Summary of Test Results From a 1 kW$_e$-Class Free-Piston Stirling Power Convertor Integrated With a Pumped NaK Loop

Summary

As a step towards development of Stirling power conversion for potential use in Fission Surface Power (FSP) systems, a pair of commercially available 1 kW class free-piston Stirling convertors was modified to operate with a NaK liquid metal pumped loop for thermal energy input. This was the first-ever attempt at powering a free-piston Stirling engine with a pumped liquid metal heat source and is a major FSP project milestone towards demonstrating technical feasibility. The tests included performance mapping the convertors over various hot and cold-end temperatures, piston amplitudes and NaK flow rates; and transient test conditions to simulate various start-up and fault scenarios. **Performance maps of the convertors generated using the pumped NaK loop for thermal input show increases in power output over those measured during baseline testing using electric heating. Transient testing showed that the Stirling convertors can be successfully started in a variety of different scenarios and that the convertors can recover from a variety of fault scenarios.**

Summary of Test Results From a 1 kW$_e$-Class Free-Piston Stirling Power Convertor Integrated With a Pumped NaK Loop

Maxwell H. Briggs and Steven M. Geng

NASA Glenn Research Center

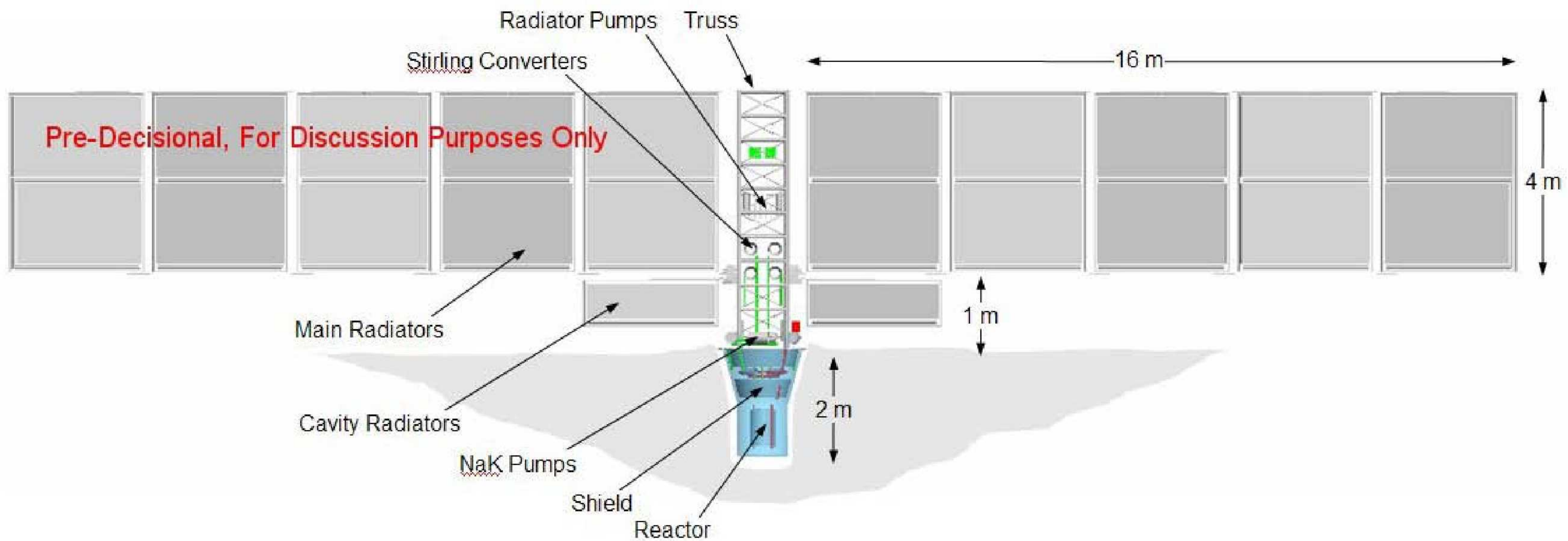
J. Boise Pearson

Marshall Space Flight Center

Thomas J. Godfroy

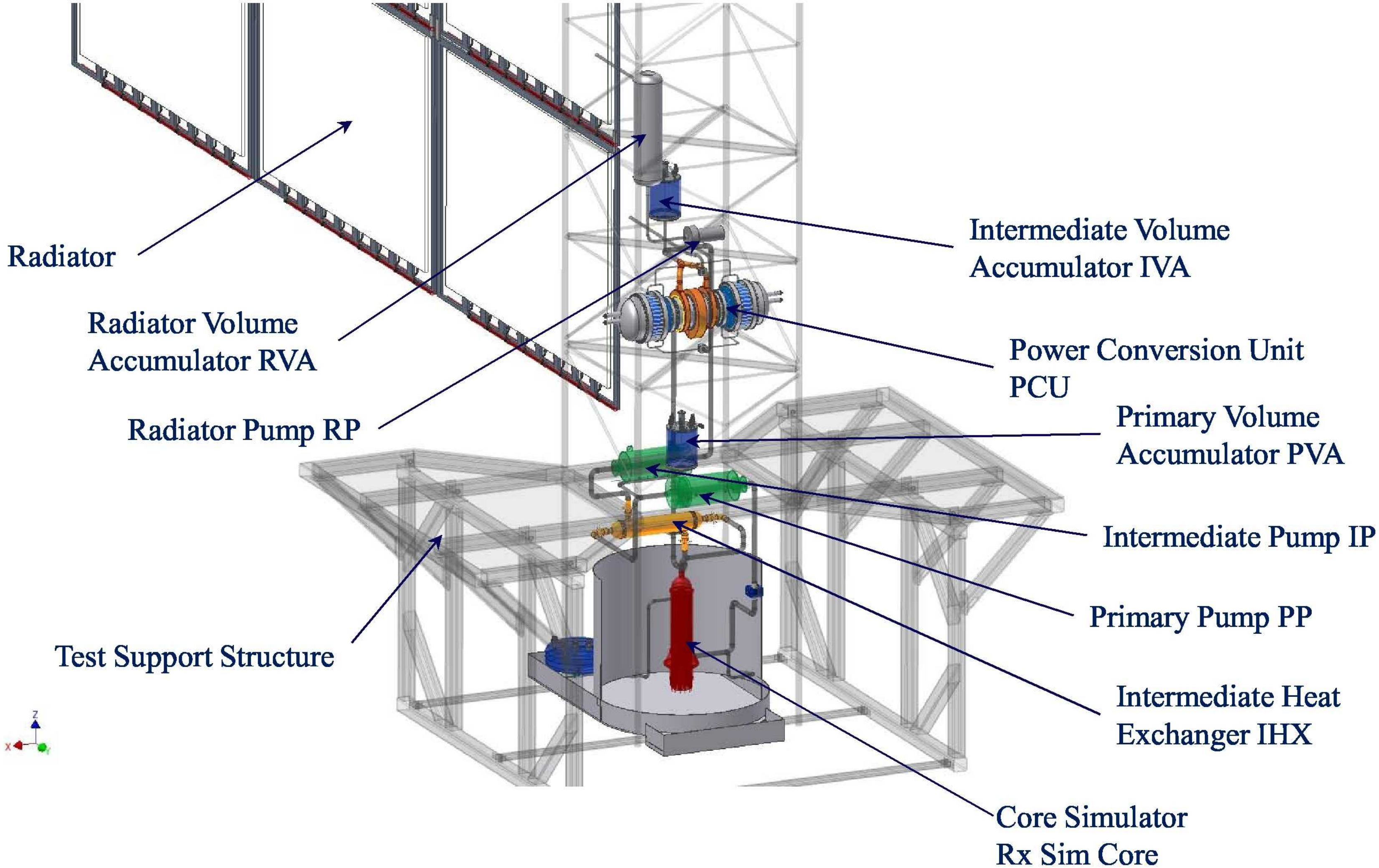
Maximum Technology Corp.

Fission Surface Power Reference Concept



- Provide 40 kW electric power for a lunar or Martian outpost
- Full power delivered day and night
- System power and mass are independent of landing sight
- Components
  - 175 kW_t Uranium-dioxide reactor
  - **Primary and Intermediate pumped liquid-metal heat transfer fluid loop**
  - **Four dual-opposed 12-kW Stirling cycle power conversion units**
  - Pumped water cooling loop
  - Titanium-water heat pipe radiators for heat rejection

Technology Demonstration Unit (TDU)



TDU Pathfinders

Reactor Simulator

Liquid Metal Pump

2 kWe Brayton Power Conversion

Radiator Sub-panel

Heat Pipes

2 kWe Stirling Power Conversion

Irradiation Testing

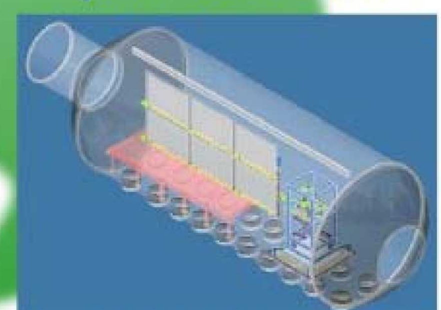
Radiator Panel Demonstration

Reactor Simulator Heater Bundle Fabrication

Power Conversion Design

Annular Linear Induction Pump

Full Scale System Demonstration



Technology Demonstration Unit Concept

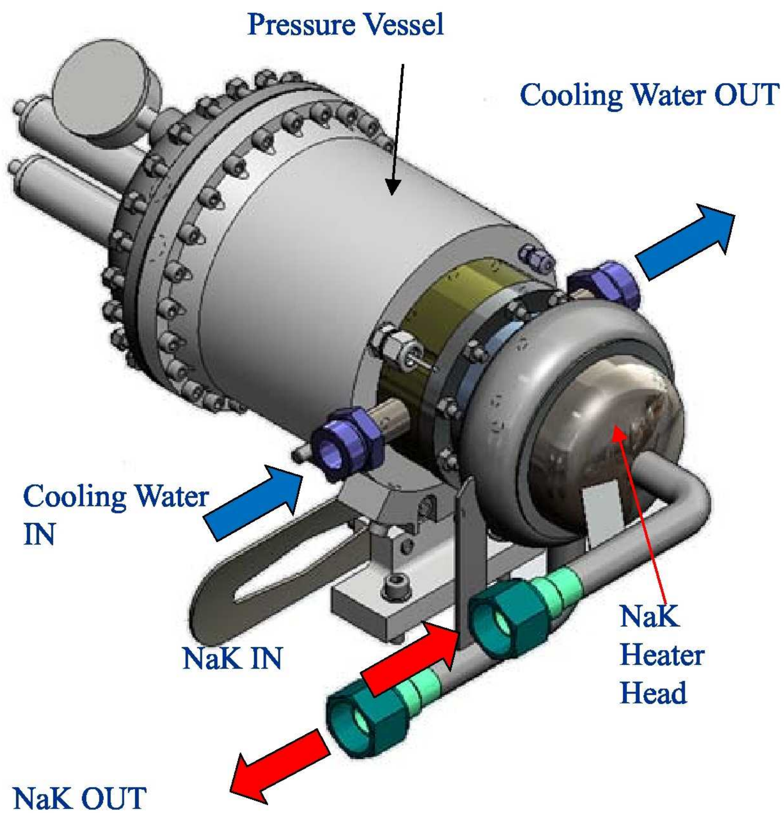
NaK Testing of 2-kW Stirling Convertors

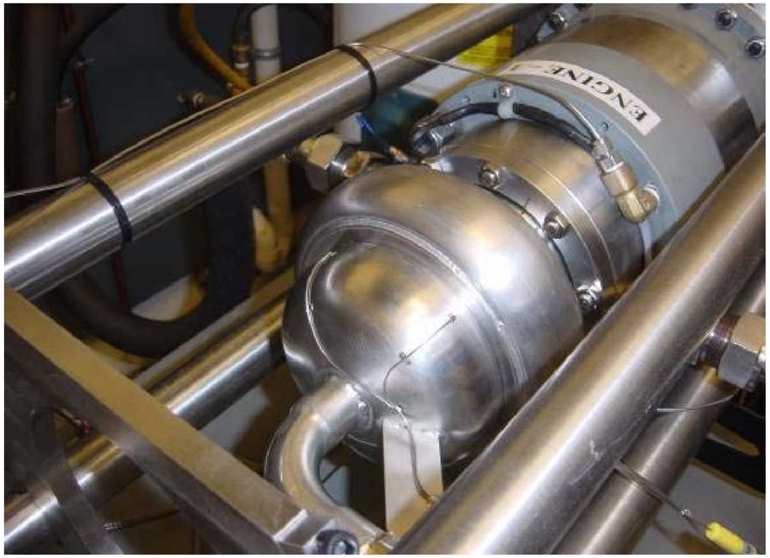
- Primary Objective
  - To demonstrate Stirling convertor electrical power generation using a pumped liquid-metal heat source.
- Secondary Objectives
  - Evaluate the performance of the Stirling convertors and NaK heat exchanger under a range of operating conditions
  - Run several startup scenarios and identify possible the advantages and disadvantages of each.
  - Simulate various system level failure mechanisms and evaluate the effect each has on the Stirling convertor

Baseline Measurements

Stirling convertors were heated using electric cartridge heaters and baseline performance was measured

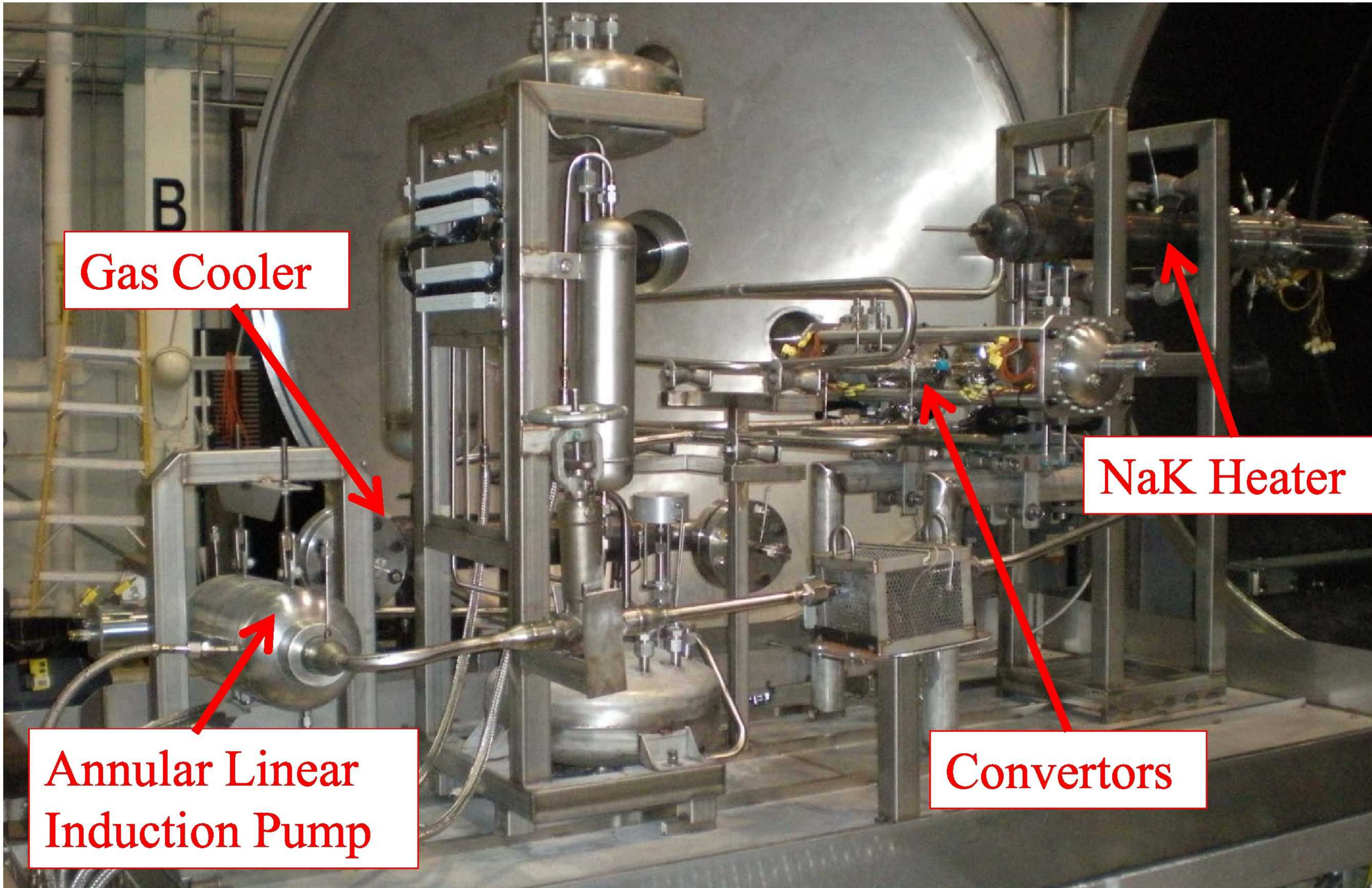
NaK Heater Heads





Electric heaters were removed and replaced with stainless steel NaK heat exchangers

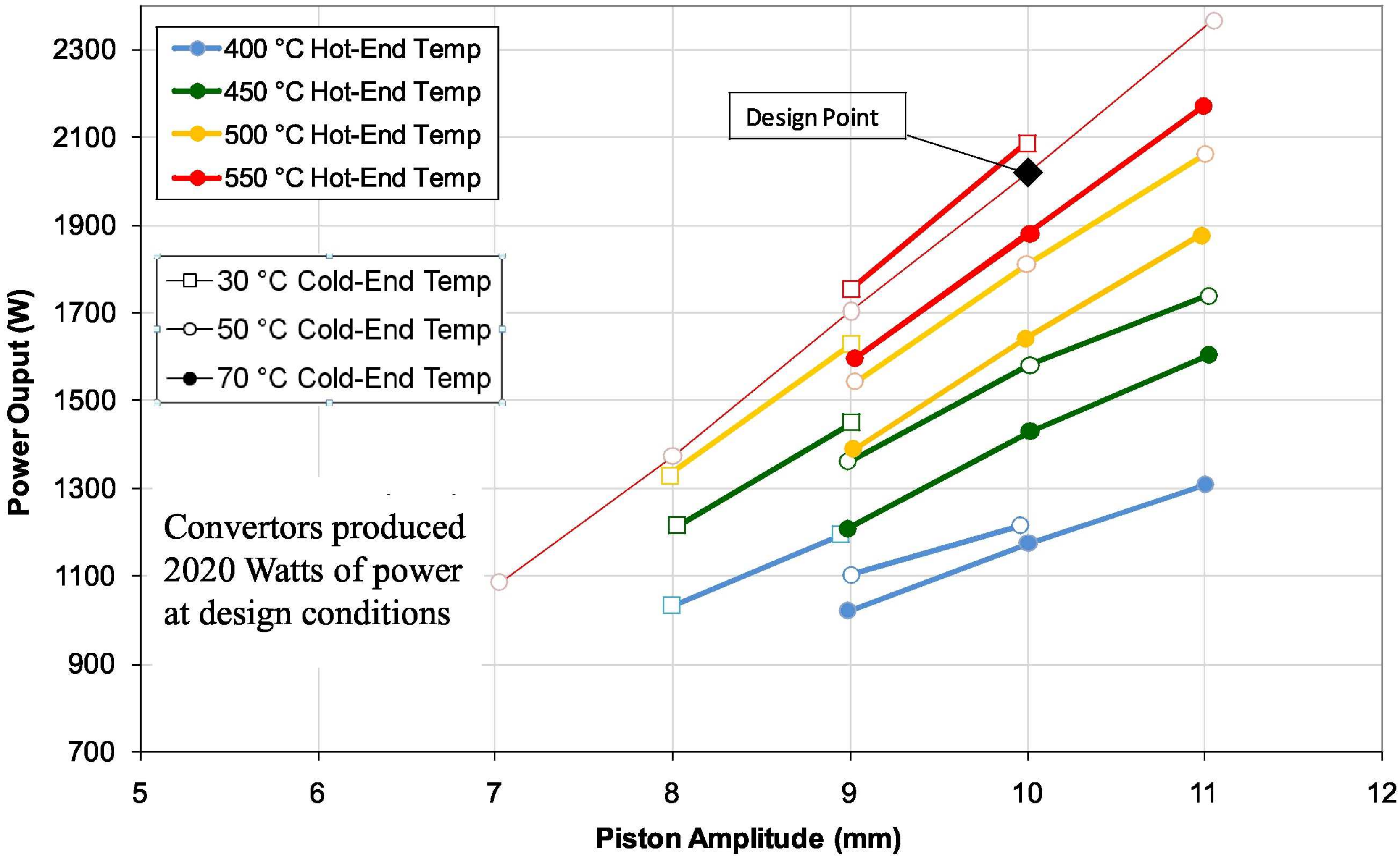
Convertors Installed in Pumped NaK Loop



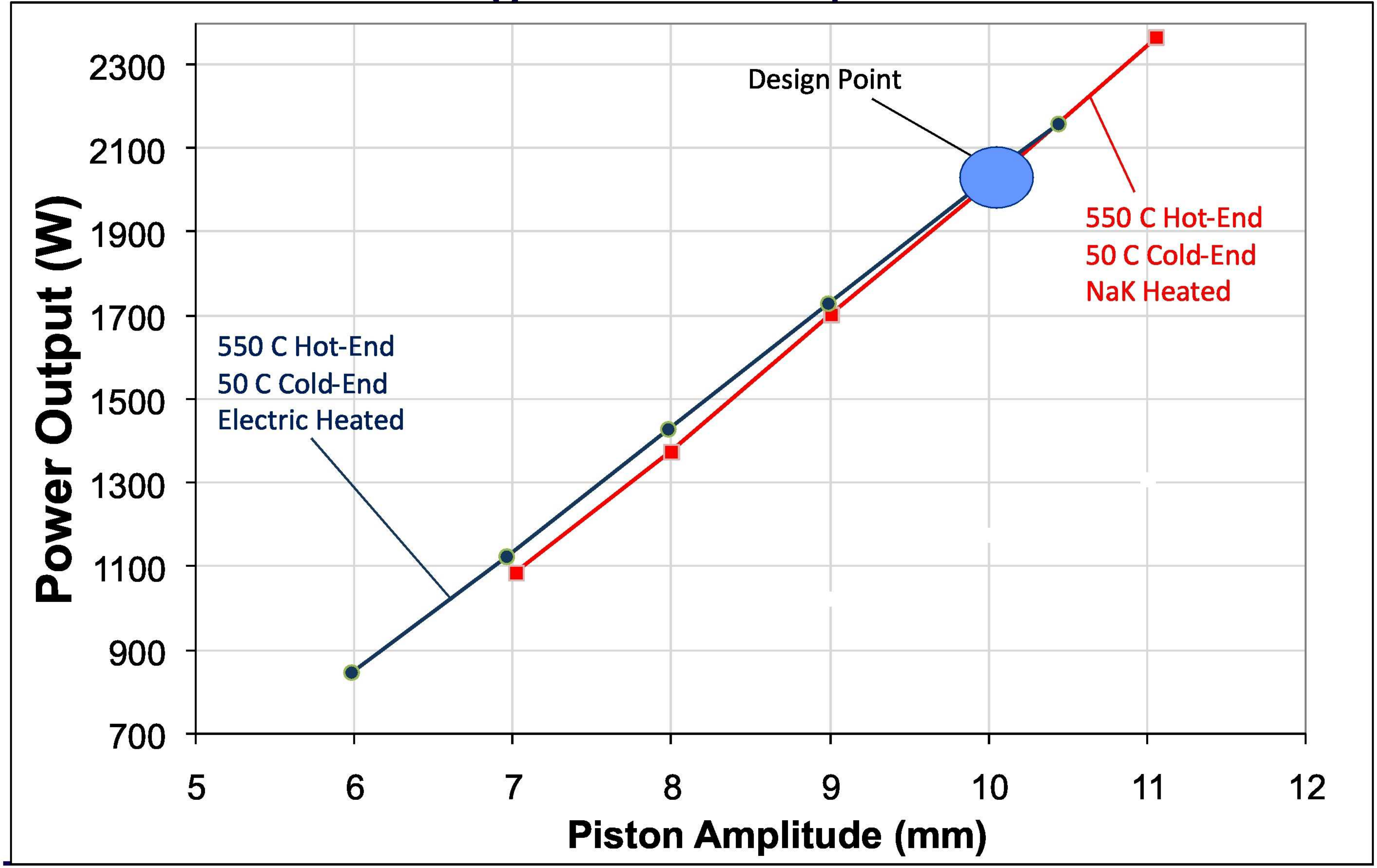
Test Conditions

- Performance Map
  - Hot-End Temperature
    - 400 °C – 550 °C
  - Cold End Temperature
    - 30 °C – 70 °C
  - Piston Amplitude
    - 7 mm – 11 mm at design temperatures
    - 9 mm – 11 mm at off-design temperatures
  - Mass Flow
    - 0.50 kg/s - 0.85 kg/s
- Start-ups
  - Low Temperature – Low Flow
  - Low Temperature – High flow
  - High Temperature – Low Flow
  - High Temperature – High Flow
- Fault Tolerance
  - Loss of ALIP pump
  - Convertor stall
  - Loss of heater

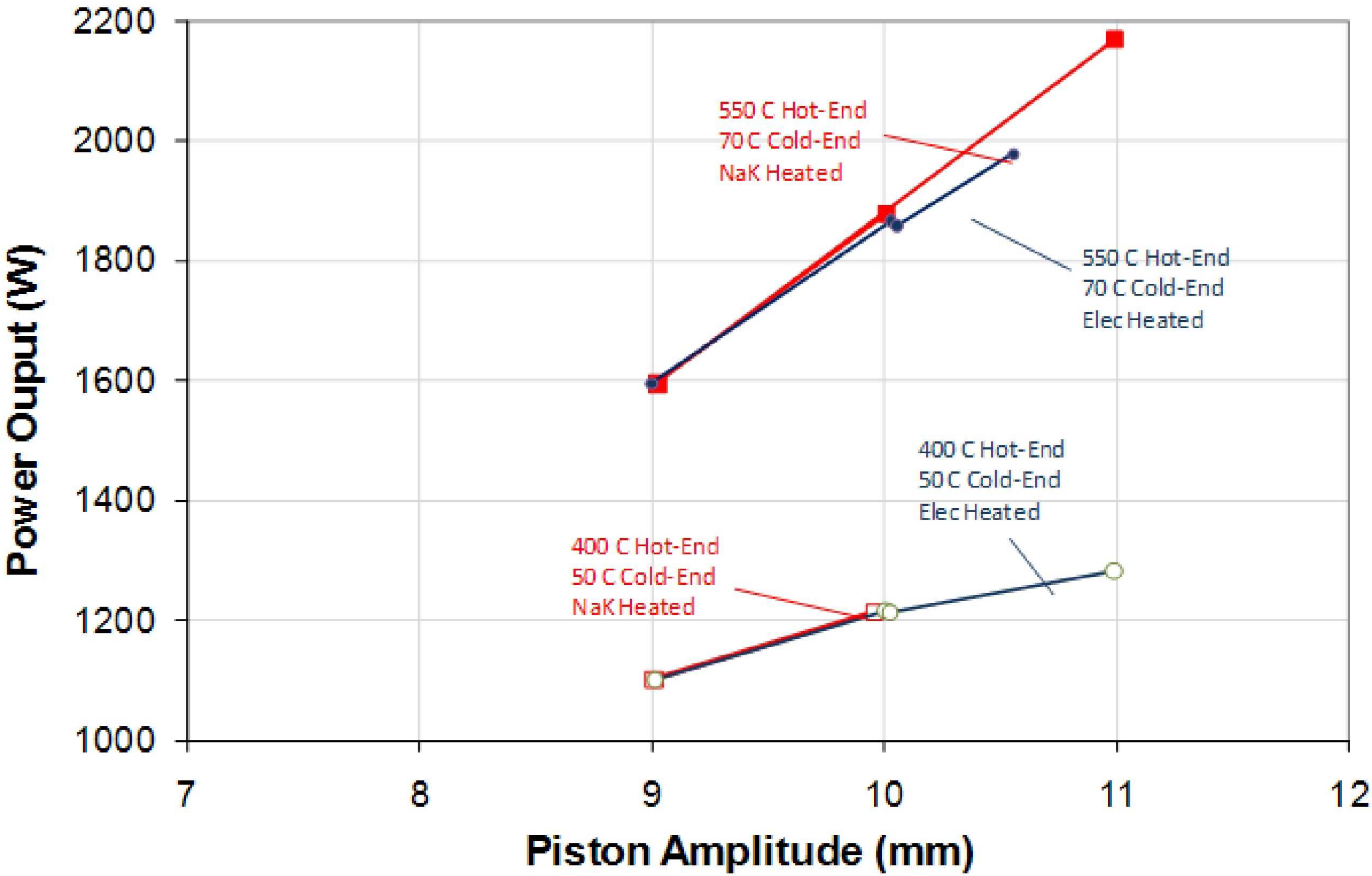
Test Results from NaK testing



Comparison of NaK and Electric Test Data at Design Point Temperatures

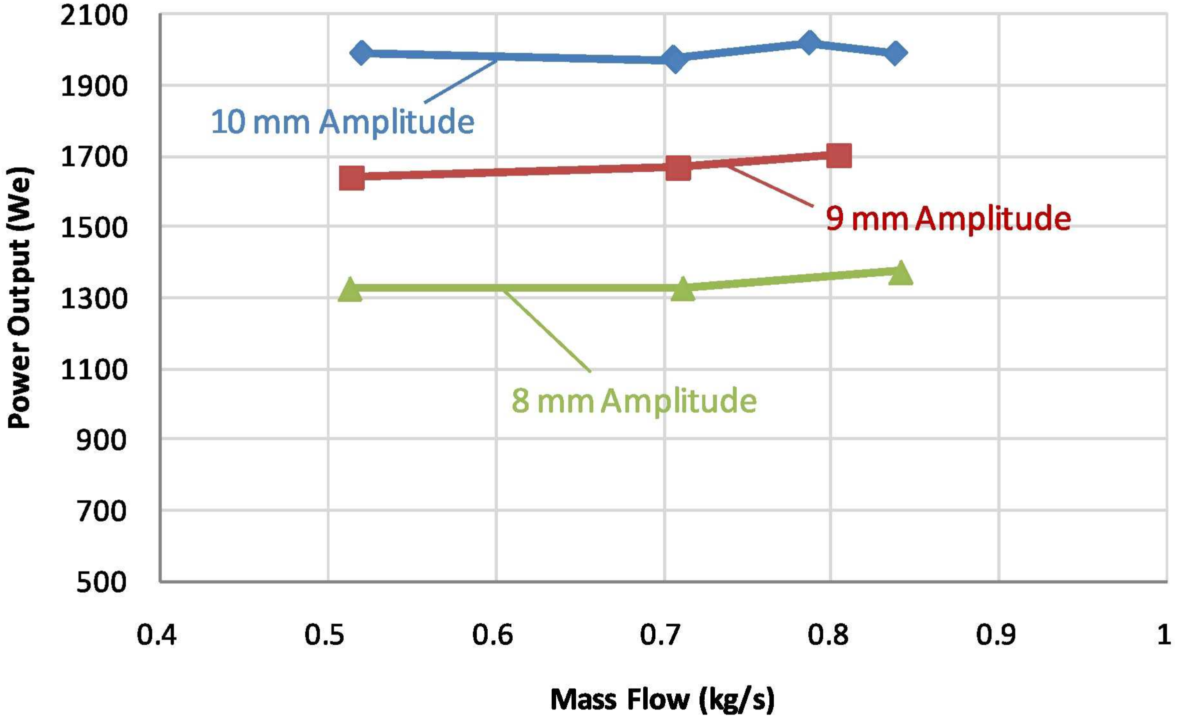


Comparison of NaK and Electric Test Data at Off-Nominal Temperatures



Mass Flow Sensitivity

550 °C Hot-End Temp and 50 °C Cold End Temp



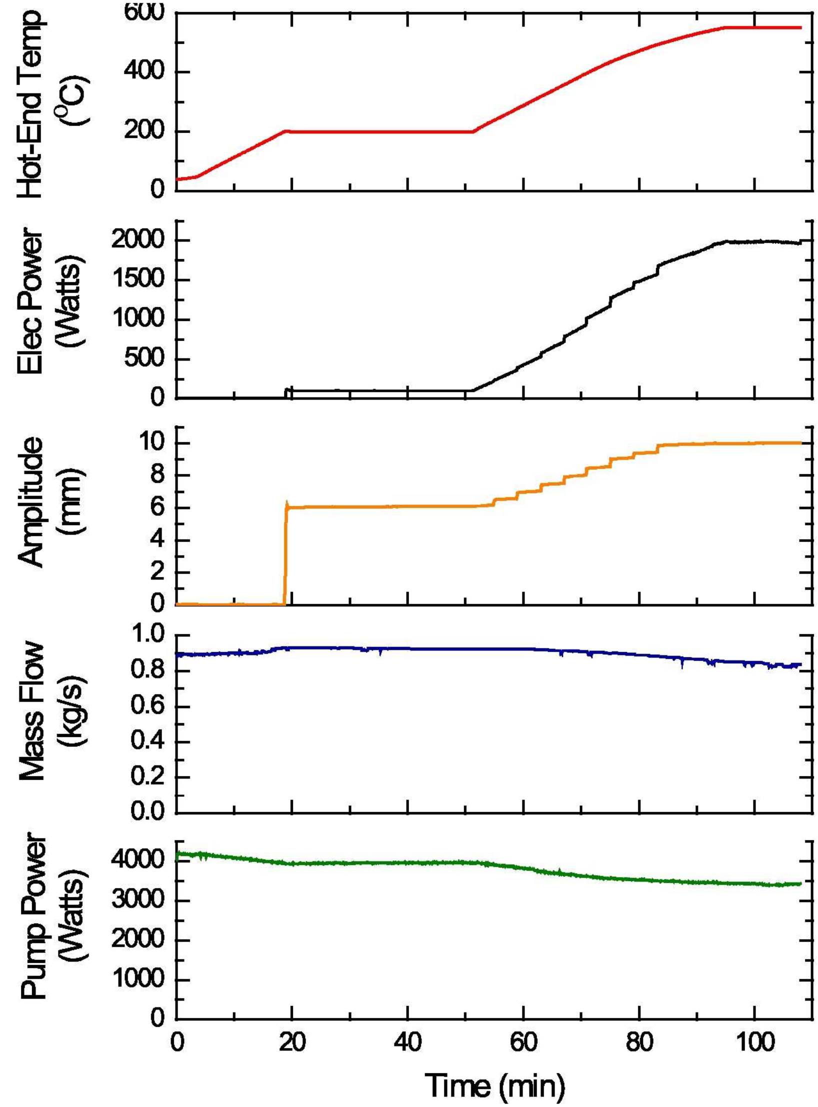
- Maximum mass flow limited by ALIP pump.
- Minimum mass flow limited by maximum heater head temperature gradient (40°C)
- Insensitivity of power output to reduction in mass flow indicates that the operating point chosen for this testing lies beyond the point of diminishing returns.

FSP PCU Startup Scenarios Trades

- Starting convertor at relatively low temperature (200 °C)
  - Reduces the need for auxiliary power
    - Convertors produce electrical power as soon as possible
    - Auxiliary water loop heating requirement is reduced
  - Changes the heat draw on the reactor early in the start-up sequence
- Starting convertor at relatively high temperature (550 °C)
  - Increases the need for auxiliary power
    - Convertors wait longer to produce power
    - Auxiliary water loop heating requirement is increased
  - May benefit the reactor or other system components
- Low NaK flow convertor start
  - Decreases pump power requirement
  - Increases temperature gradient in the reactor
- High NaK flow convertor start
  - Increases pump power requirement
  - Decreases temperature gradient in the reactor

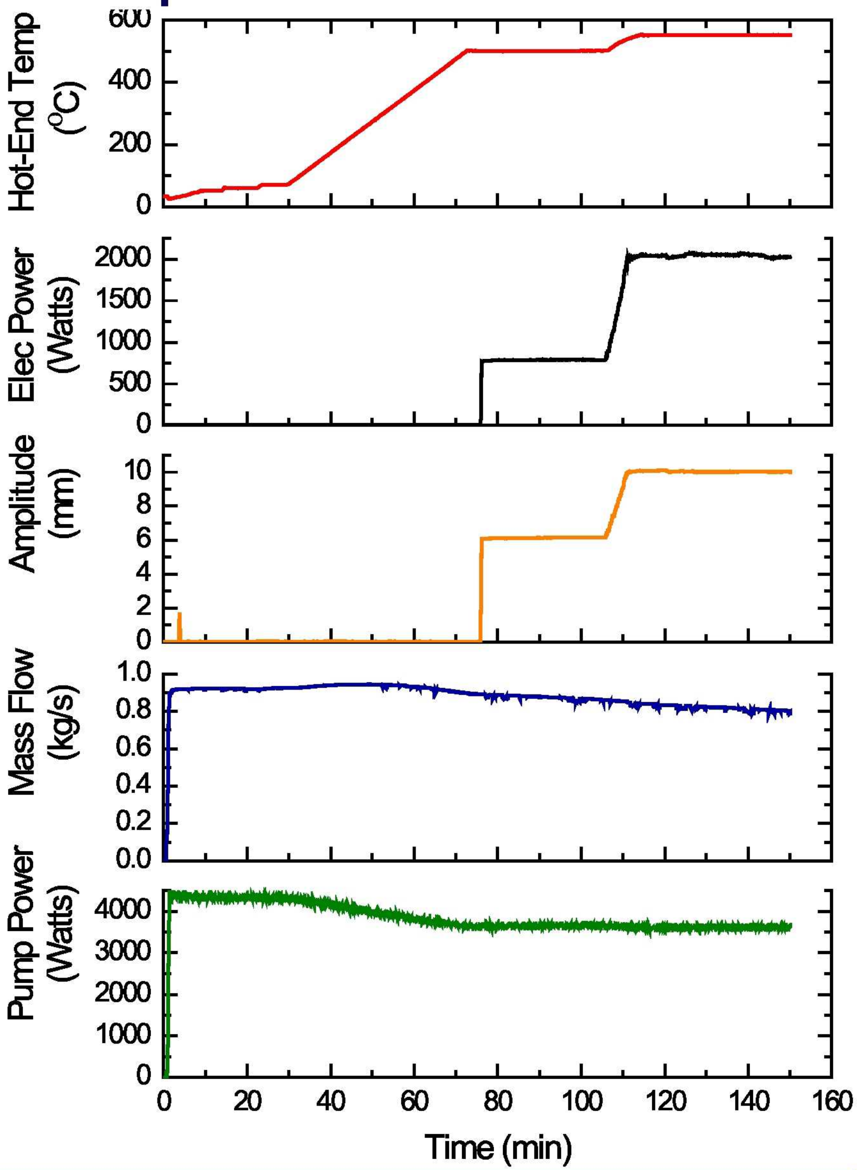
High NaK Flow Low Temperature Start

- Similar to standard startup procedure
- Amplitude set to 6 mm at 200 °C on the hot-end
- 30 minute dwell
- Piston amplitude ramped to 10 mm
- Power increased to full power as piston amplitude was increased to 10 mm



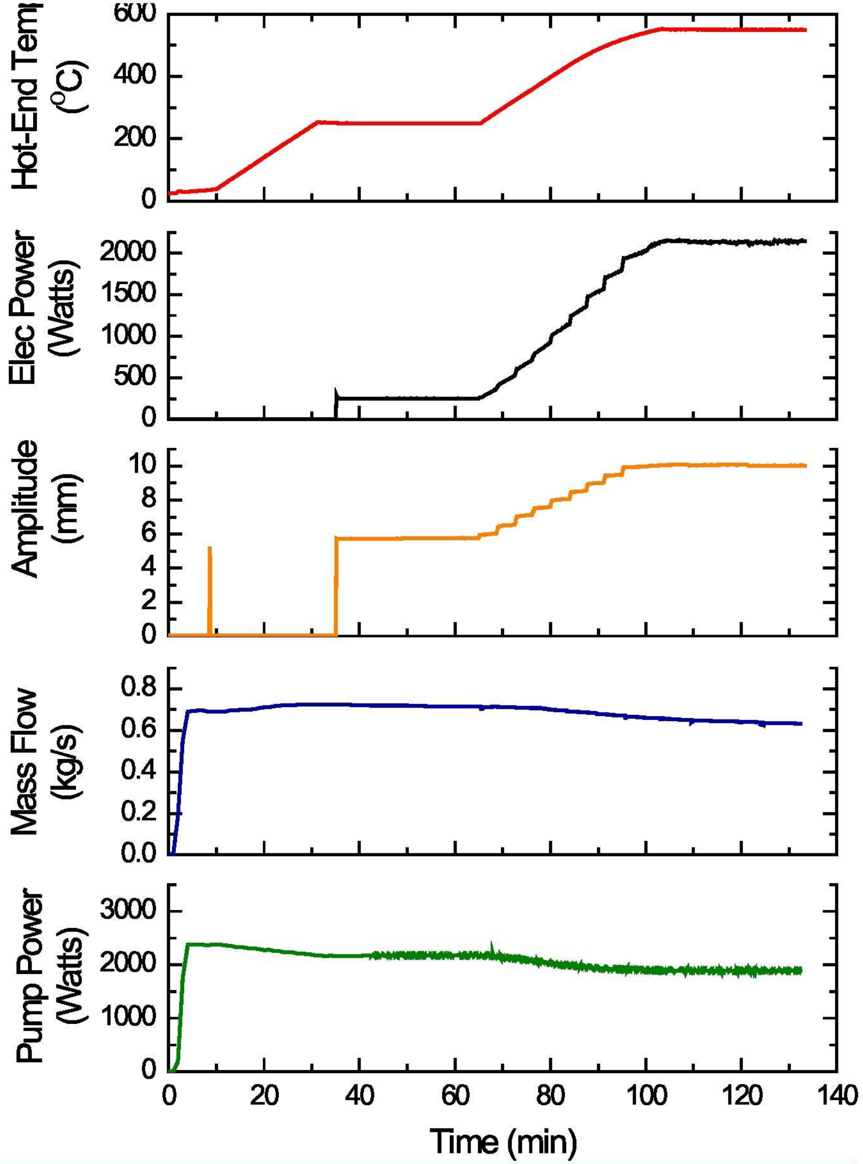
High NaK Flow High Temperature Start

- Amplitude set to 6 mm at 500 °C on the hot-end
- 30 minute dwell
- Ramped piston amplitude to 10 mm
- Power increased as piston amplitude was increased to 10 mm



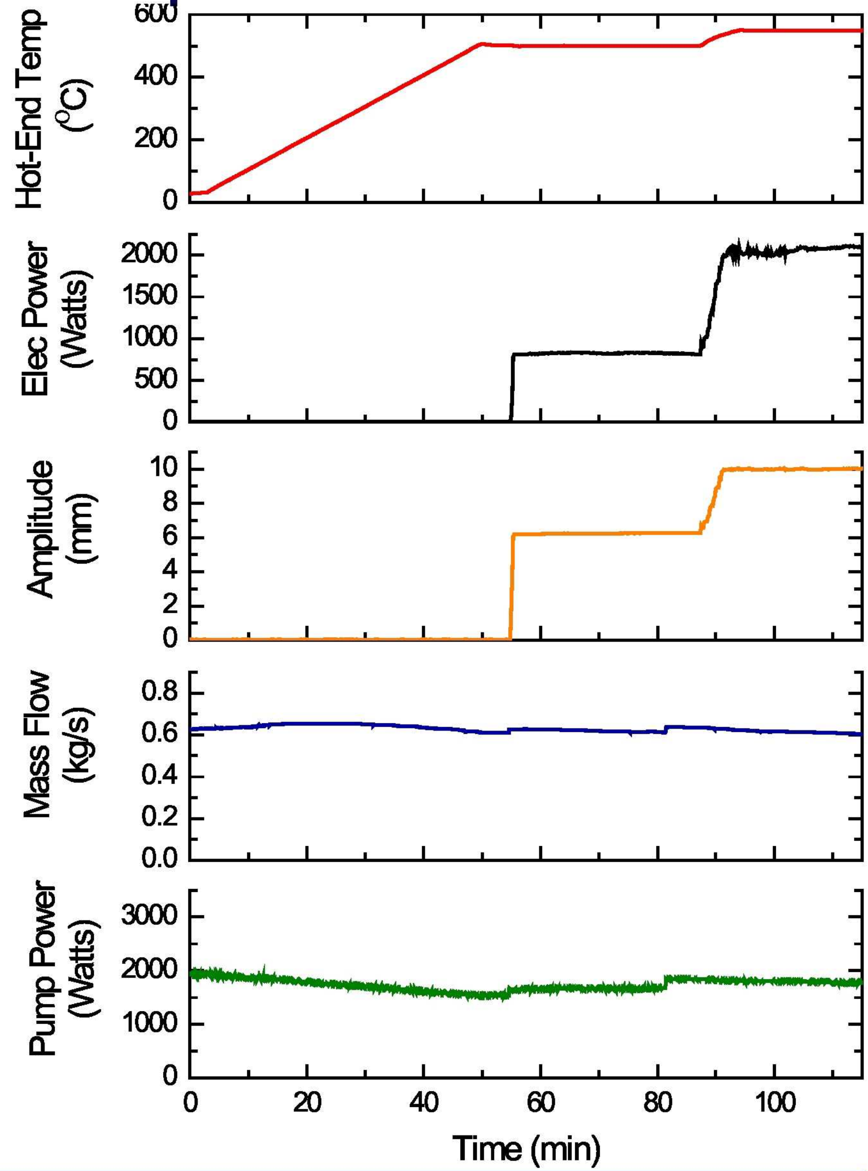
Low NaK Flow High Temperature Start

- Amplitude set to 6 mm at 250 °C on the hot-end
- 30 minute dwell
- Ramped piston amplitude to 10 mm
- Power increased to full power as piston amplitude increased



High NaK Flow High Temperature Start

- Amplitude set to 6 mm at 500 °C on the hot-end
- 30 minute dwell
- Ramped piston amplitude to 10 mm
- Power increased to full power as piston amplitude increased



Fault Tolerance Scenarios

- Loss of ALIP Pump
  - Considered most dangerous to convertors
  - Could potentially create a very cold slug of NaK
  - Could induce large temperature gradients in the NaK heat exchanger

- Piston stall
  - Can the pistons safely be restarted.
  - How soon can full power operation be restored?

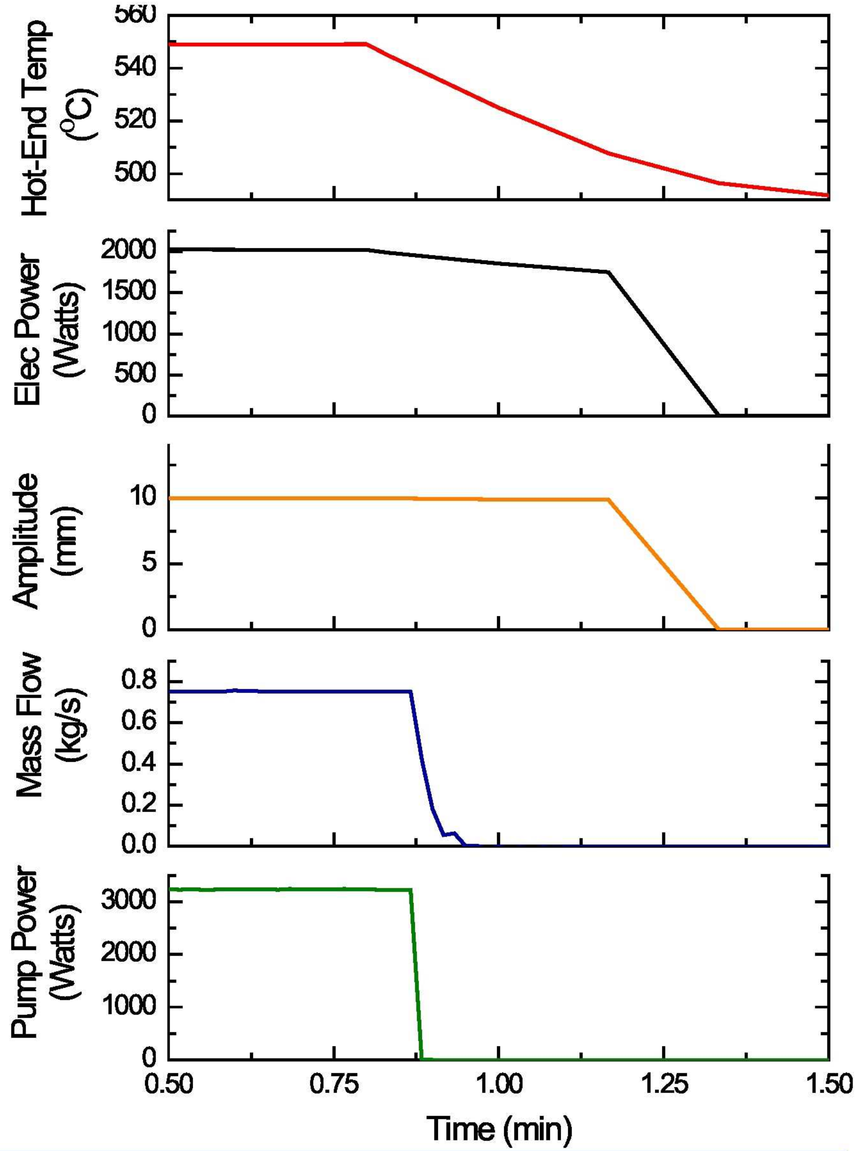
- Loss of heater
  - Considered most benign
  - Similar to standard convertor shutdown

Loss of ALIP Pump

- Hot-end temperature drops as convertor continues to pull heat from stationary fluid

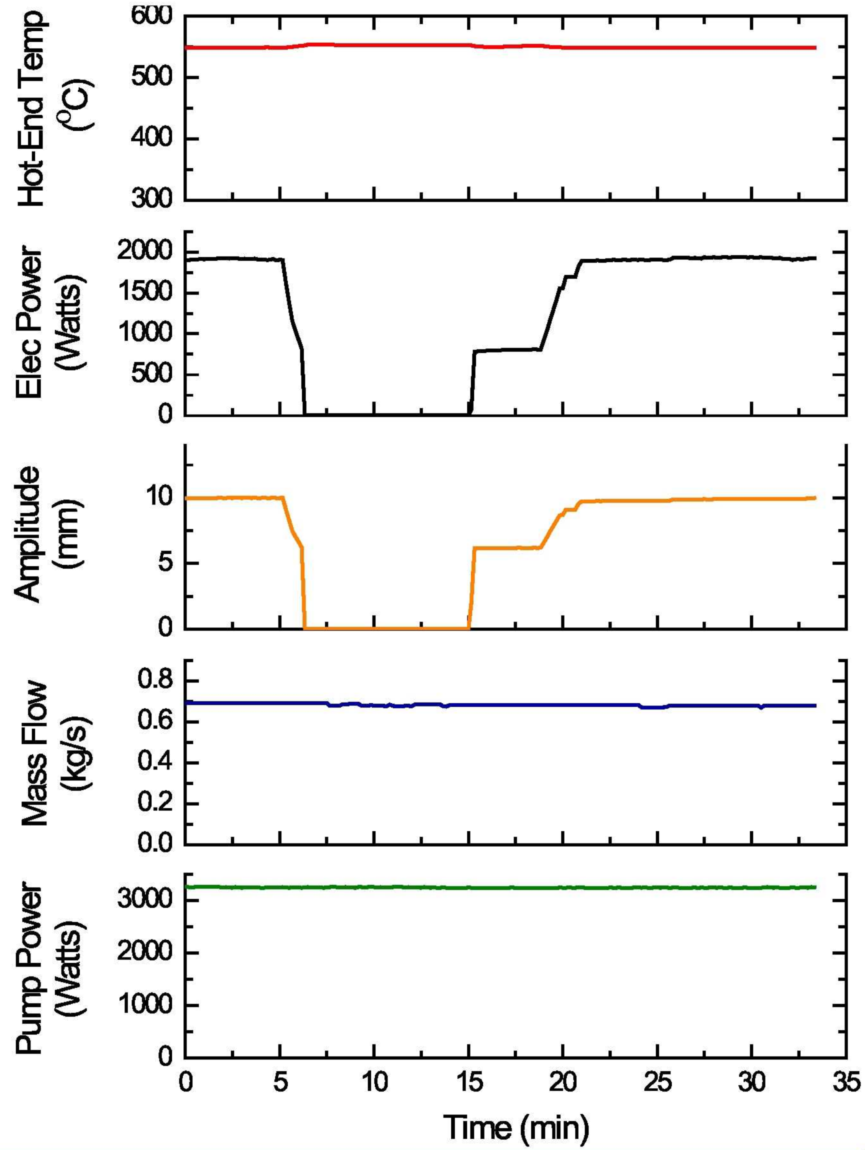
- Cold slug of NaK introduces the risk of thermal shock if the pump is restarted

- After approximately 40 seconds the pistons were stalled in order to prevent further drop in NaK temperature



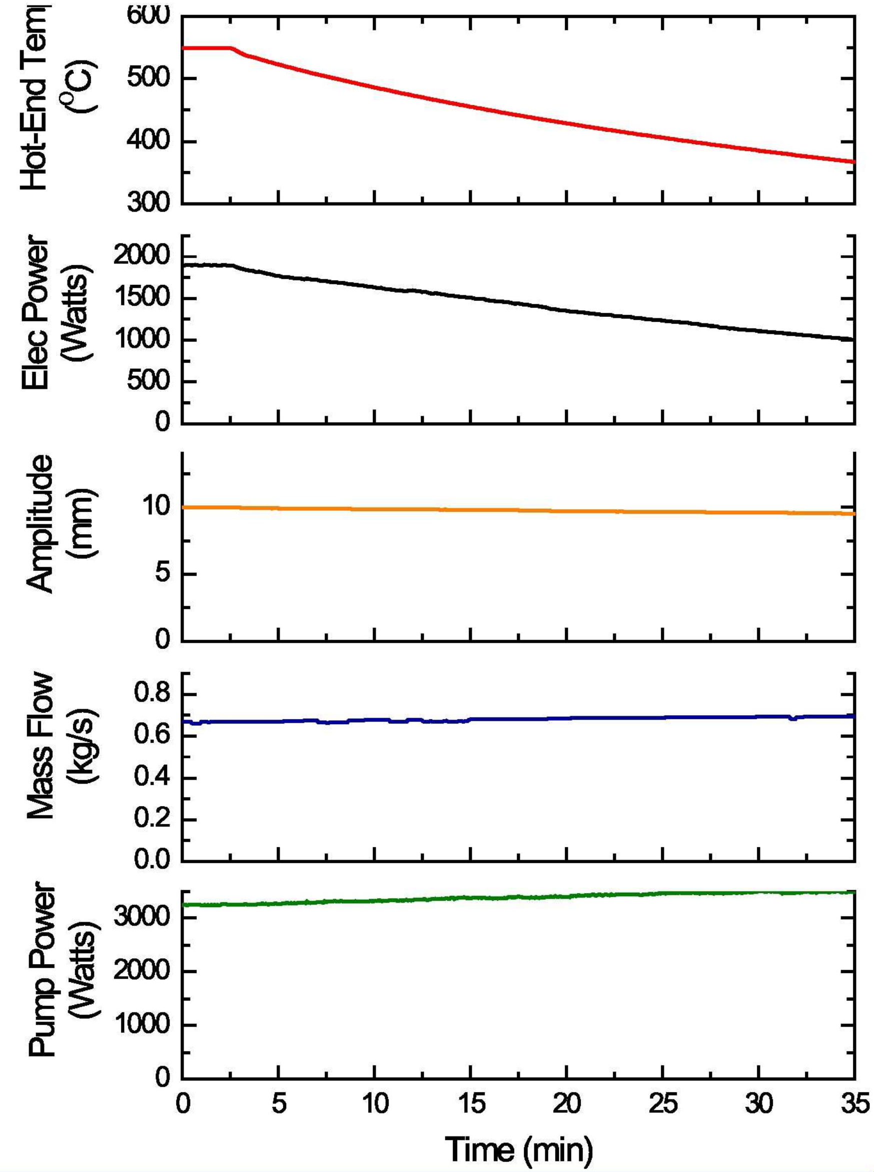
Piston Stall

- Pistons were quickly stalled
- 10 minute dwell
- Piston amplitude was returned to 6mm amplitude
- After a 5 minute dwell the piston amplitude was incrementally increased to 10 mm.



Loss of heater

- The NaK heater was turned off with the ALIP pump running
- The PCU continued to draw residual heat from the NaK slowly, similar to the standard shutdown
- Amplitude was held constant



Conclusions

- A dual-opposed 2-kW power conversion unit was successfully operated at full power using a NaK heat exchanger for thermal input.
- When compared with electrical resistance heating, PCU performance was very similar and in some cases better when using the NaK heat exchanger.
- None of the tested startup scenarios raised concerns for the health of the convertors themselves. Therefore constraints on the choice of startup scenario is are likely to come from other components.
- Loss of the ALIP pump was shown to be a significant threat to the Stirling convertors. The pistons must be stalled quickly to avoid rapid cooling and possible freezing of the NaK.
- As long as the piston is brought to full amplitude gradually, convertors may be restarted after a stall, returning to full power operation
- Loss of the heat source did not present any major concerns to the health of the convertor as it can be treated as part of a normal shutdown.
- Loss of the cooling loop was not simulated as it is considered the most risky event for the convertors, too risky to accommodate with the test hardware.
  - Backup cooling methods are suggested for future testing to avoid potential issues.

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The opinions expressed in this presentation are those of the author and not necessarily those of the NASA.