 160 ˚C between core and Stirling engine hot end
  - Significant portion, 120 ˚C , is between the heat pipe itself and the hot end
  - Clamp design carries notable thermal losses that need to be addressed



Delta T noted between Engine Hot End and adiabatic section of Heat Pipe

Clamp Design

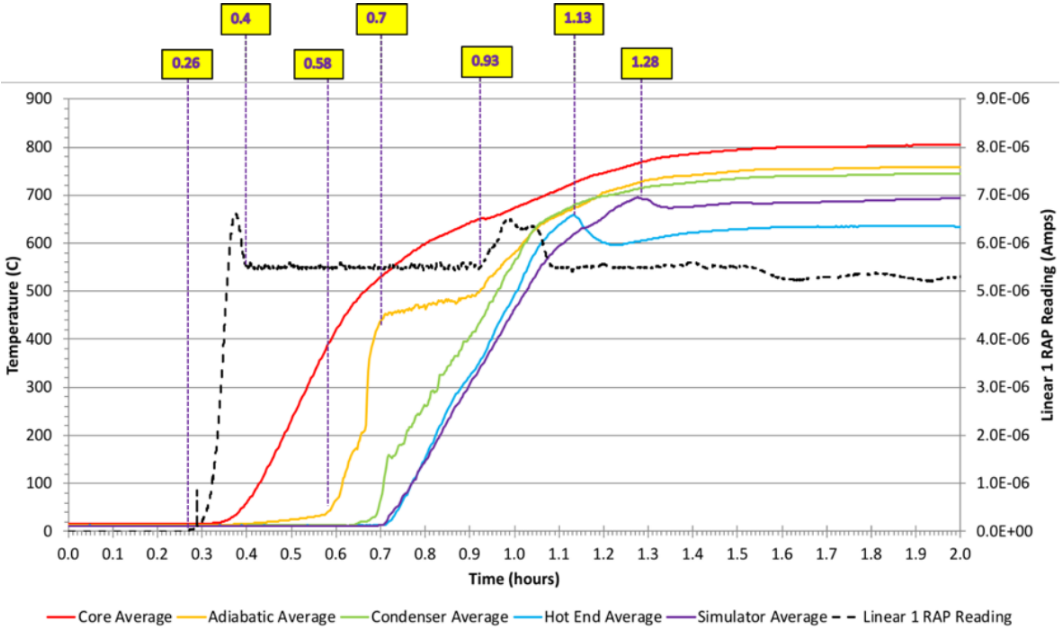
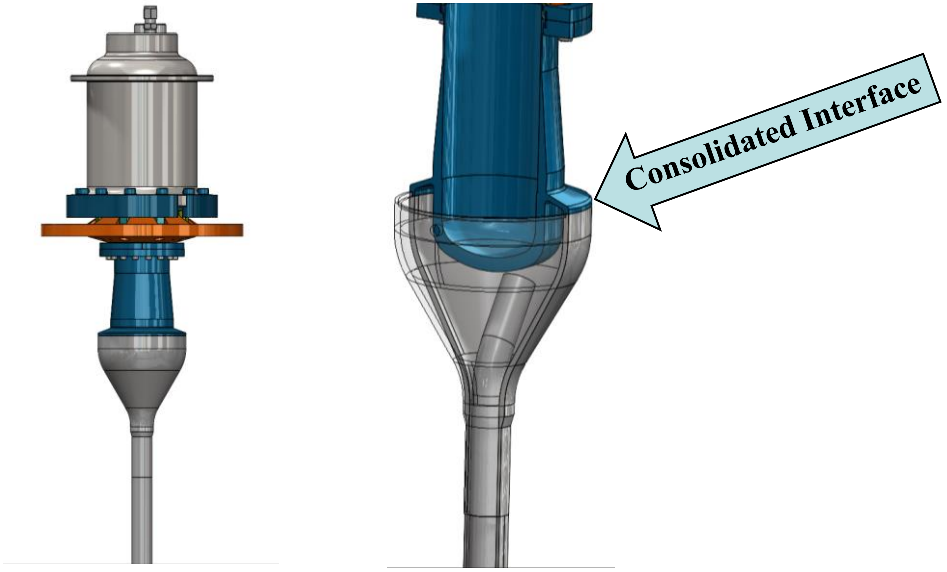


Figure 8.—Average system temperatures and neutron count during reactor startup.

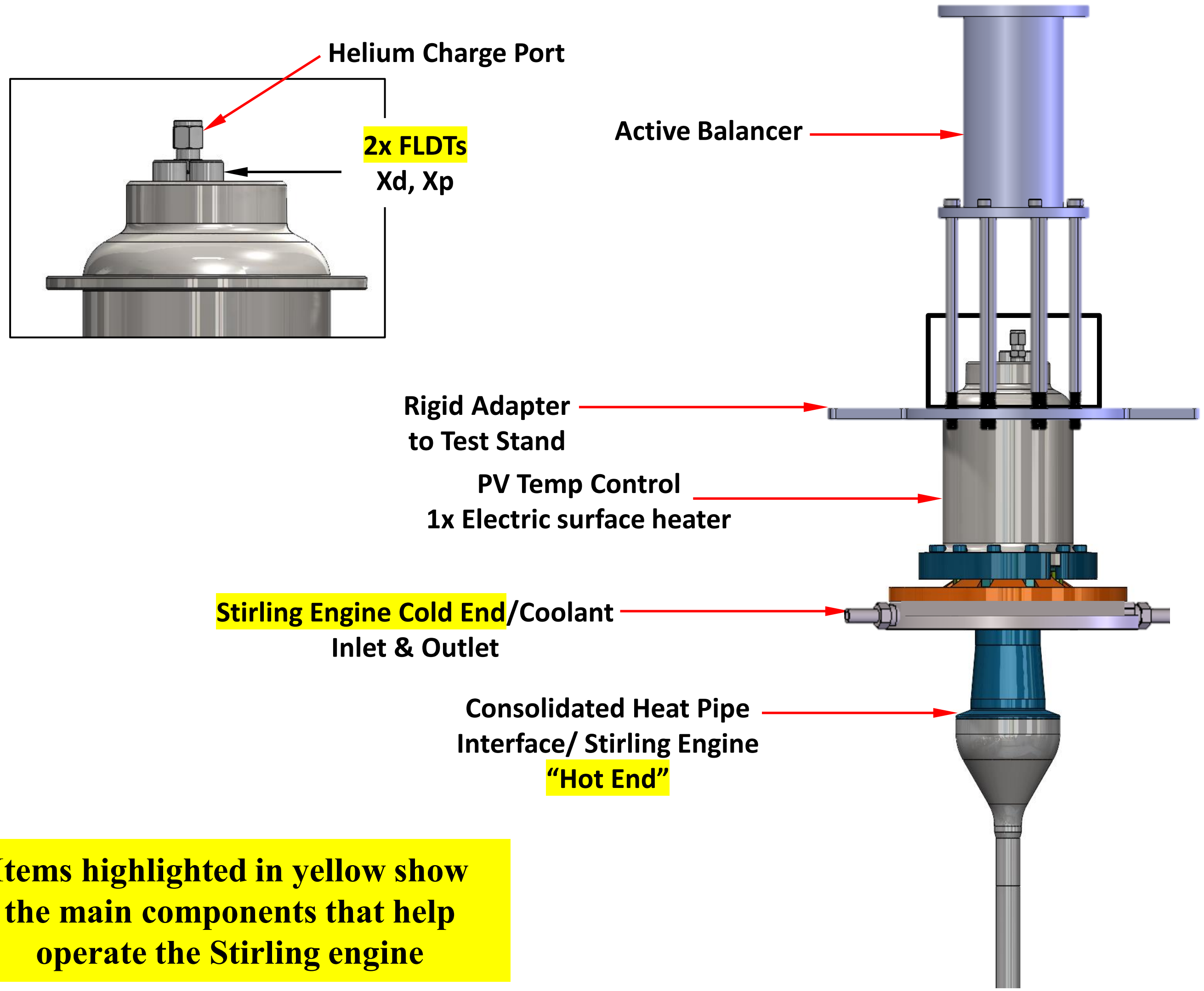
20180007389.pdf (nasa.gov)

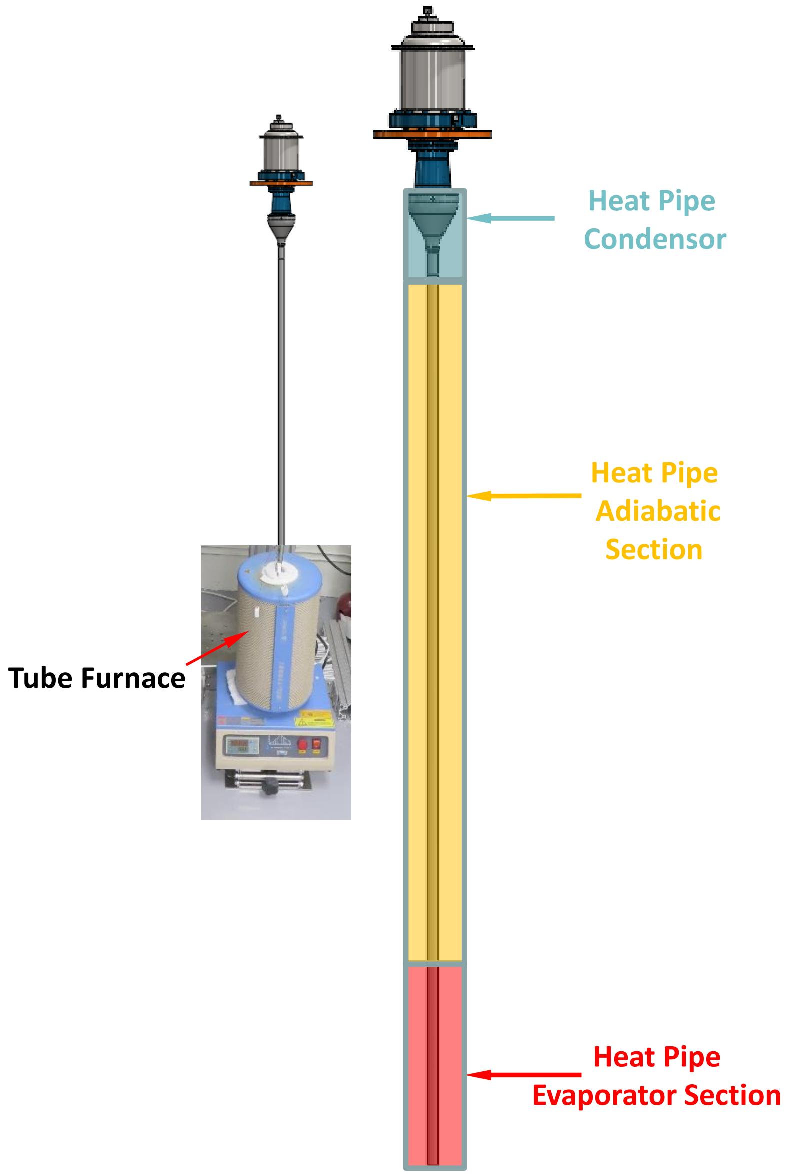
Consolidated Heat Pipe (CHP) Design

- CHP improves the thermal interface between heat pipe & Stirling engine hot end
  - Stirling Heater Head, “hot end”, is buried within the heat pipe’s condenser
  - Working fluid can condense directly on the hot end
  - Directly delivers thermal power to Stirling engine
  - An annular pipe inside is used as wick to enable lower gravity operations
  - Designed to operate at 700 ˚C and 800 ˚C Sodium as working fluid



Test Setup





Items highlighted in yellow show the main components that help operate the Stirling engine

Test Setup

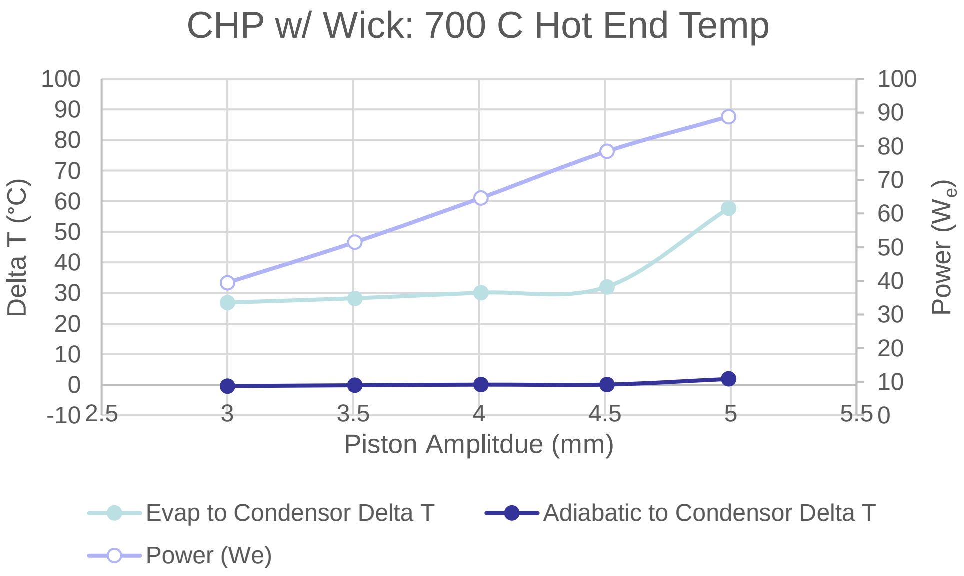
- Stirling Engine Control
  - Hot end temperature -> Tube Furnace
  - Cold end temperature -> PolyScience chiller
  - Stirling engine piston amplitude -> Sunpower Controller
- Charge Pressure
  - Stirling engines are not hermetically sealed and so require helium top-offs
  - Top-offs completed via Fill-Purge cart located behind the center rack.
- Mounting
  - Koawool insulation used for heat pipe exposed to ambient air
  - Single engine vertical orientation
  - Protective cage

Test Matrix

- Three Main Test Sections
  - Hot end temp -> 700 ˚C , Cold end temp -> 60 ˚C , piston amplitude varied from 3-5 mm
  - Hot end temp -> 800 ˚C , Cold end temp -> 60 ˚C , piston amplitude varied from 3-5 mm
  - Piston amplitude -> 5 mm, Cold end temp -> 60 ˚C , Hot end temp decreased from 600 – 800 ˚C (25 ˚C increments)

Hot End Temperature	600 °C - 800 °C
Piston Amplitude	3 mm to 5 mm
Cold End Temperature	60 °C
Stirling Engine Pressure	500 psig (Helium working fluid)

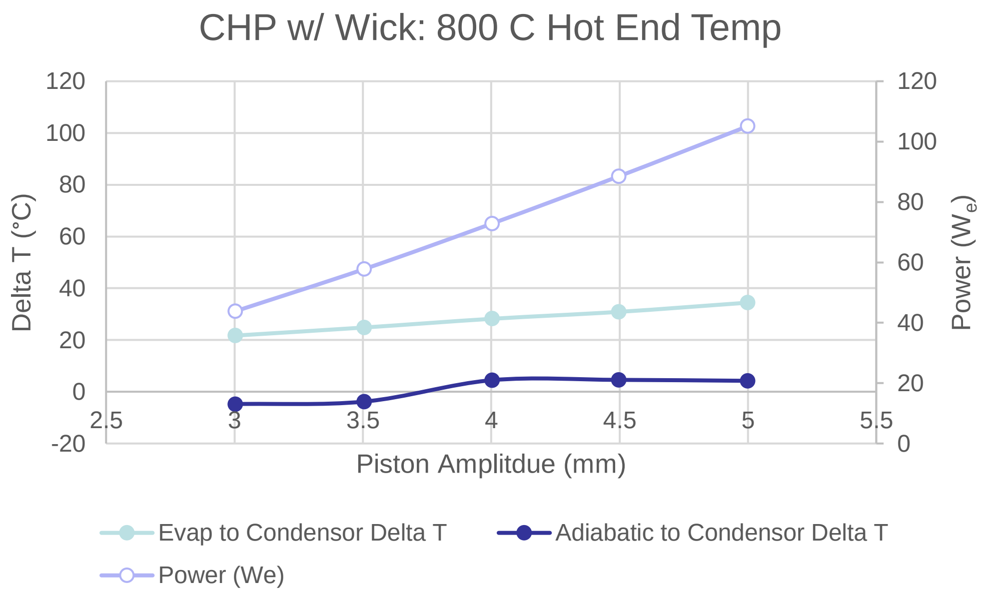
- Test Section 1: 700 ˚C Hot End Temperature, Varied Piston Amplitude
  - ΔT between heat pipe adiabatic and condenser has been lowered to 2 ˚C at 5 mm!!
  - Heat pipe is able to deliver thermal power to Stirling hot end directly
  - Evaporator to Condenser ΔT (light blue curve): ranges from 27-58 ˚C
    - The “knee” between 4.5- 5mm: no known root cause for this change in behavior
    - Another similar test point indicates there would be no “knee” (Table to the right)
    - Further testing needed: different heating ramp rates, vacuum environment, better insulation, etc.



	1st Test Point	2nd Test Point
Hot End Temperature	700 °C	700 °C
Piston Amplitude	5 mm	5 mm
Cold End Temperature	60 °C	60 °C
Stirling Engine Pressure	500 psig	493 psig
Stirling Power Output	89 W	90 W
Adiabatic to Condenser	2 °C	6 °C
Evaporator to Condenser	58 °C	40 °C

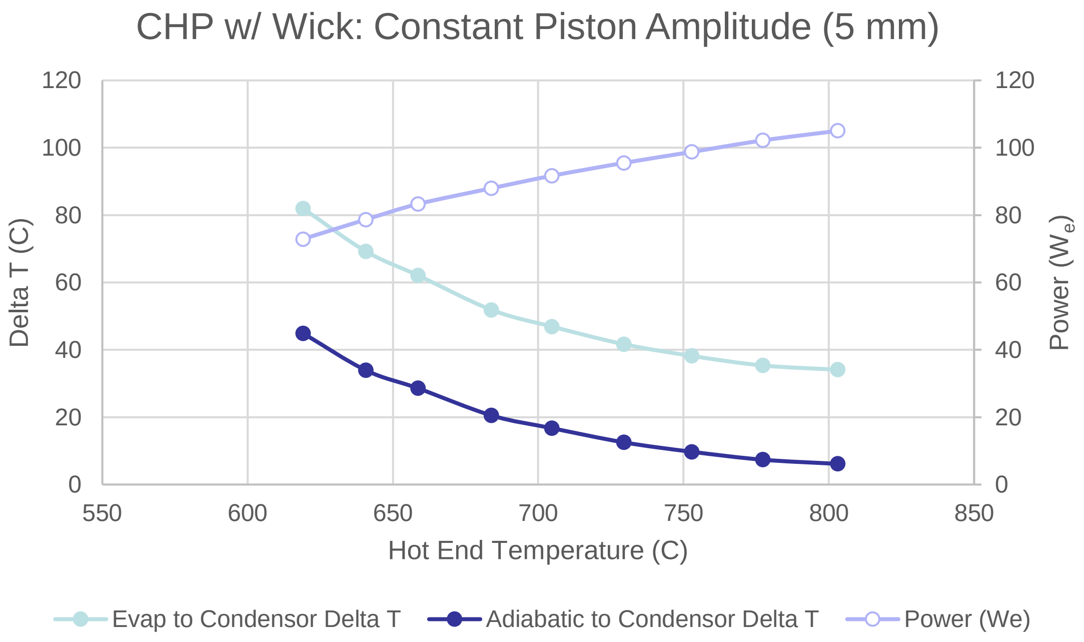
Results

- Test Section 2: 800 ˚C Hot End Temperature, Varied Piston Amplitude
  - ΔT between heat pipe adiabatic and condenser has been lowered to 4 ˚C at 5 mm!!
  - Adiabatic to Condenser ΔT -> negative between 3 mm to 3.5 mm
    - Caused by chiller failure that led to an abrupt shutdown
    - Heat pipe working fluid froze at the condenser
    - Had to manually heat the condenser to bring the fluid back down to the evaporator
  - Overall Evaporator to Condenser ΔT is stable, ranges from 22-34 ˚C



Results

- Test Section 3: 5 mm Piston Amplitude, Varied Hot End Temperature
  - Hot End decreased from 800 ˚C to 600 ˚C in 25 ˚C increments
  - Adiabatic to Condenser ΔT ranges 6-48 ˚C
  - Overall Evaporator to Condenser ΔT ranges 34-82 ˚C



Conclusions/Forward Work

- Consolidated Heat Pipe design is successful!
  - Compared to KRUSTY's 120 ˚C ΔT, CHP shows 2-4 ˚C ΔT between the Stirling Engine Hot End and Heat Pipe
- Forward Work
  - The CHP will be tested in a vacuum environment for further investigation
    - Overall Evaporator to Condenser ΔT anomaly in the 700 ˚C test needs to be investigated further
    - Overall Evaporator to Condenser ΔT might also be further reduced for all test conditions with a better environment (vacuum) and insulation

References

1. Gibson, Marc A., et al. "Kilopower Reactor Using Stirling TechnologY (KRUSTY) Nuclear Ground Test Results and Lessons Learned." 2018.

2. Poston, David I., et al. "Results of the KRUSTY Nuclear System Test." Nuclear Technology (2020): S89-S117.

Questions?

Thank you!!