Supercritical CO_2 Power Cycles Symposium

Design of a High-Temperature Test Facility for an Additive Manufactured Supercritical Carbon Dioxide Turbine

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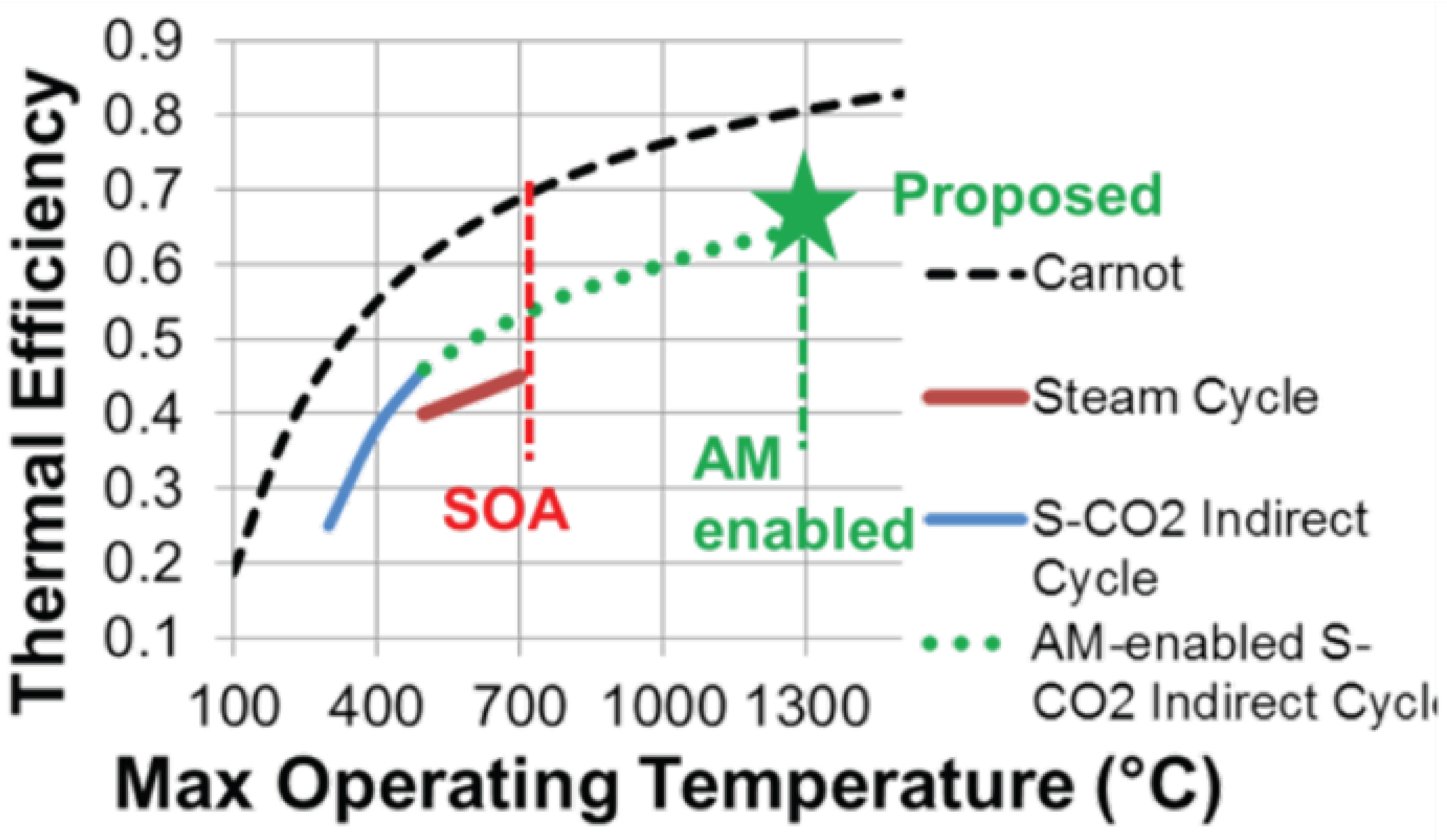
ADDLab Alloy Design and Development · Raytheon Technologies · Sandia National Laboratories · SCL · Thermal Hydraulics Laboratory · WEMPEC

Motivation

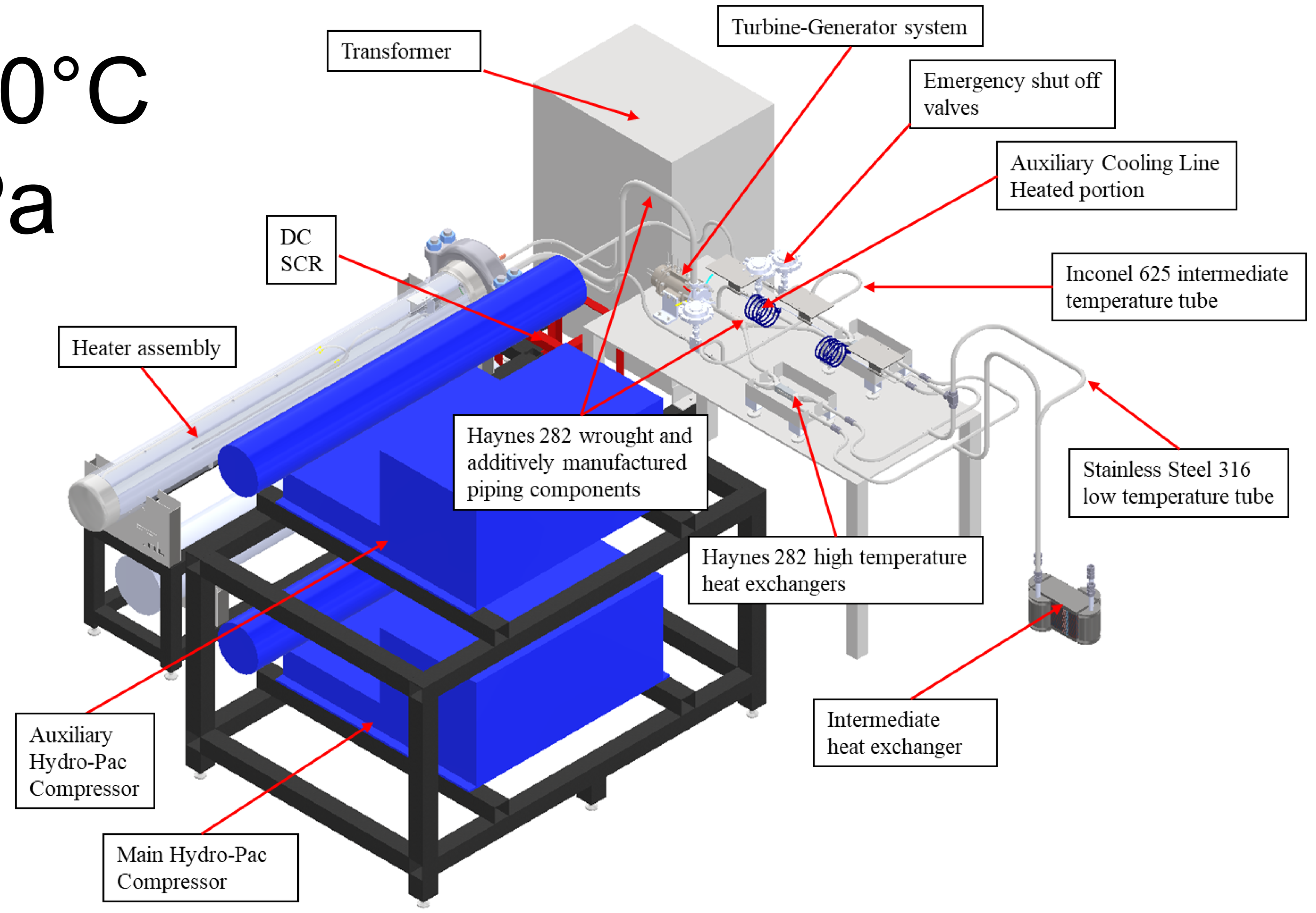
- Supercritical carbon dioxide (sCO2) power cycle has the potential to provide higher heat to power conversion efficiencies in combined heat and power applications than competing technologies
- Very high turbine inlet temperatures are required to achieve high thermal efficiency
- Department of Energy's target of 65% efficiency will require turbine inlet temperatures approaching 1300ºC
- Further metallurgical advancements needed
- Development of complex turbine and generator cooling systems required
- Additive manufacturing of turbine systems using advanced nickel-based super-alloys such as Haynes 282 has the potential to allow for higher temperature operation, and provides design flexibility
- Additive manufacturing provides a potential path towards addressing both material and cooling design challenges associated with high efficiency, high-temperature cycle operation
- Need development of test facilities that can be used to characterize and validate the performance of novel turbine-generator system designs enabled by additive manufacturing

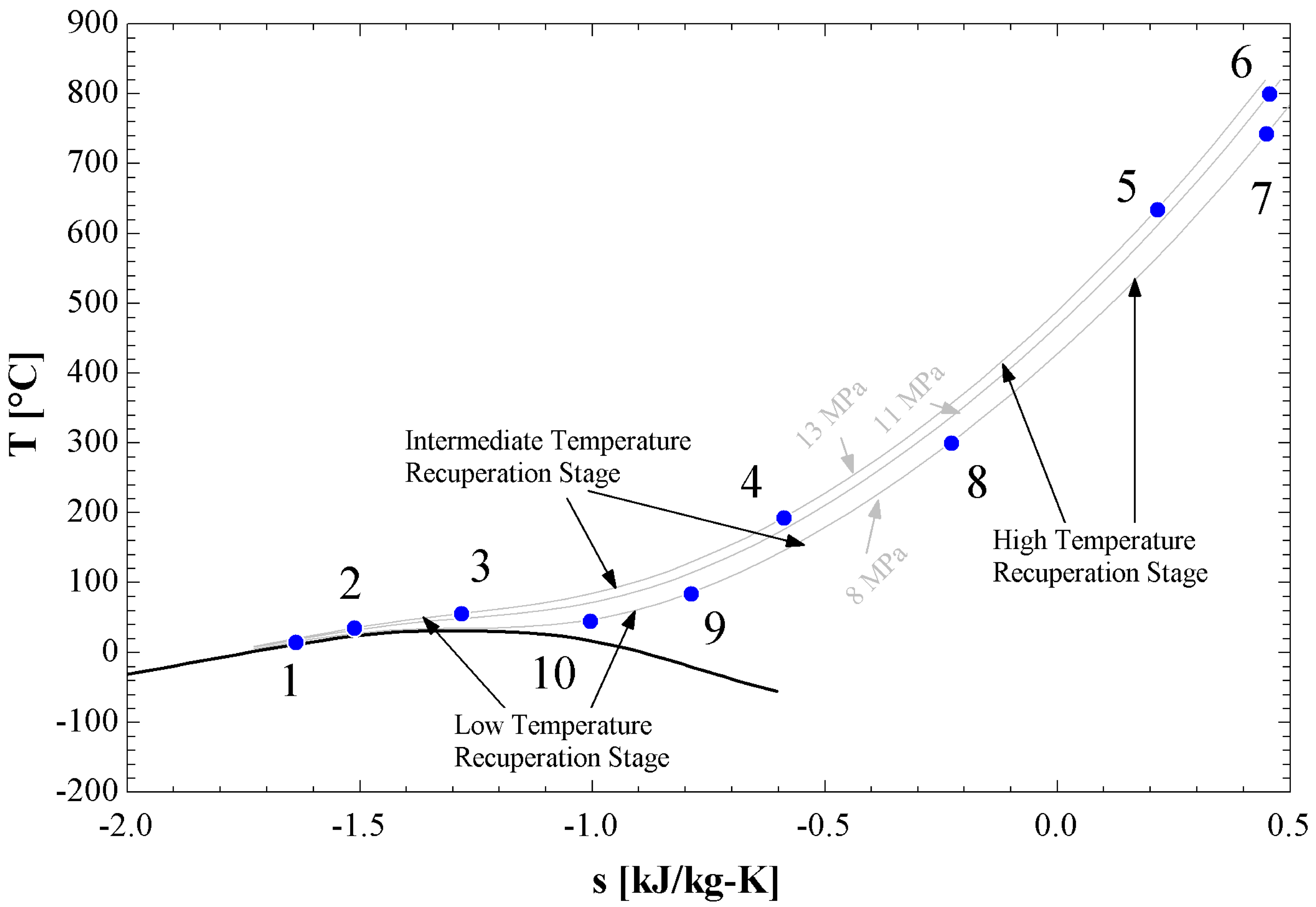


Objective

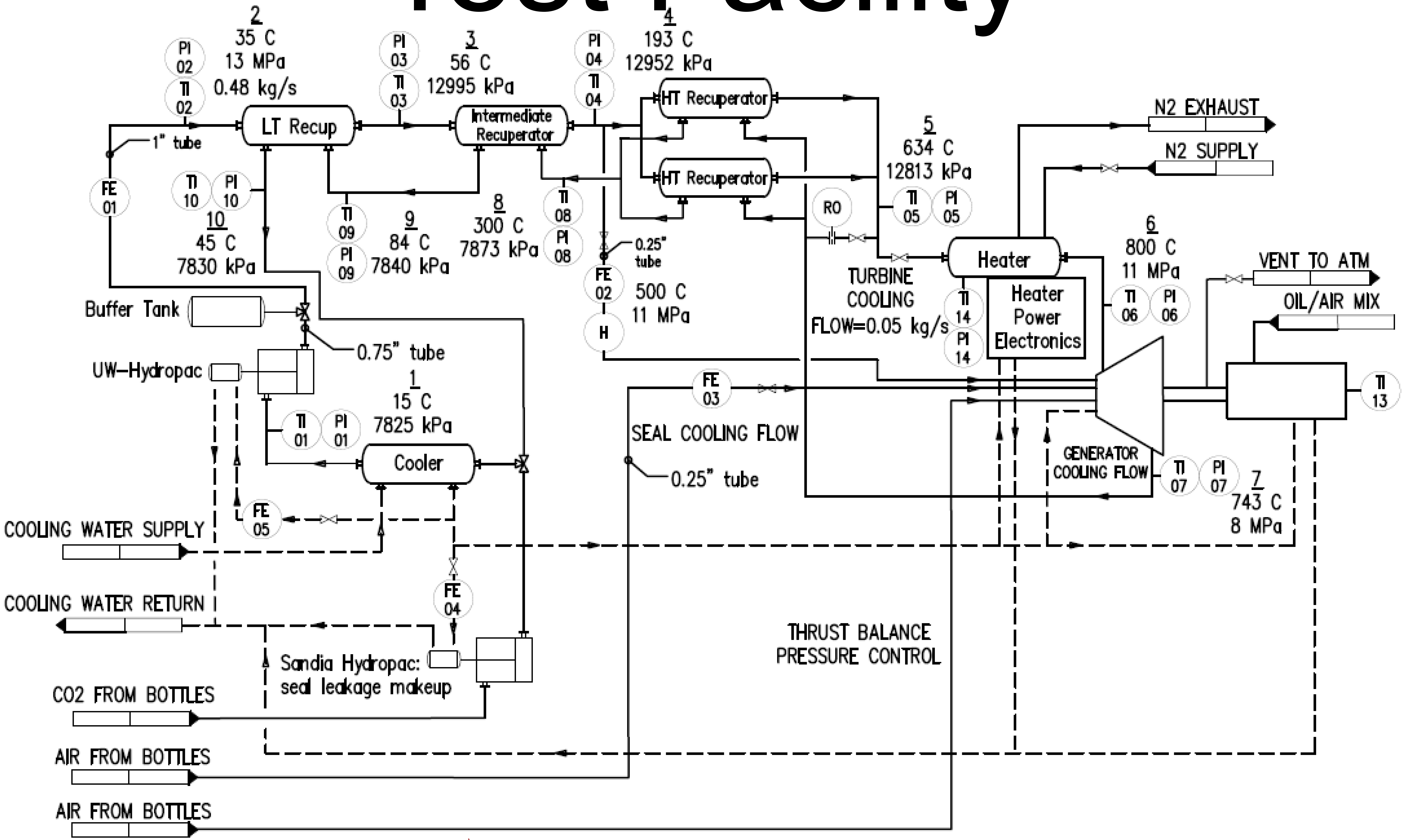
Design and build a test facility capable of meeting the required conditions for an additive manufactured turbine and facilitate auxiliary flow requirements

- Turbine Inlet Temperature: 800°C
- Turbine Inlet Pressure: 11 MPa
- Turbine Exit Pressure: 8 MPa
- Mass Flow Rate: 0.43 kg/s





Test Facility



2
35 C
13 MPa
0.48 kg/s
3
56 C
12995 kPa
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193 C
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634 C
12813 kPa
6
800 C
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7
743 C
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LT Recup
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Cooler
UW-Hydropac
0.75" tube
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TURBINE COOLING FLOW=0.05 kg/s
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N2 EXH
N2 SU
THRUST BALANCE PRESSURE CONTROL
COOLING WATER SUPPLY
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Sandia Hydropac: seal leakage makeup
CO2 FROM BOTTLES
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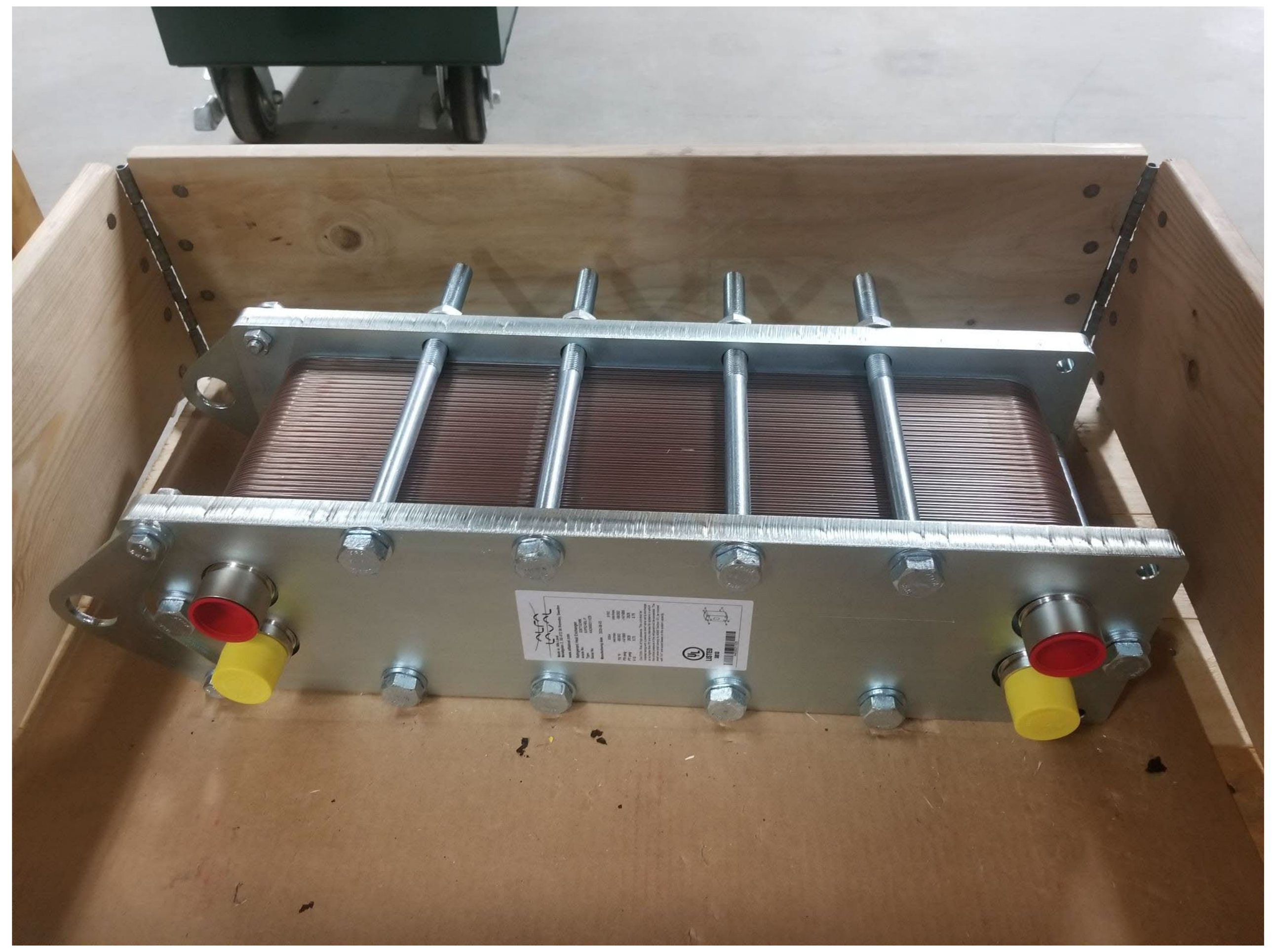
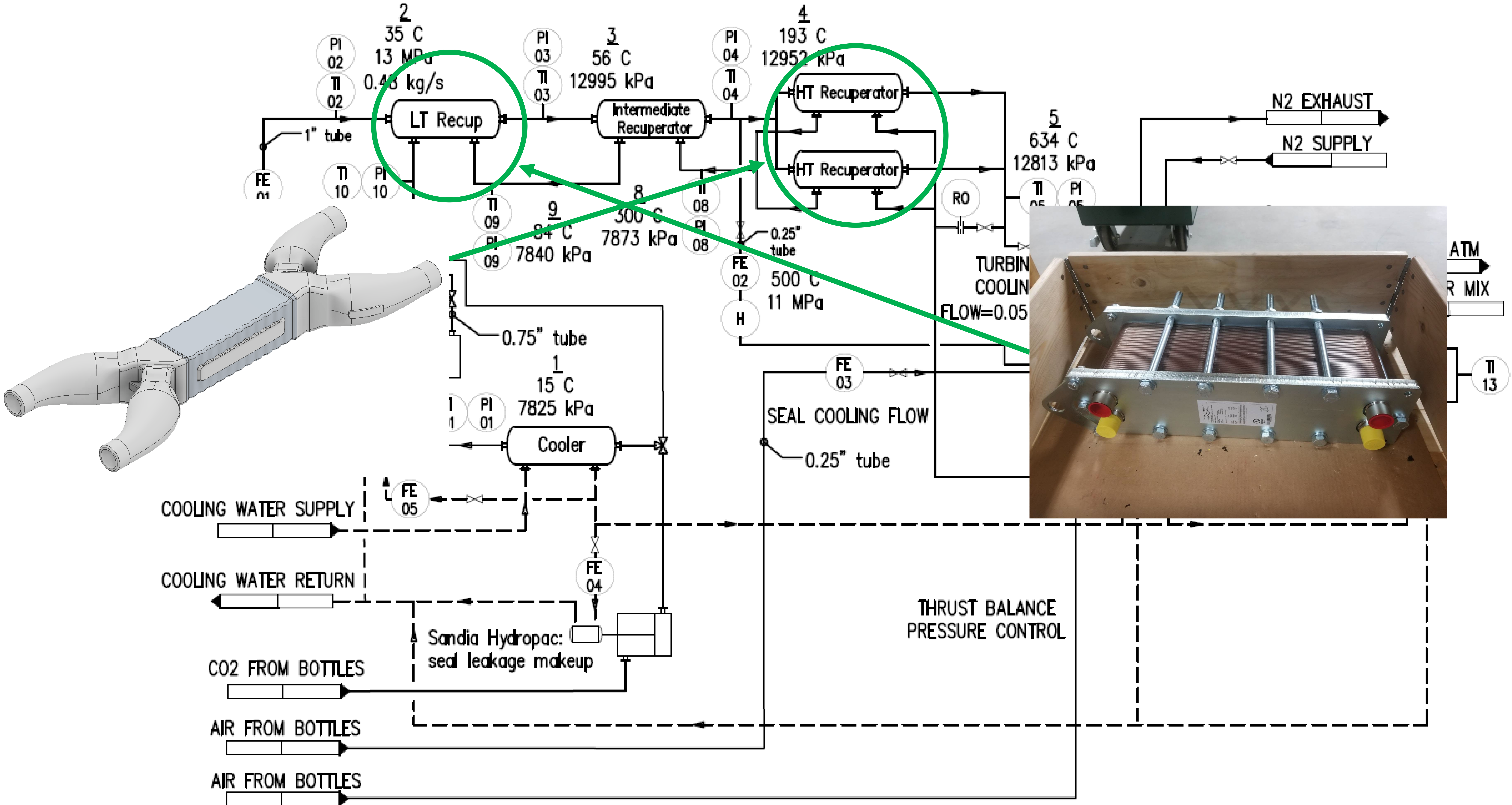
Compressor

- Single-stage, dual-piston Hydro-Pac LX compressor
- Confirmed full system flow rate of 0.48 kg/s and sufficient pressure rise in previous tests
- Reciprocation leads to unavoidable pulsations, but attenuated by system pressure drop and buffer volume to < 1% nominal turbine inlet pressure

Cooler



- Provides heat rejection to low-temperature, incompressible state
- Requirements: Cool sCO_2 50ºC to 15ºC using 40 GPM of 10ºC water
  → 100 kW cooling, 6.1 kW/K conductance
- Oversized Alfa Laval 60 brazed-plate HX
- 122 kW cooling, 7.7 kW/K conductance
- ΔP_{CO2}: 3.7 kPa, ΔP_{H2O}: 30.1 kPa



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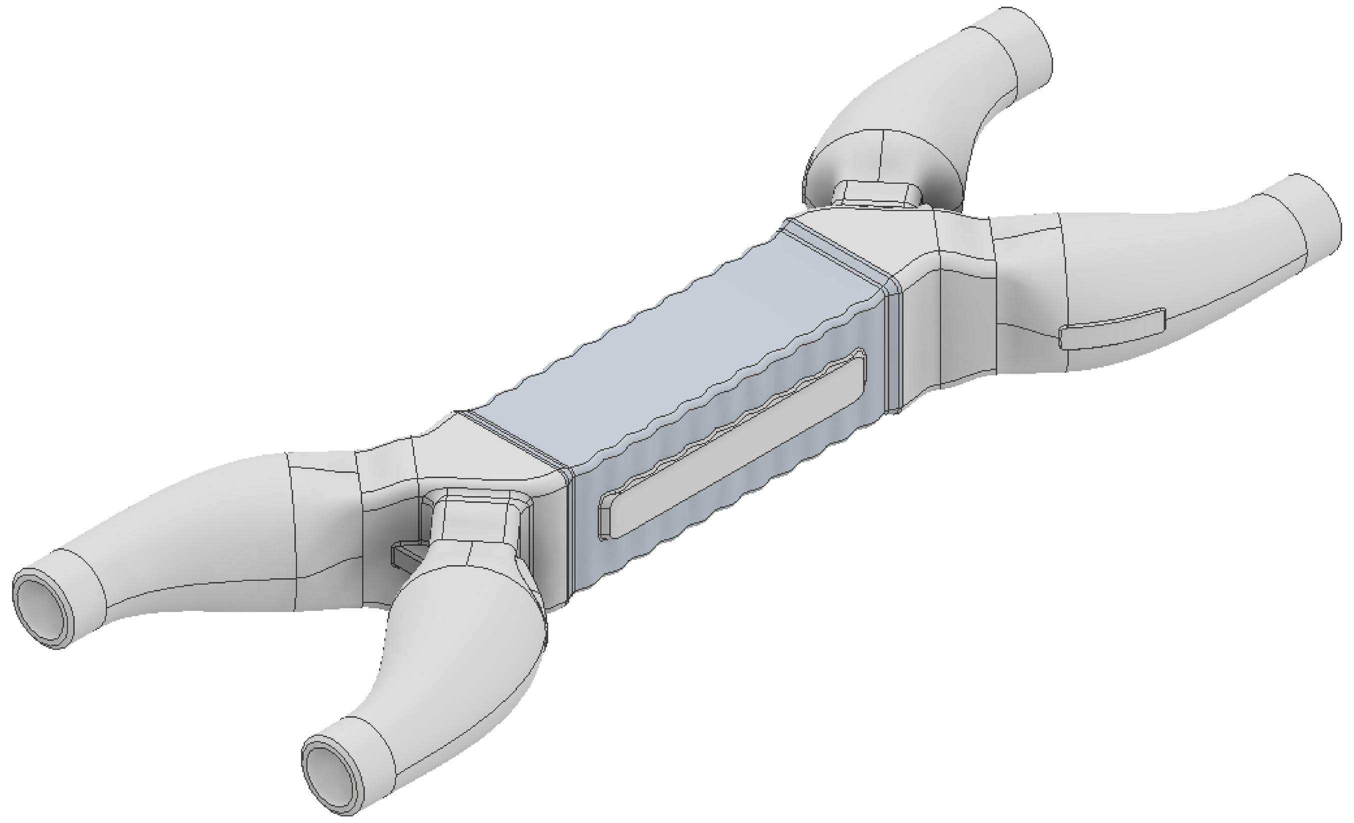
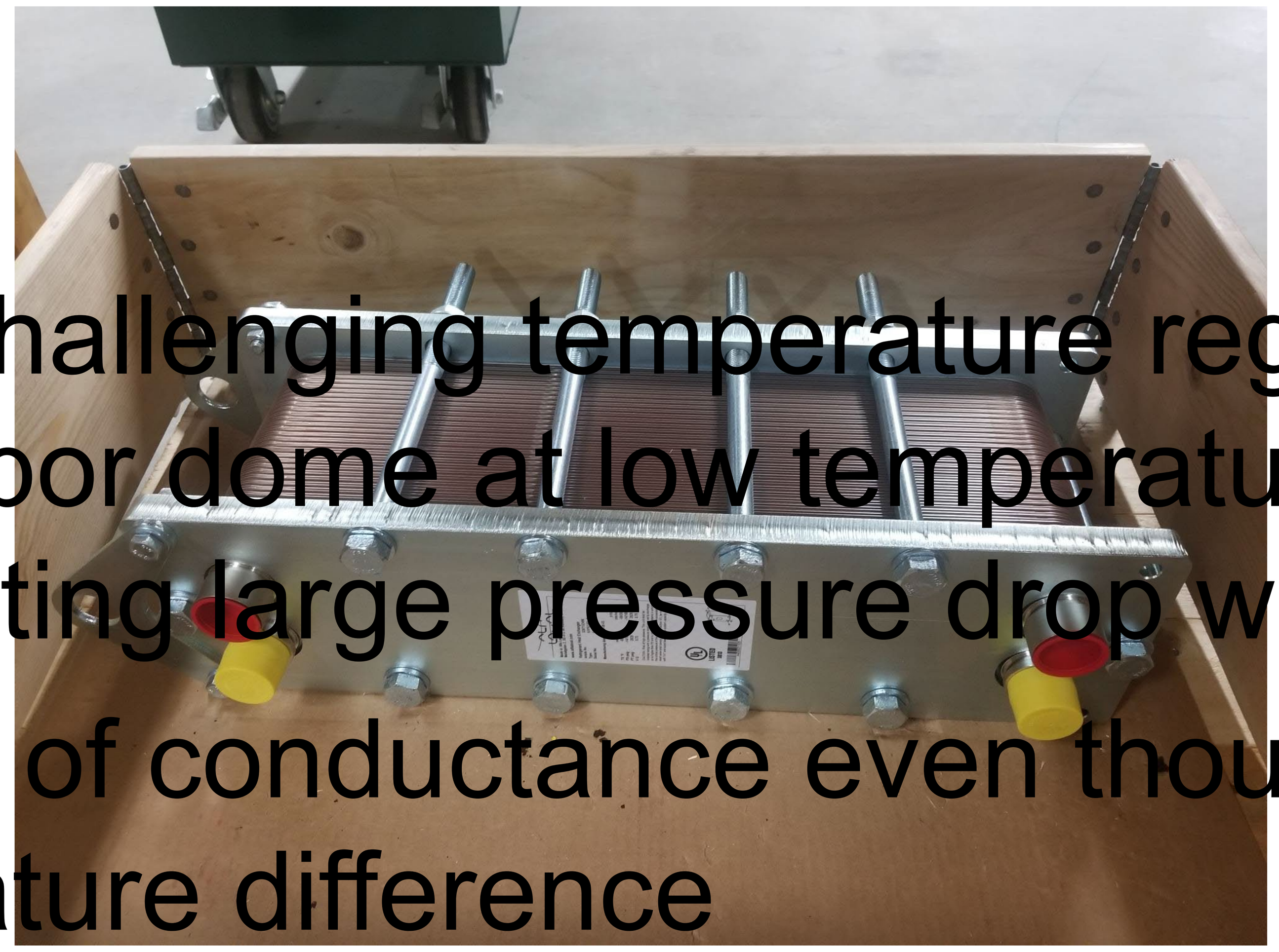
High-Temperature Recuperators

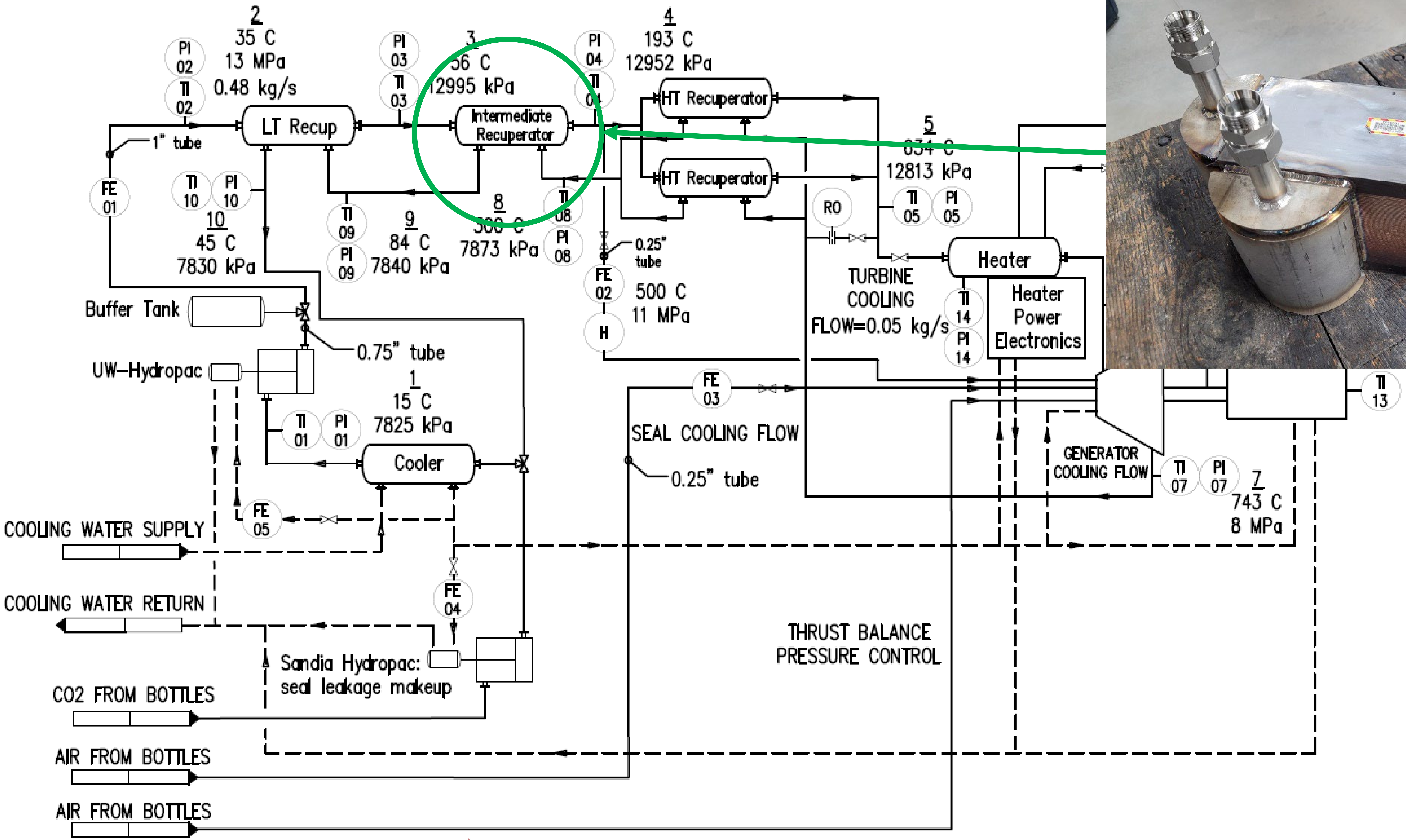


- …red high temperature …at turbine exhaust
- …e 2X AM HX to meet …s and pressure drop constraints
- Cold stream: 193ºC to 634ºC, ΔP: 139 kPa
- Hot stream: 743ºC to 300ºC, ΔP: 127 kPa
- Duty: 125 kW
- UA: 1.13 kW/K
- effectiveness: 0.81

Low-Temperature Recuperators



- Cover challenging temperature regime of recuperation near vapor dome at low temperatures without contributing large pressure drop with brazed plate HX
- Majority of conductance even though small temperature difference
- Cold stream: 35ºC to 56ºC, ΔP: 5 kPa
- Hot stream: 84ºC to 45ºC, ΔP: 10 kPa
- Duty: 35 kW
- UA: 2.5 kW/K
- effectiveness: 0.72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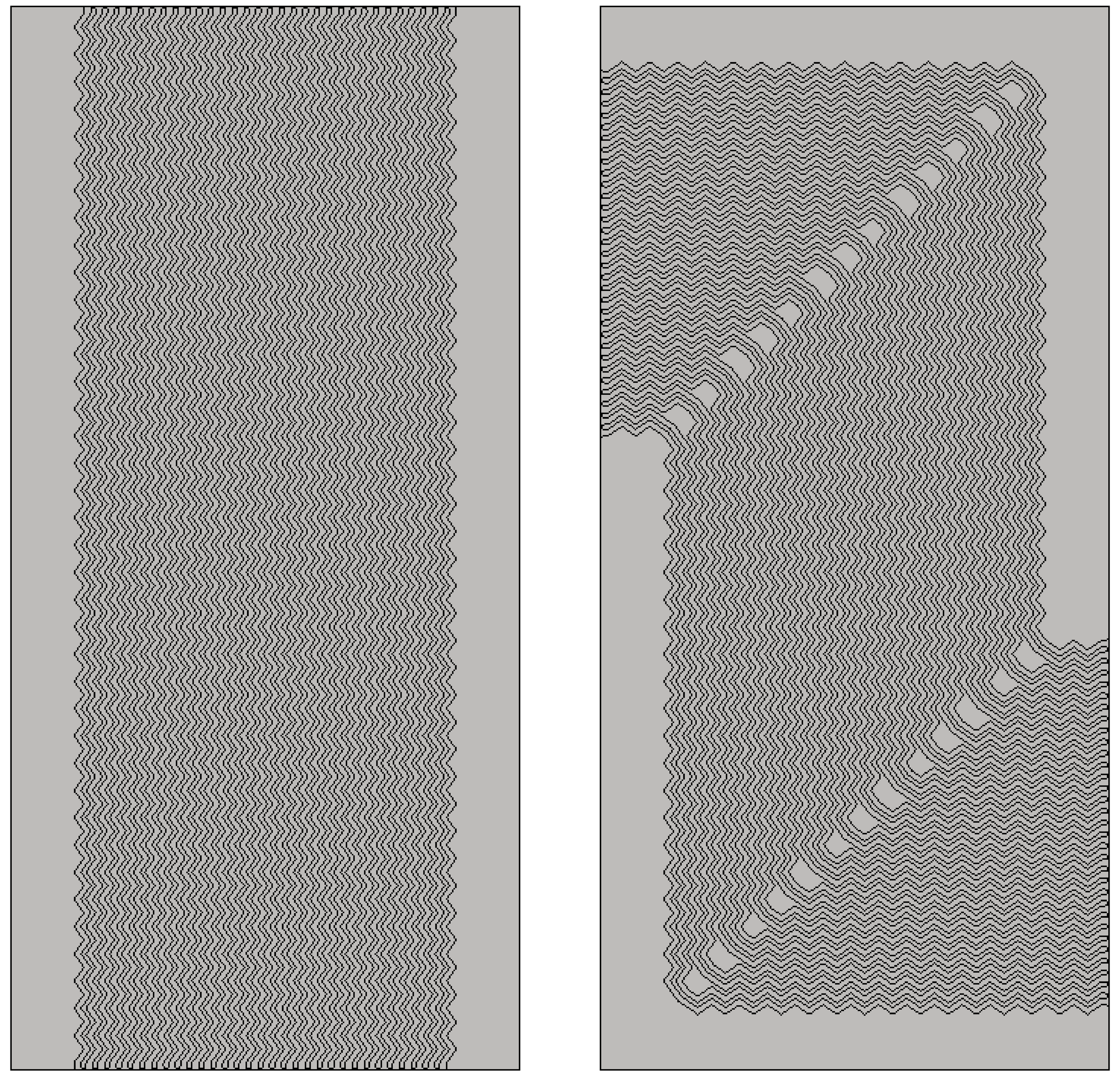
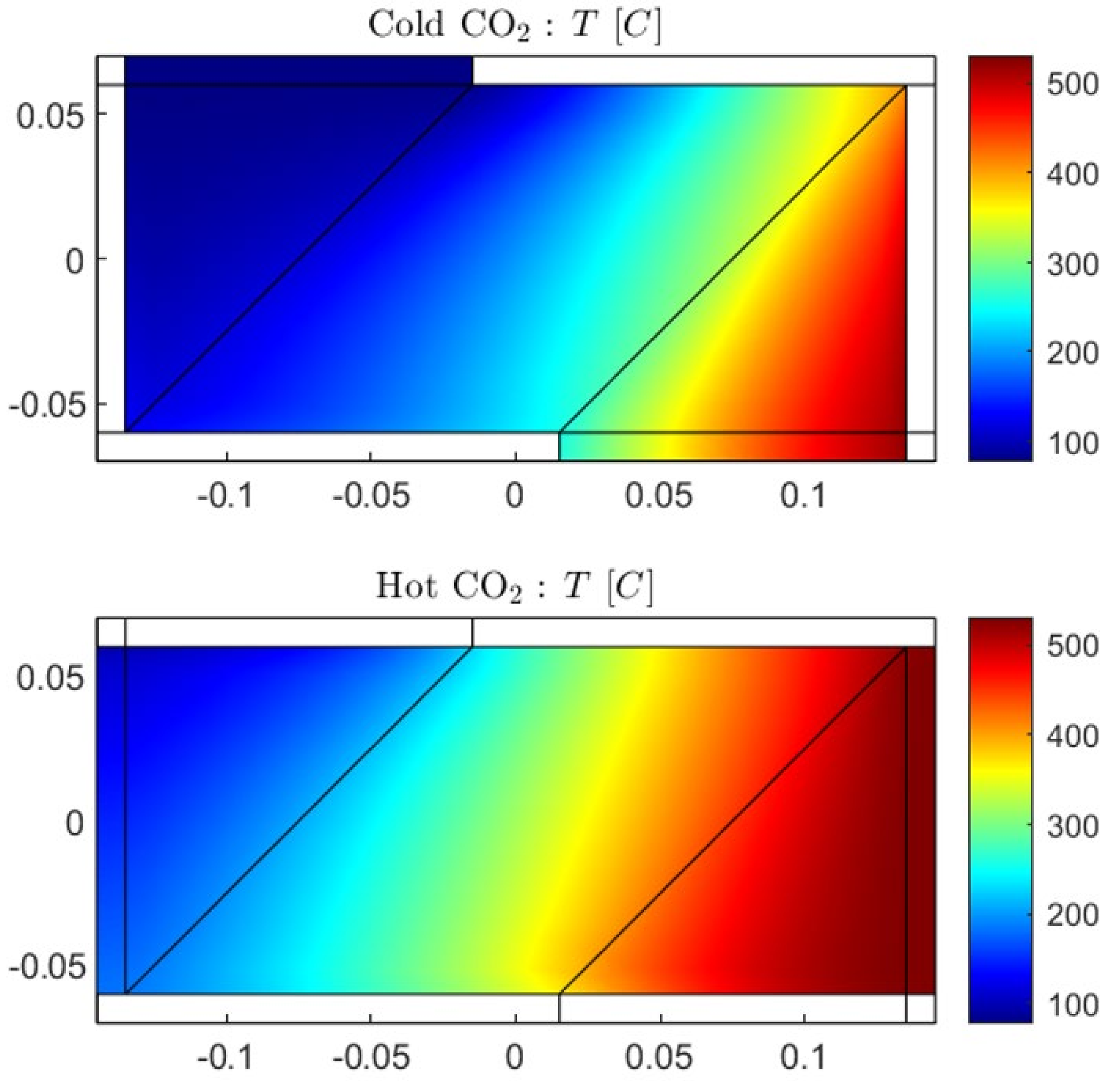
THRUST BALANCE PRESSURE CONTROL

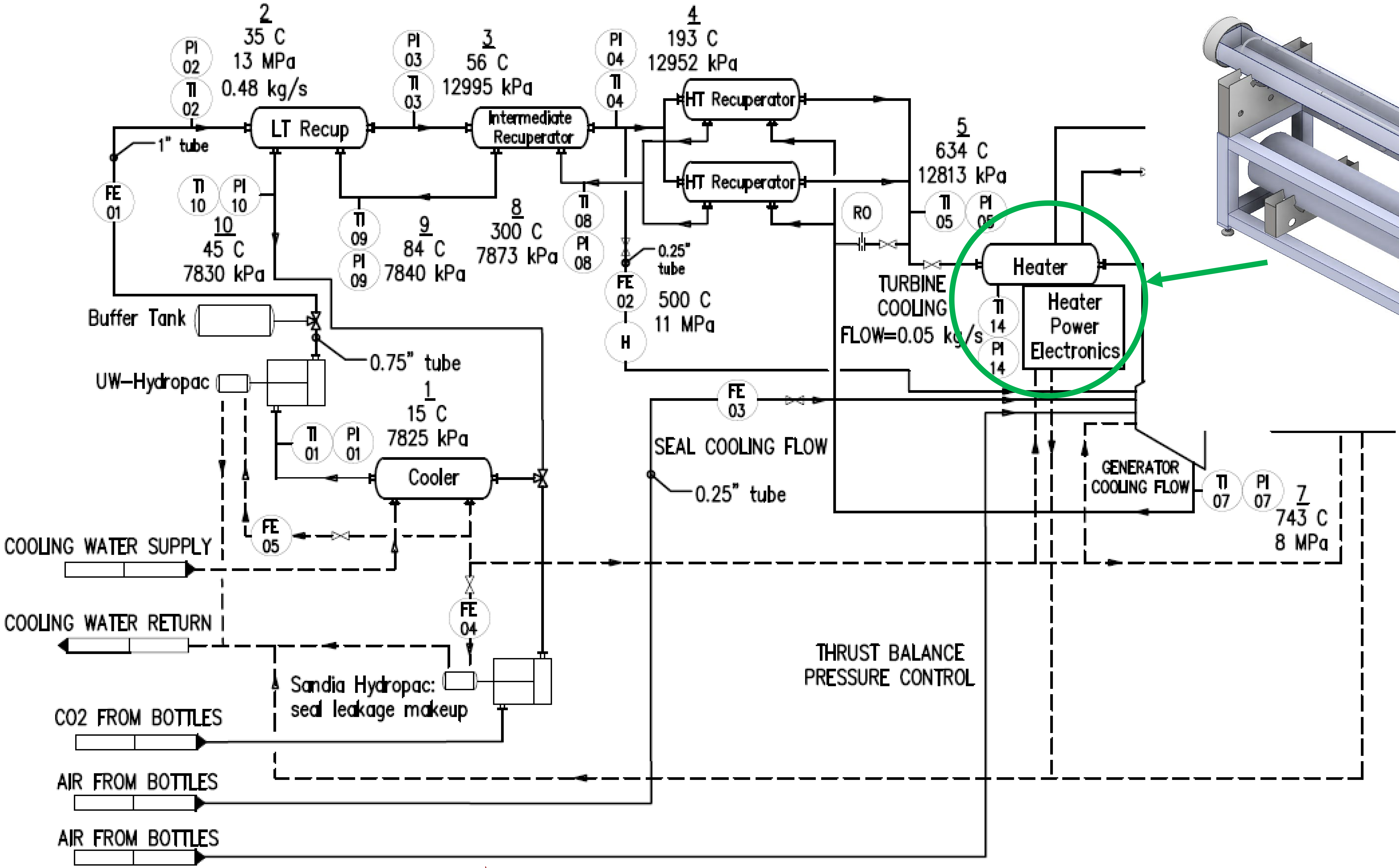
Intermediate-Temperature Recuperator

- Covers range after low-temperature HX braze limit (150ºC)
- Diffusion-bonded, printed circuit heat exchanger
- Custom-designed using heat transfer correlations and modeling infrastructure previously developed in the THL
- 94 zig-zag channeled plate stack (32 cold, 62 hot to decrease hot side pressure drop)

- Cold stream: 56ºC to 193ºC, ΔP: 43 kPa
- Hot stream: 300ºC to 84ºC, ΔP: 33 kPa
- Duty: 125 kW
- UA: 1.86 kW/K
- effectiveness: 0.86



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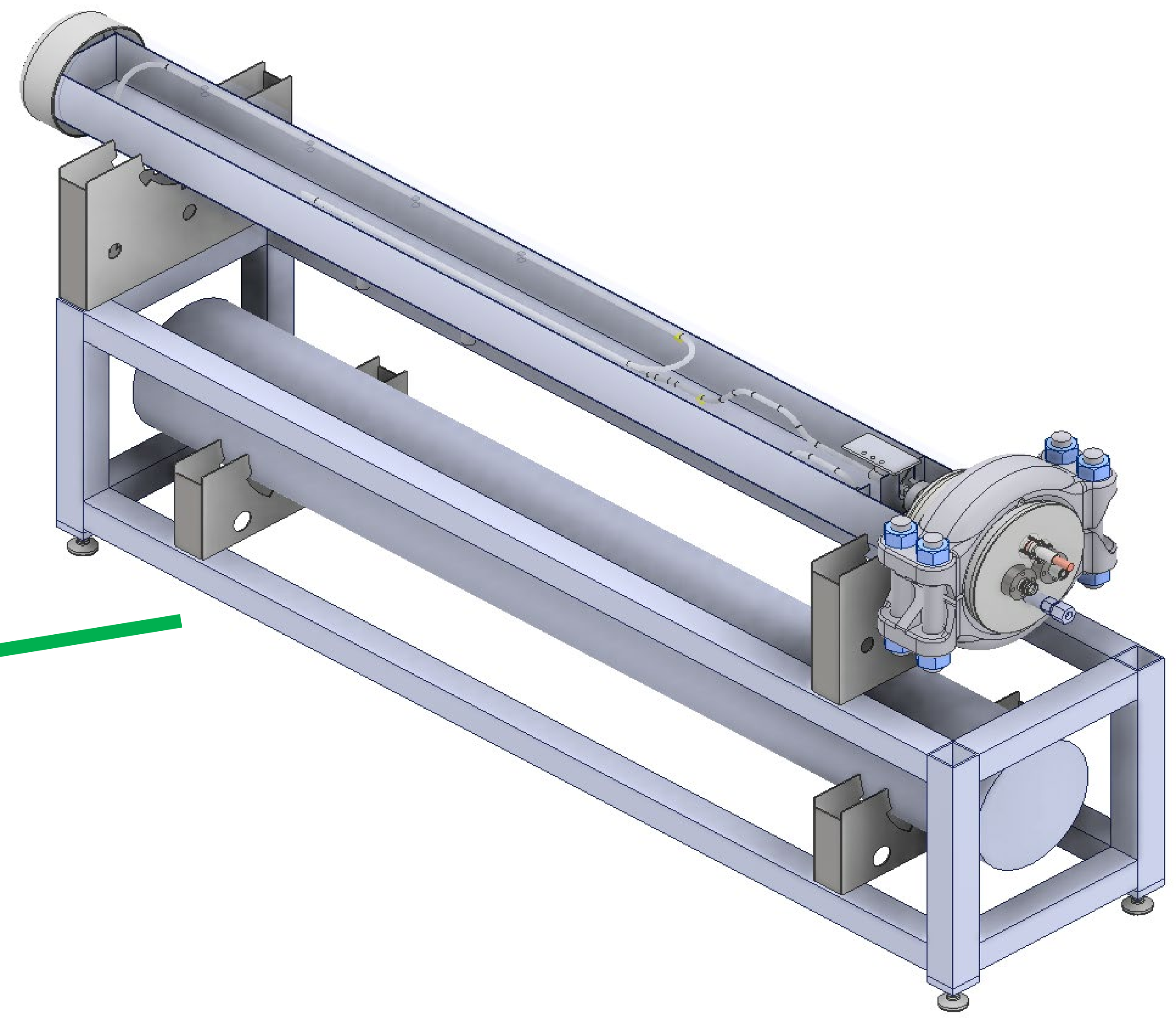
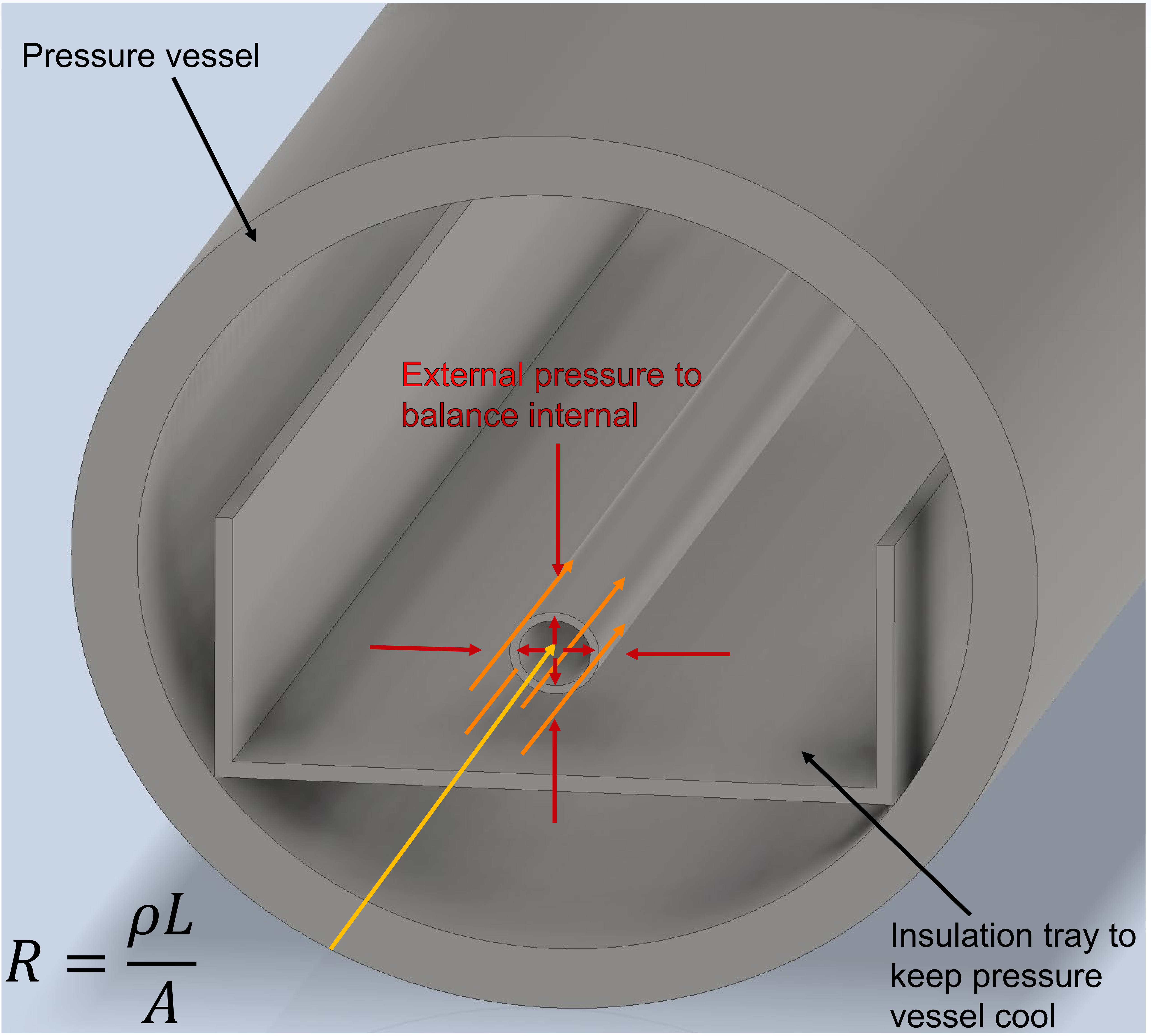


Heater Design Challenges

- Design Specifications: 120 kW for 600→800°C
- High heat transfer rate at high temperature
- CO_2 runs through inside of tube – yellow
- Electrical current conducts through tube to heat the CO_2 –orange
- As metal temperature increases, its strength decreases making it hard to contain internal pressure – red
- Also need to limit pressure drop (length limit)
- Electrical Resistance vs Pressure Containment (cross sectional area)

Solution: thin-walled heating element inside a pressurized vessel

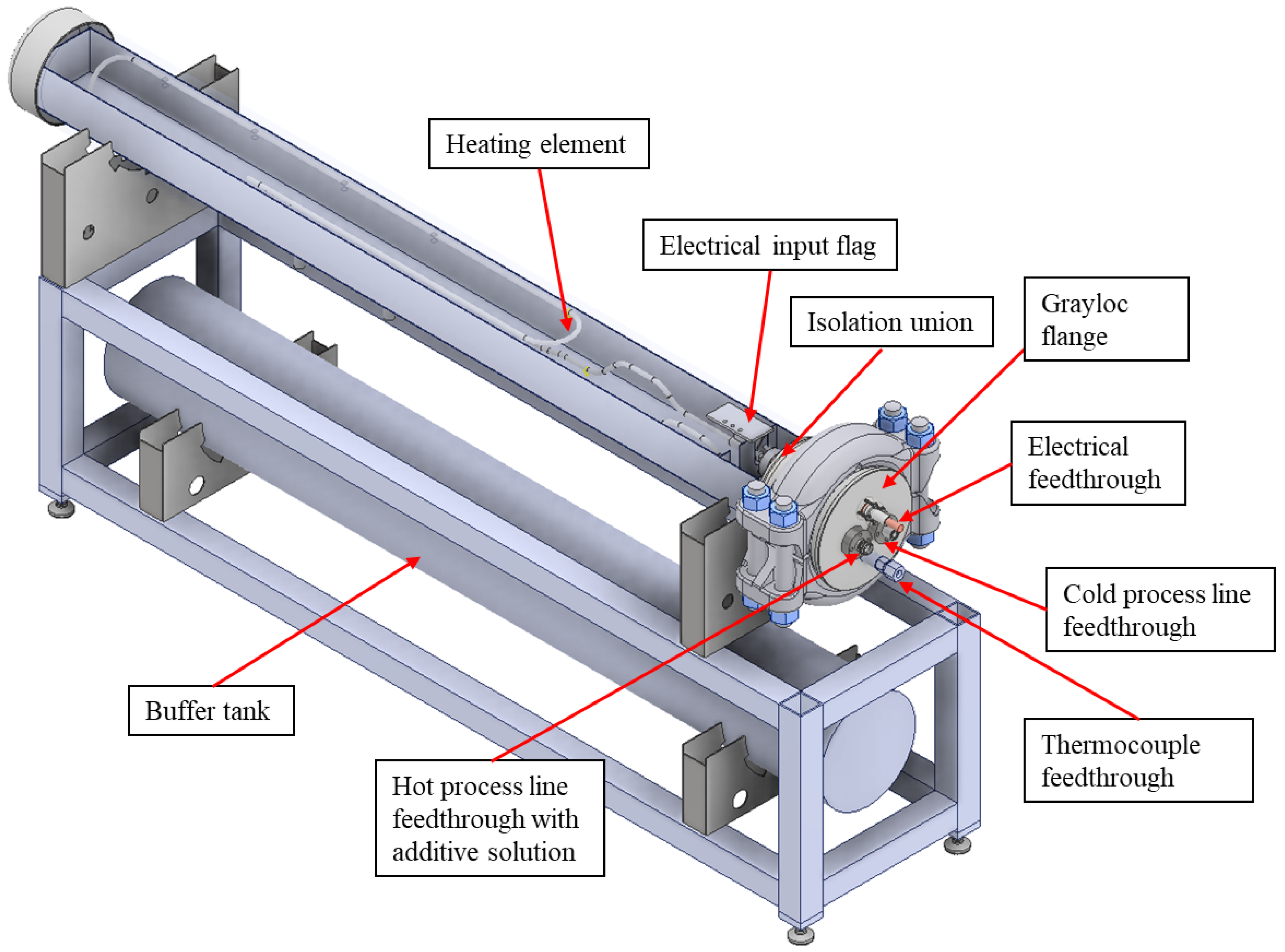


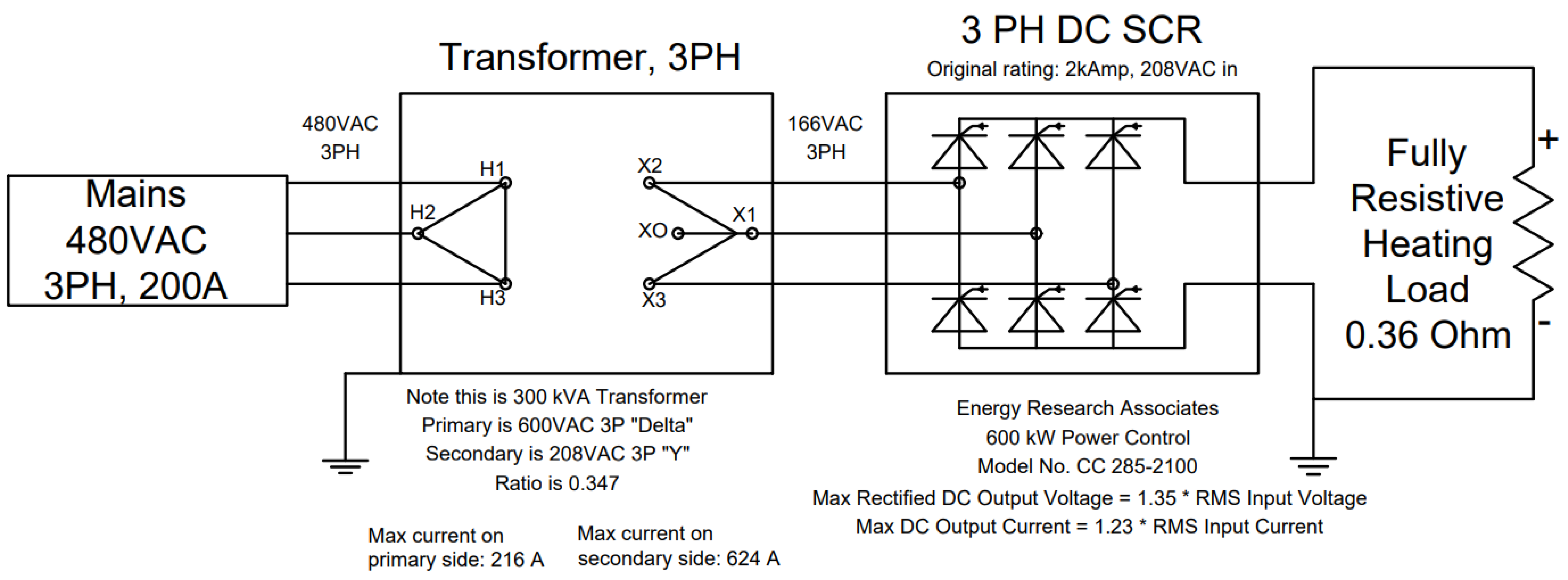
$$R = \frac{\rho L}{A}$$

Heater Design

To meet heating requirements with 710A :

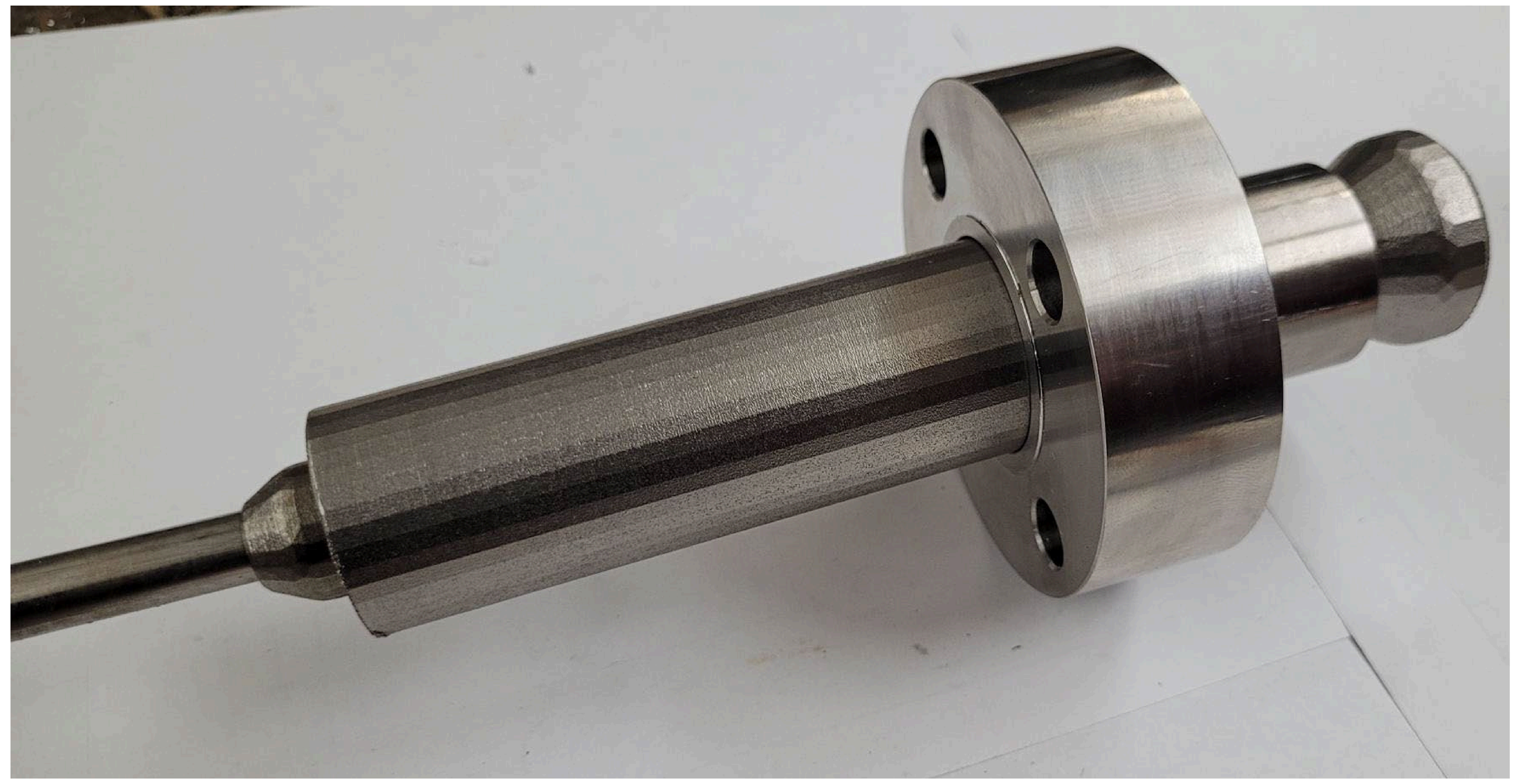
- Material: Inconel 625
- Heated Length: 23.3 ft
- OD: ½”
- Wall Thickness: 0.028”
- Pressure Drop: 1800 kPa
- Power supplied from 480 VAC, 200A → transformed through 600 to 208 VAC transformer (for higher ratio)
- → rectified through DC SCR

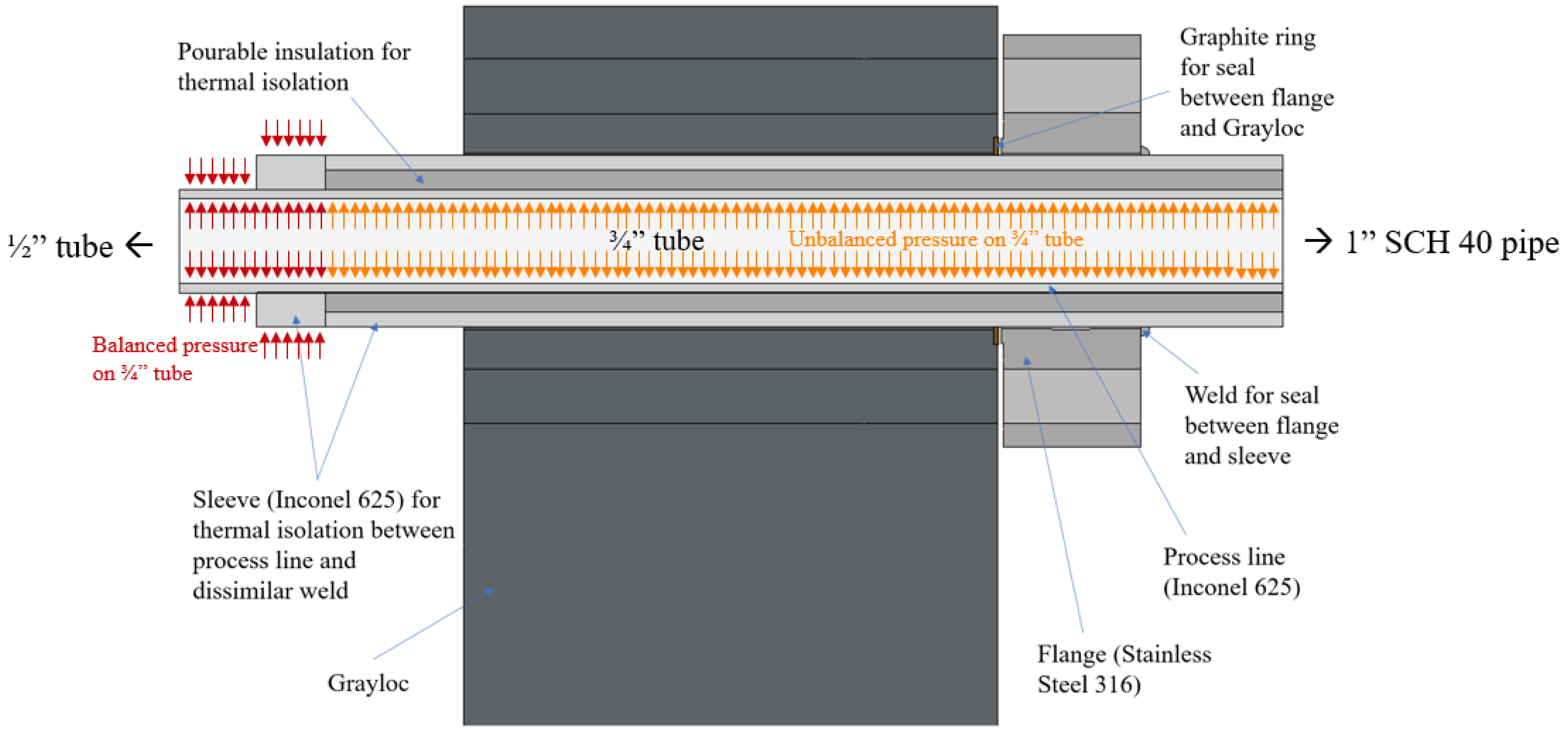


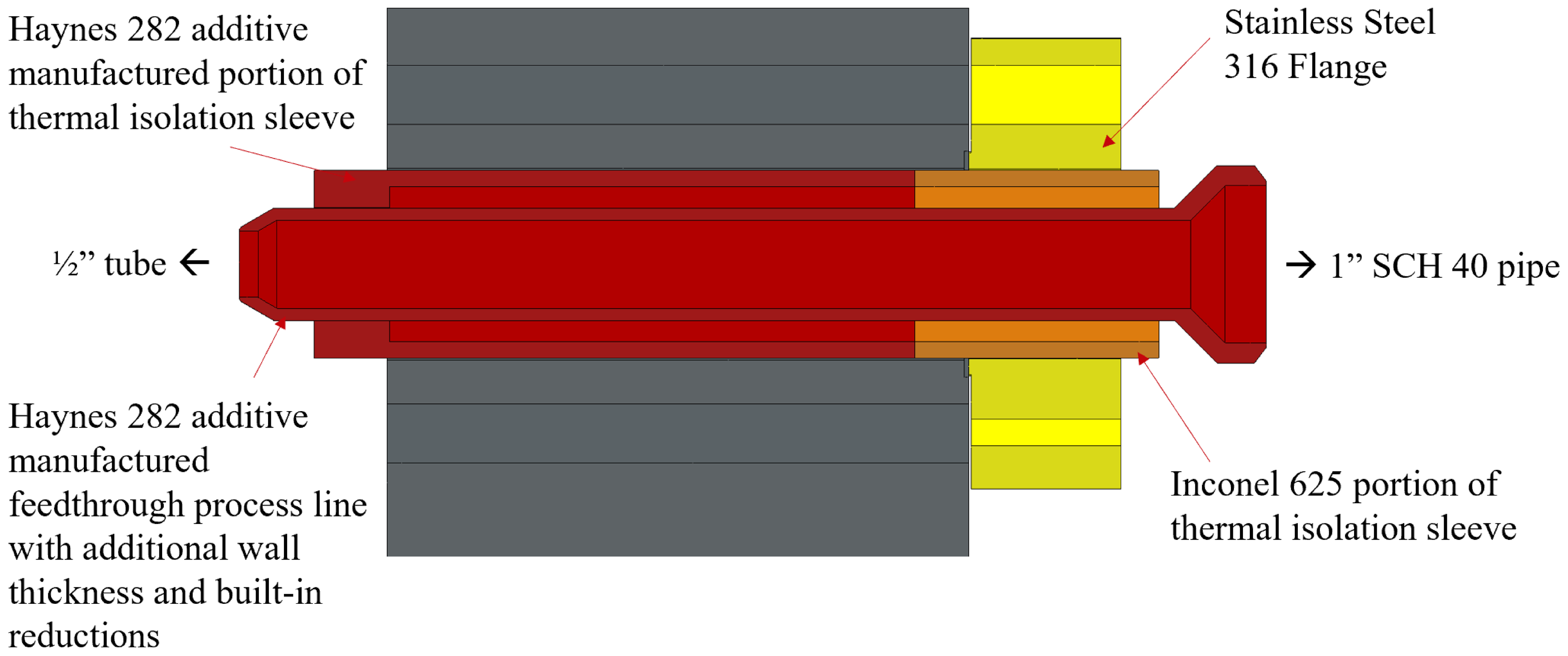


Process Line Feedthroughs

- Flange designed using ASME codes and confirmed with thermo-mechanical FEA
- Thermal sleeve containing pourable insulation limits the conductive path from the process line to the graphite seal
- Additive manufactured Haynes 282 feedthrough line provided extra strength on high-temperature side to account for unbalanced pressure of process line tube within pressure vessel
- Transition from Haynes 282 → Inconel 625 → Stainless Steel 316 to reduce stresses from dissimilar weld

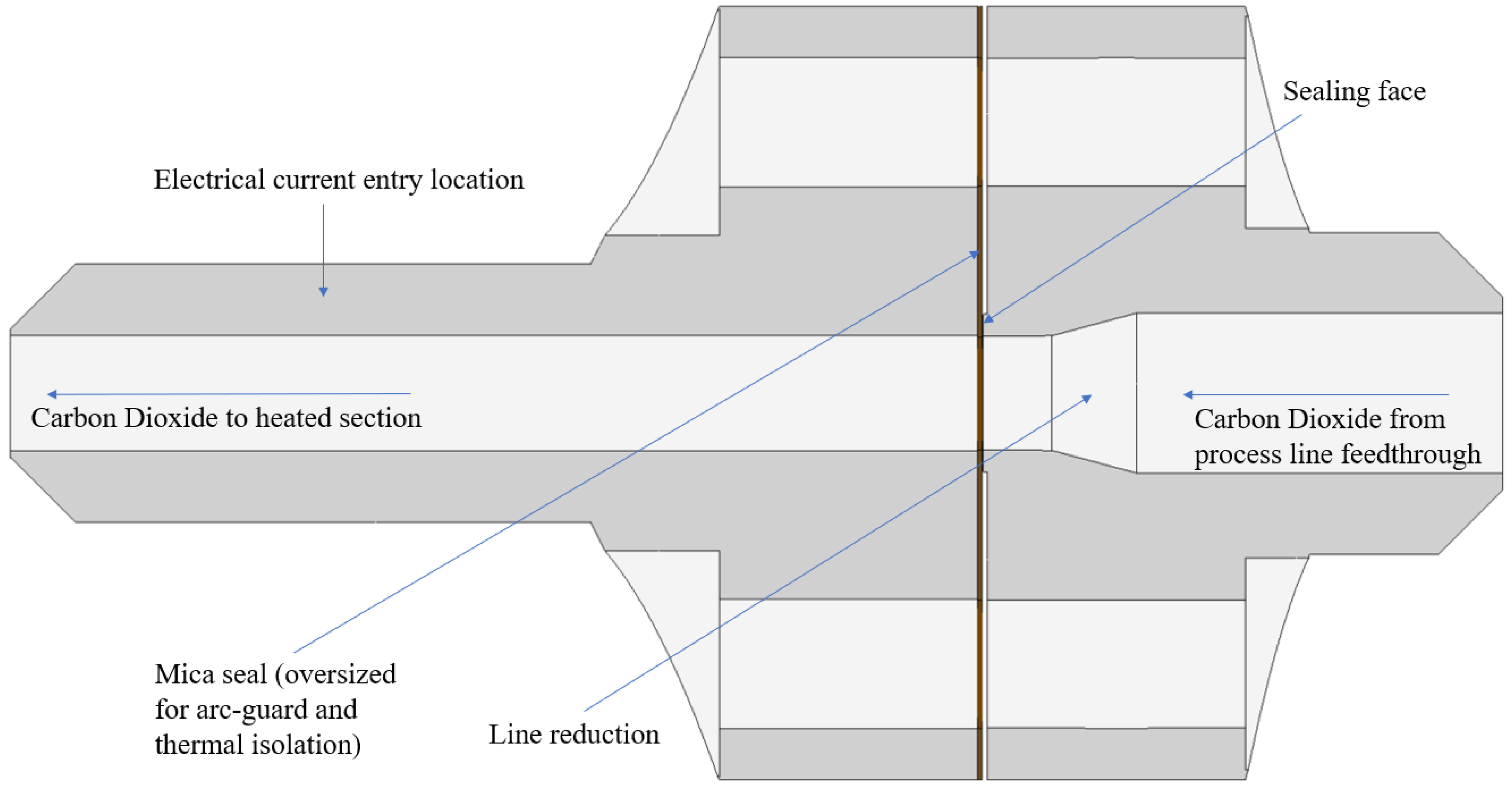


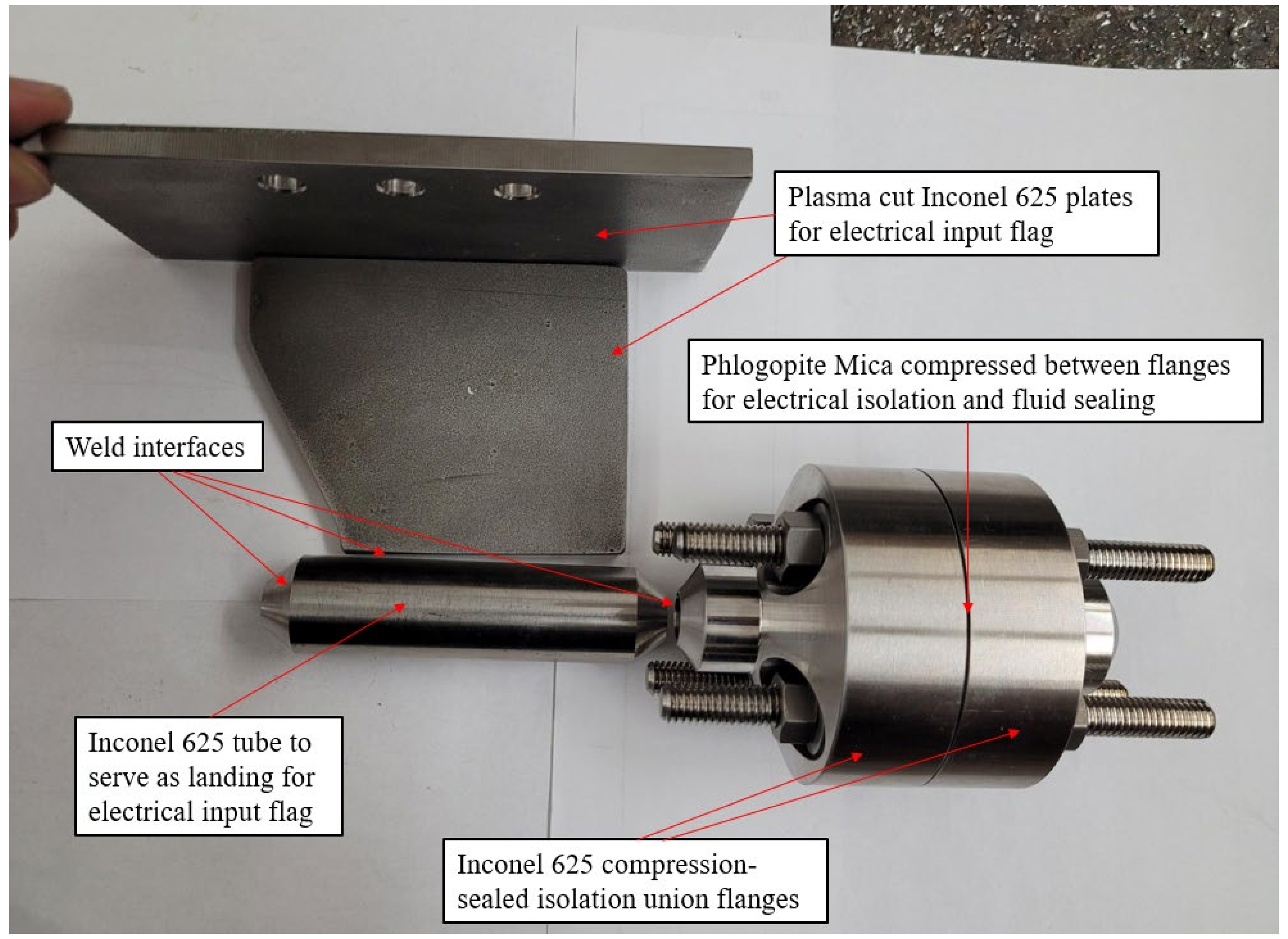


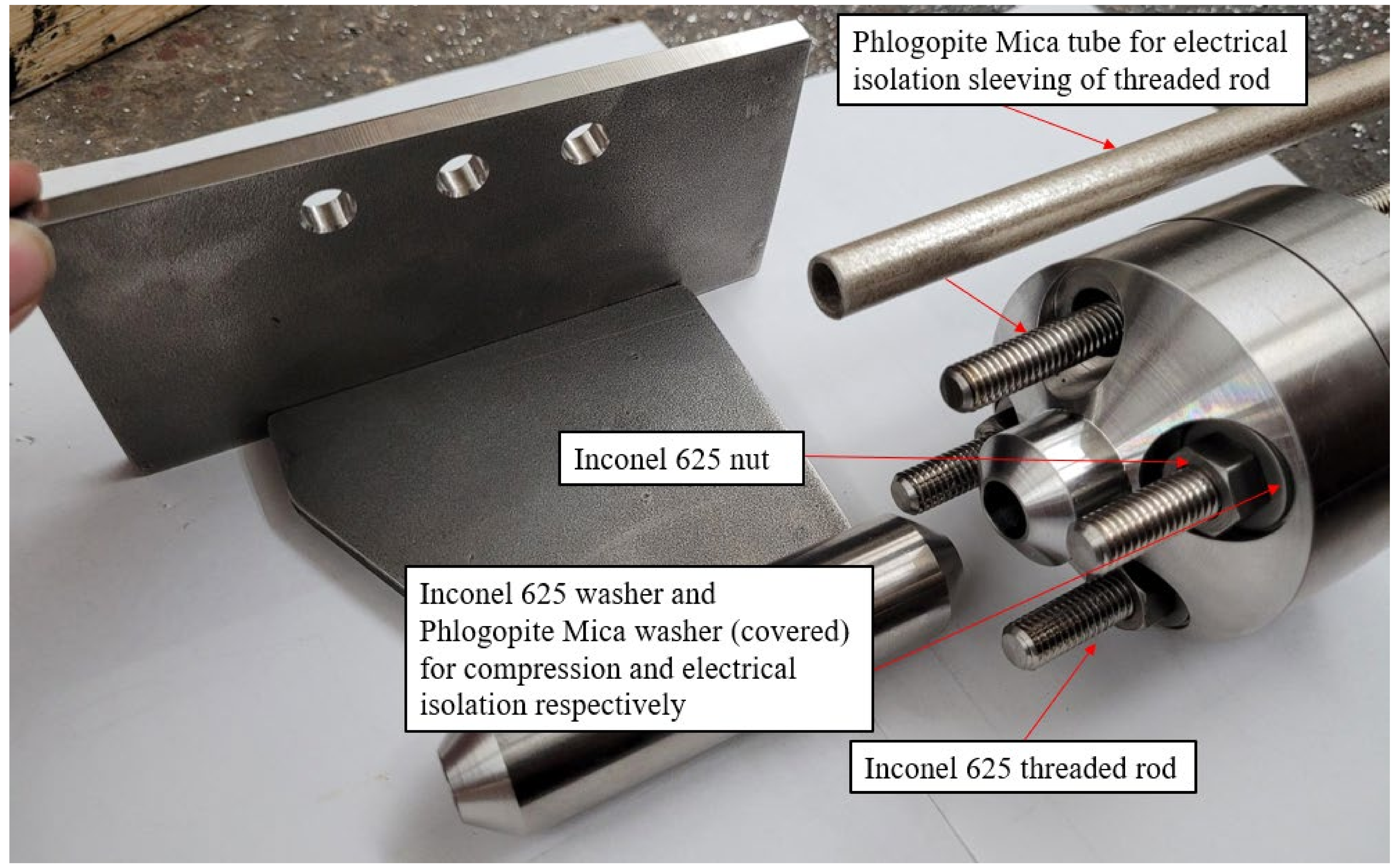


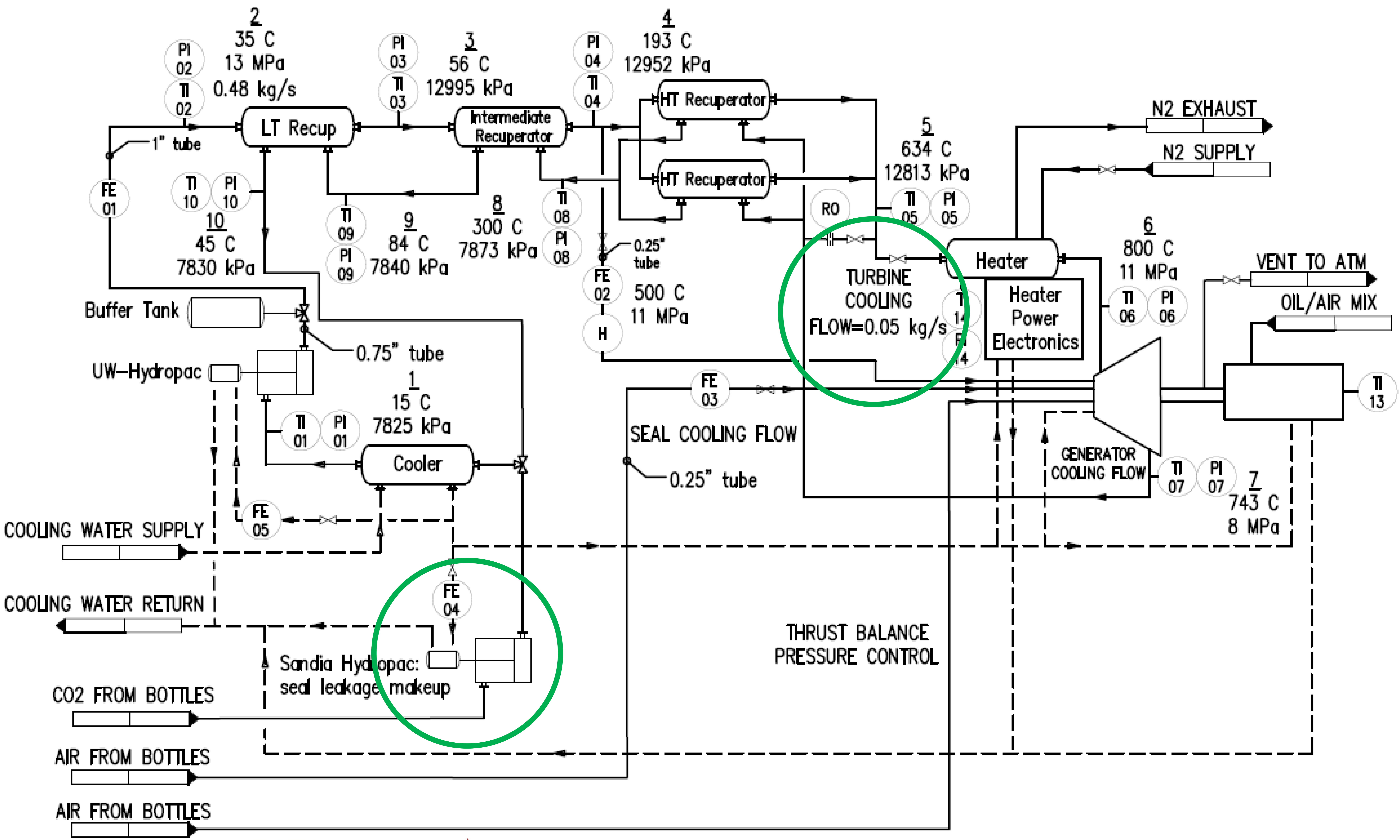
Isolation Union and Electrical Input

- Need to electrically isolate process line from the heated section with current entry on one side and grounding on the other side
- Isolation union designed using ASME flange codes and confirmed with mechanical FEA simulations
- Flange sealed with Mica to prevent electrical conduction, arc across gap, and CO_2 leakage





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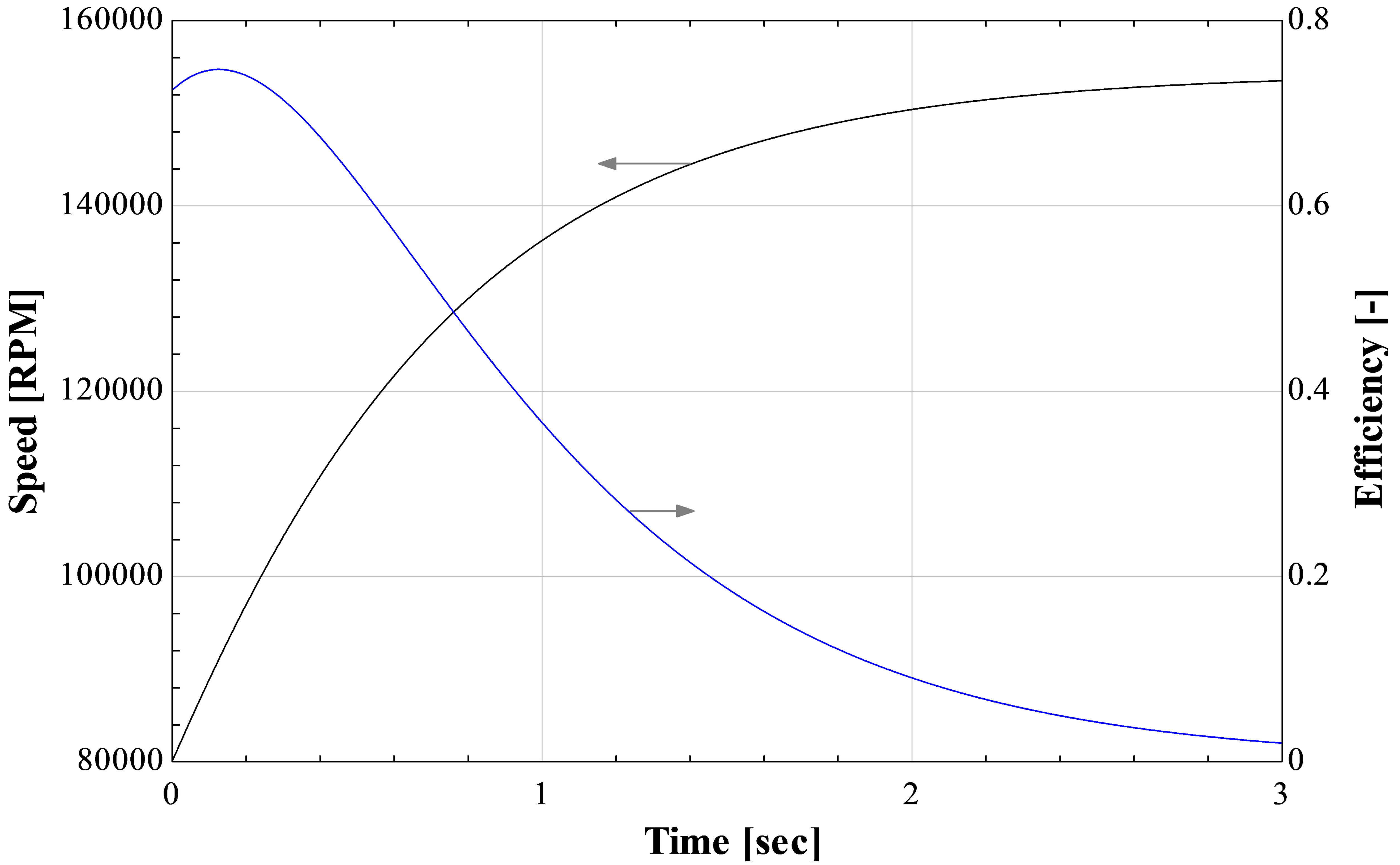
Auxiliary Requirements for Turbine Operation

- Need 0.05 kg/s of CO_2 at 500ºC and 11 MPa for turbine blade cooling
  - Auxiliary heater developed to bring carbon dioxide from before the high-temperature heat exchangers (state 4) from 193ºC up to 500ºC
  - Feasible to use a Coriolis flow meter to measure the flow rate before heating at inlet temperature
- Need to make up 0.02 kg/s of seal leakage with secondary Hydro-Pac compressor provided by Sandia National Labs to pump from bottle manifold into loop
  - Not recycling leakage due to required low turbine cavity pressure and potential for oil from the lubrication system to enter the main flow

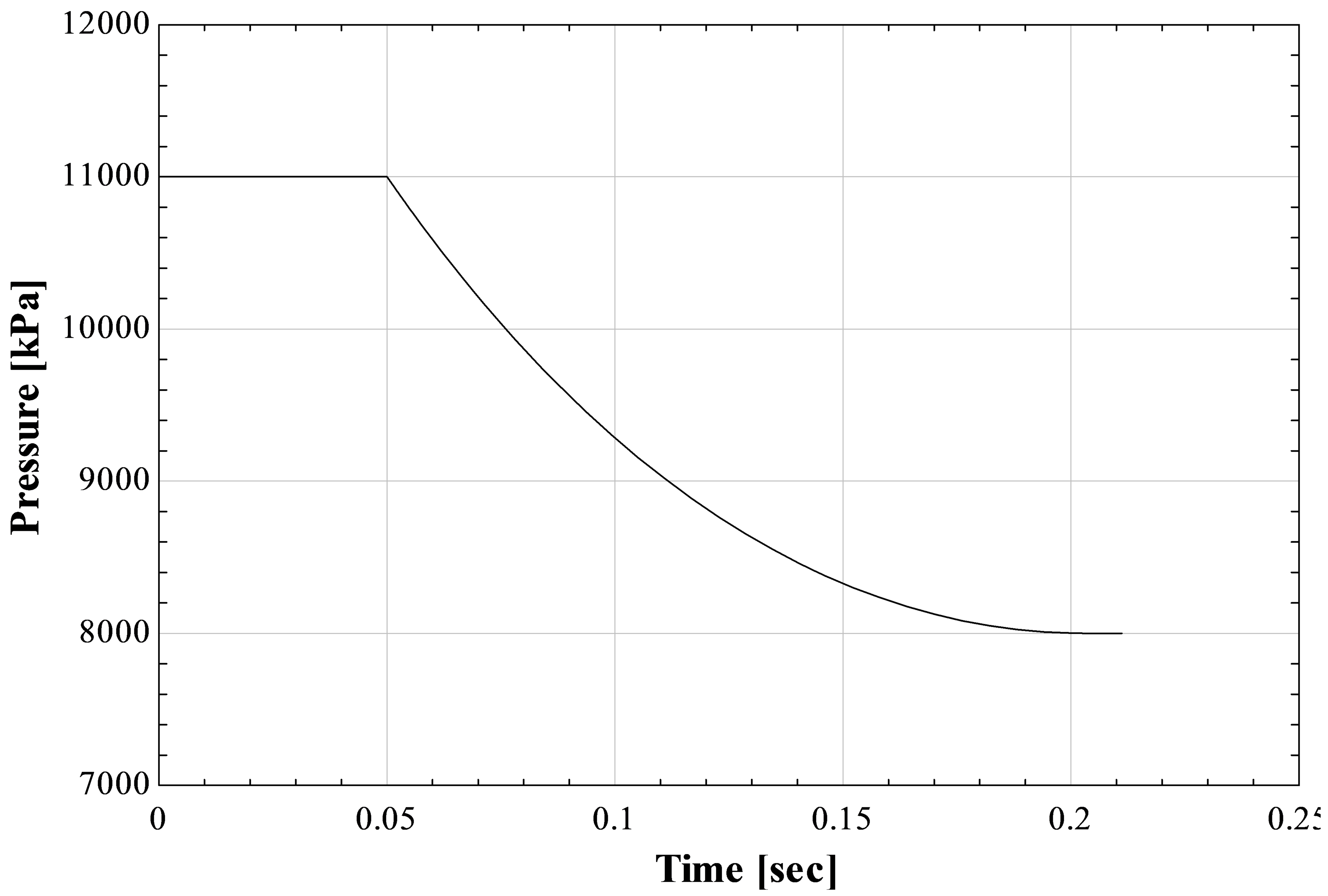
Emergency Shut-down Transients

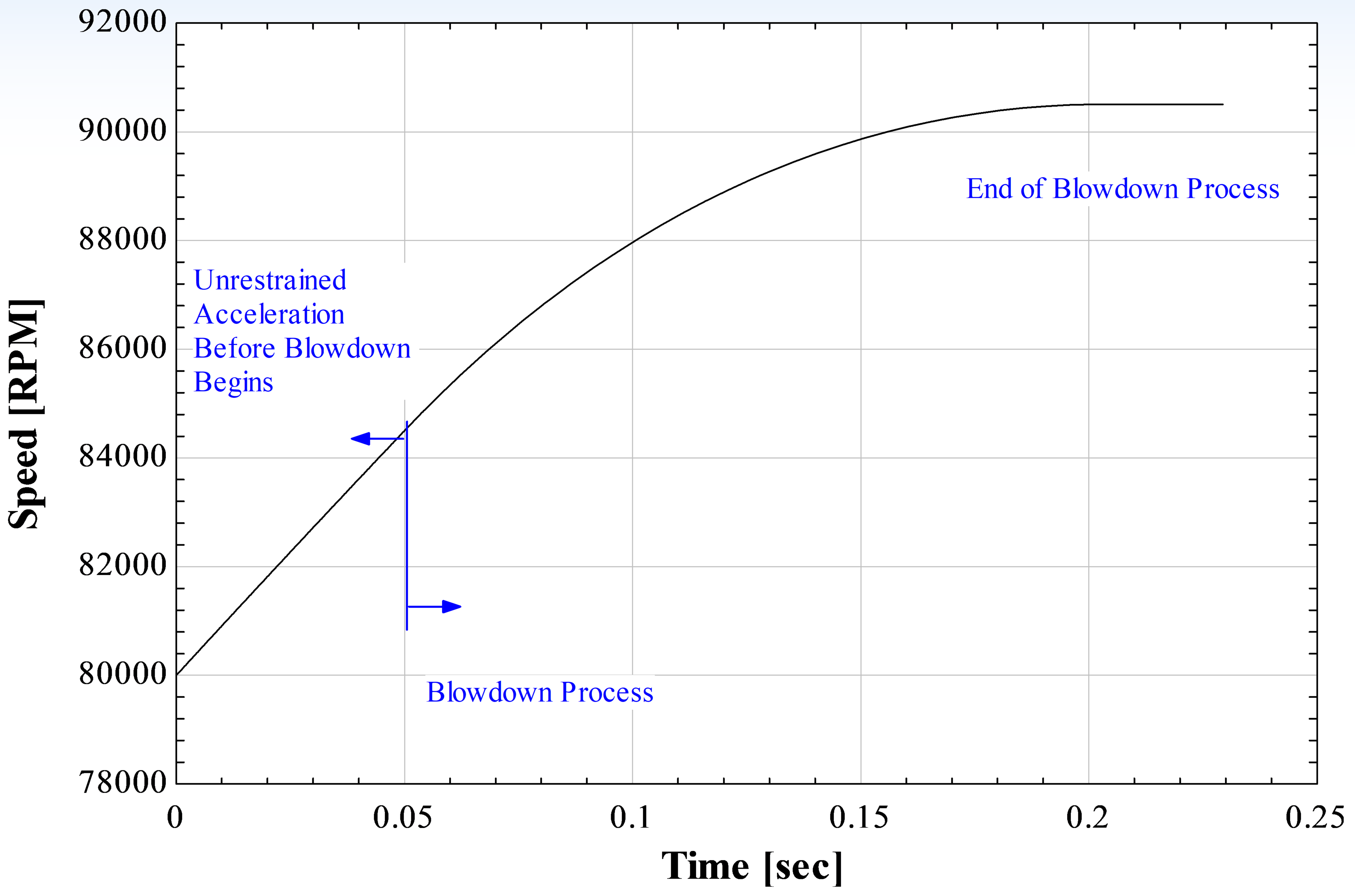
- Unconstrained speed-up plateau due to efficiency drop
- Critical overspeed at 96.8 kRPM due to bearing and 121% standard from API
- Occurs at 0.2 seconds

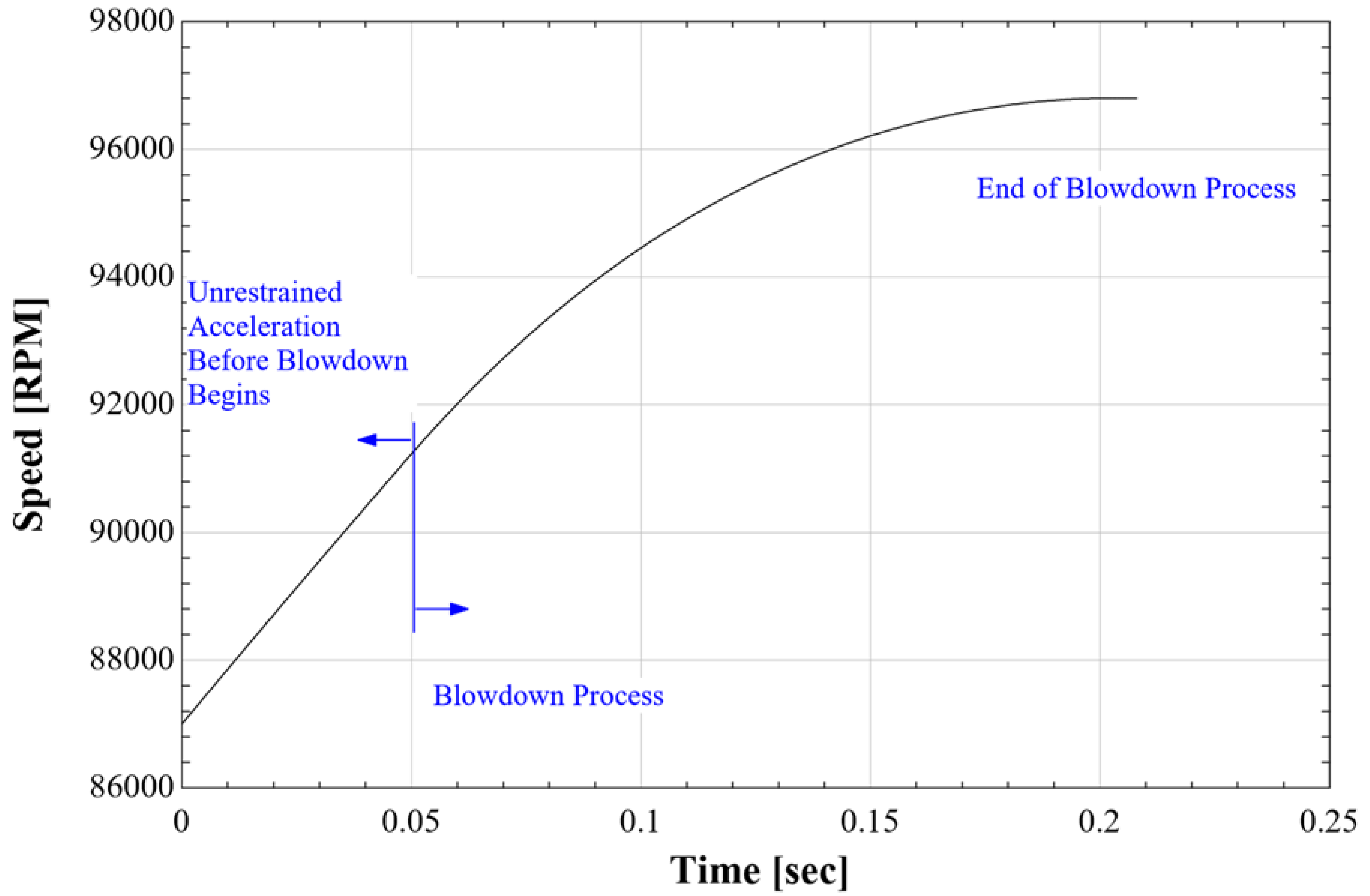


Emergency Shut-down Transients

- Pneumatic valves bypass heater and turbine
- Mechanical delay, blowdown exhaust
- Emergency trip at 87 kRPM corresponding to critical overspeed

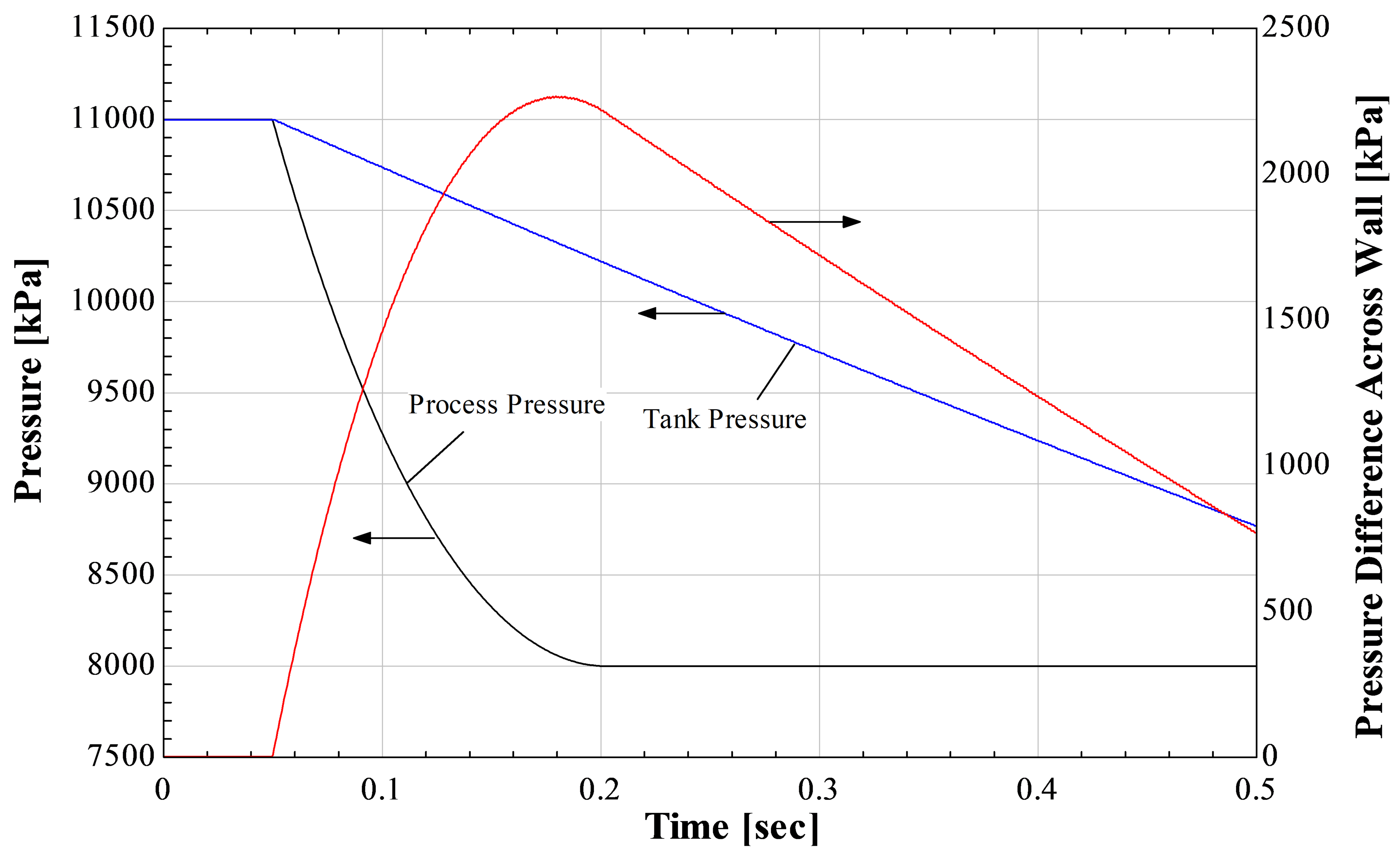


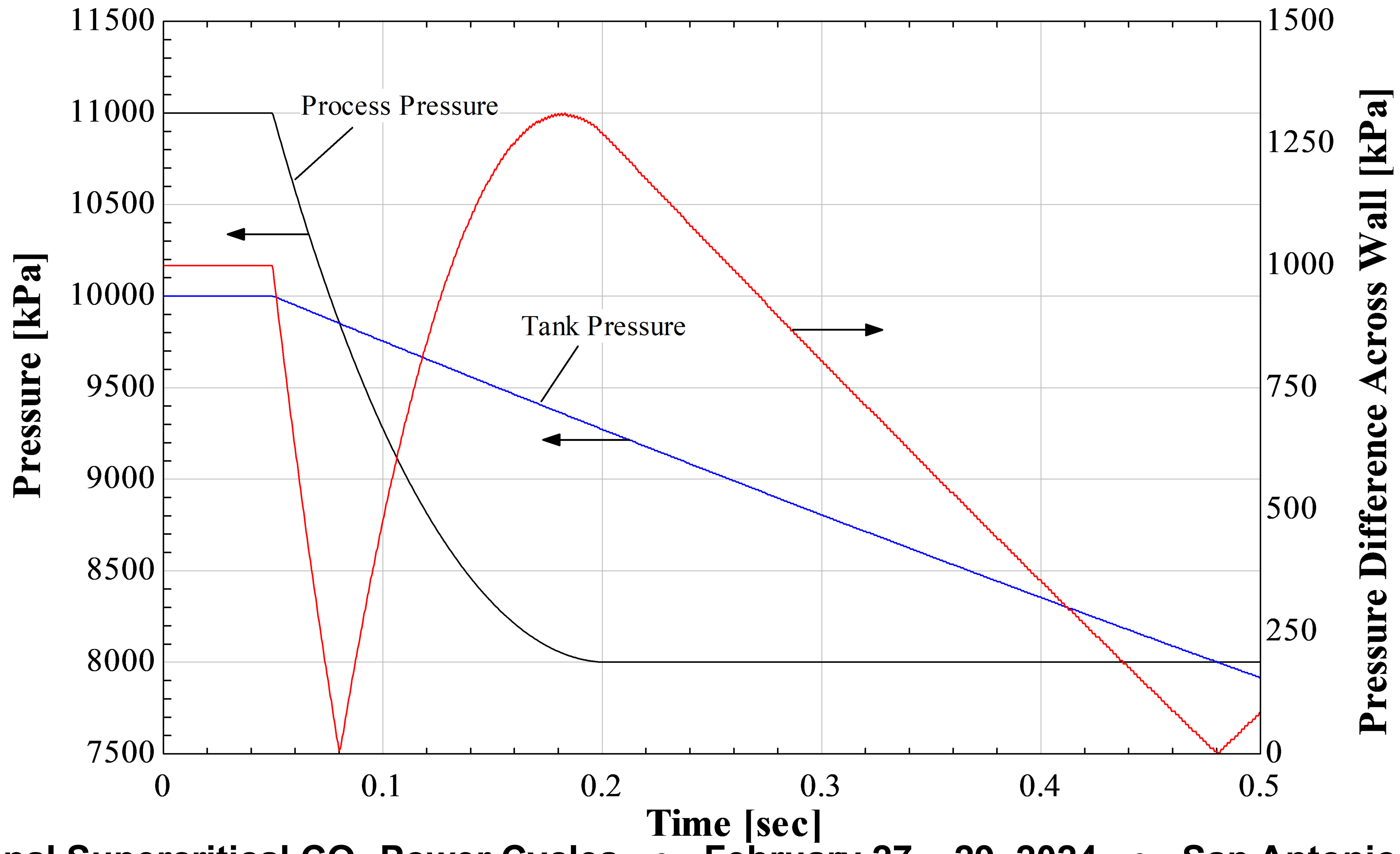




Emergency Shut-down Transients

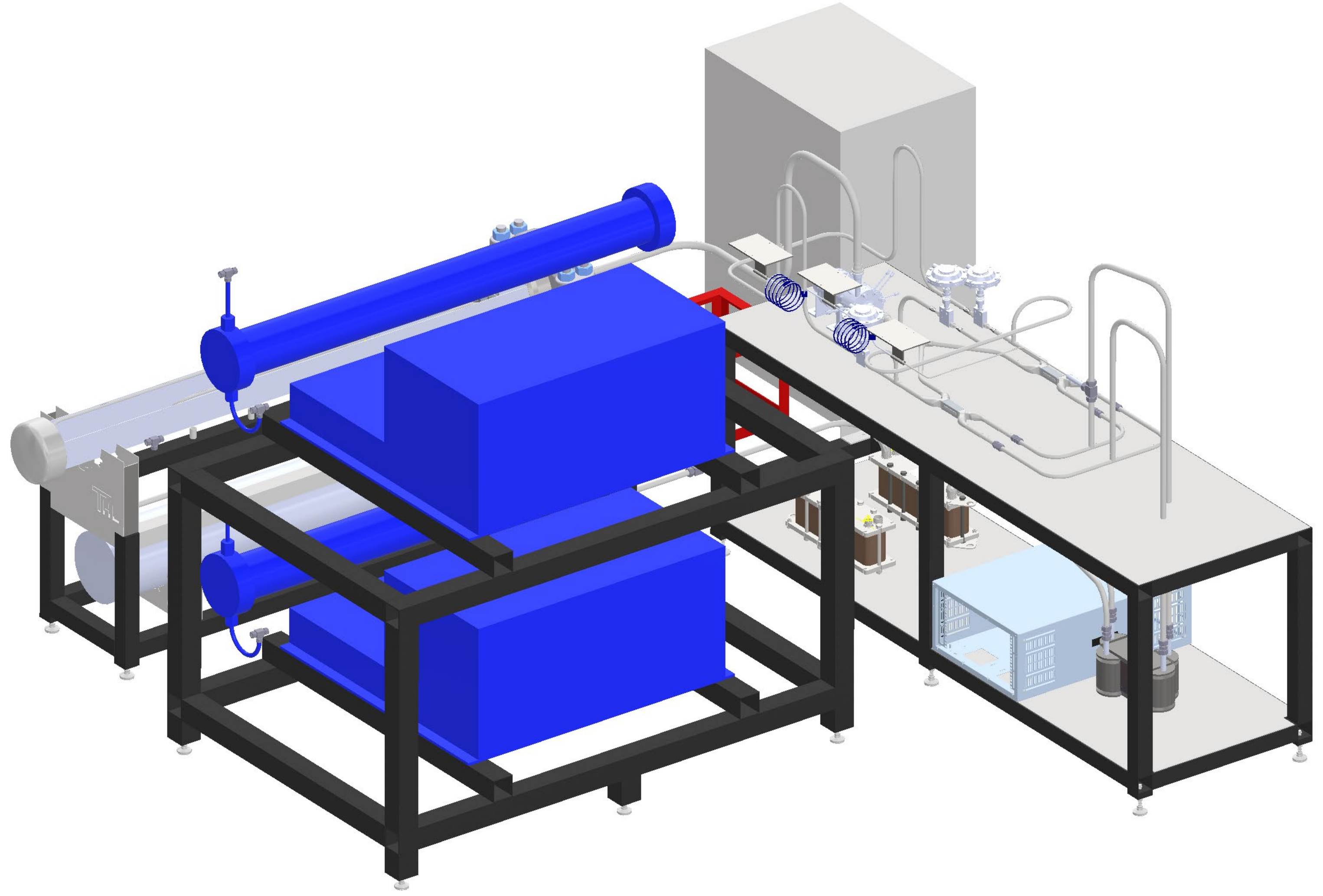
- Nitrogen exhaust from heater pressure vessel has higher time constant than previously described transient process
- Need pressure difference across heater tube less than 2000 kPa
- Steady state nitrogen pressure offset lower than process pressure to avoid excessive imbalance during shut-down



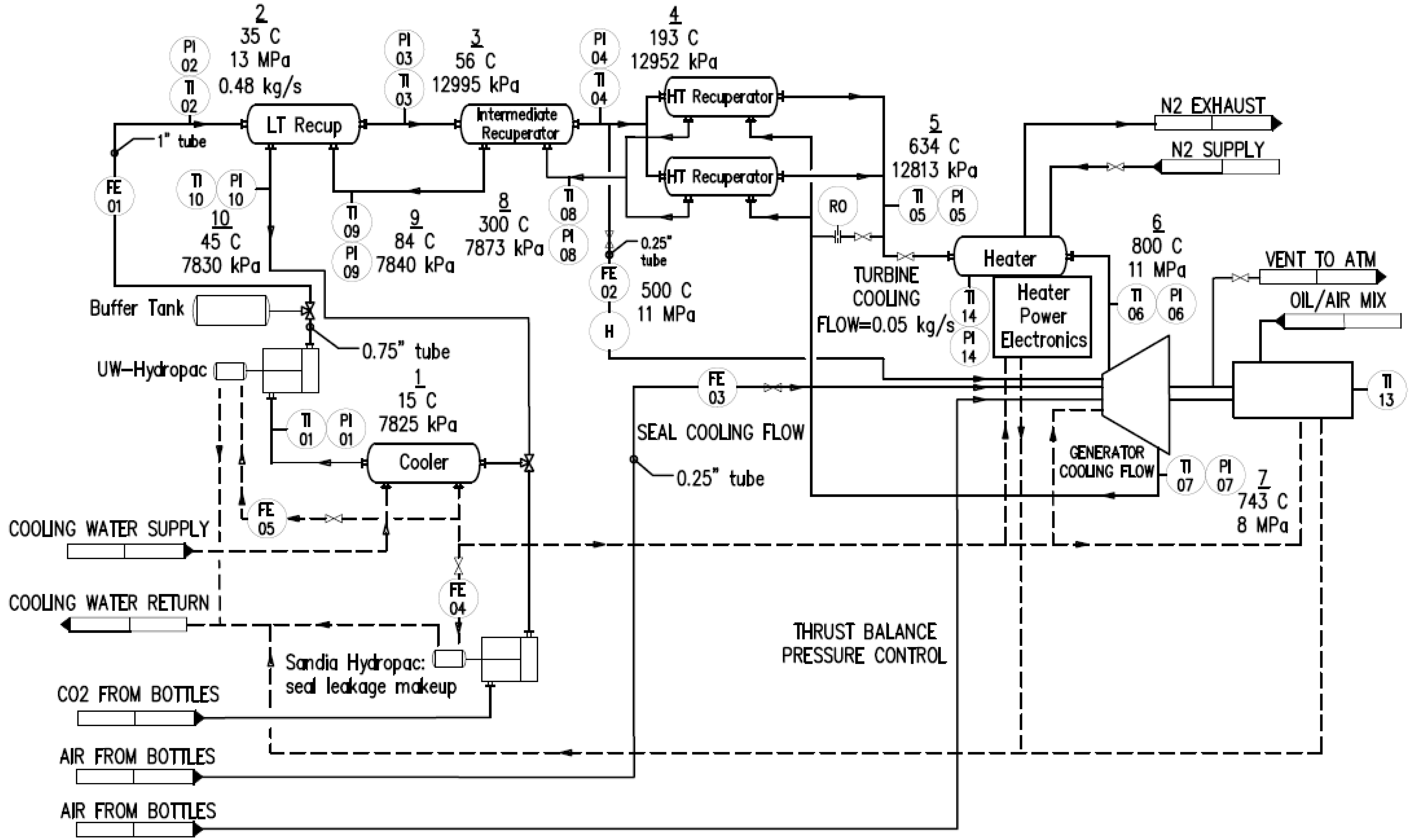


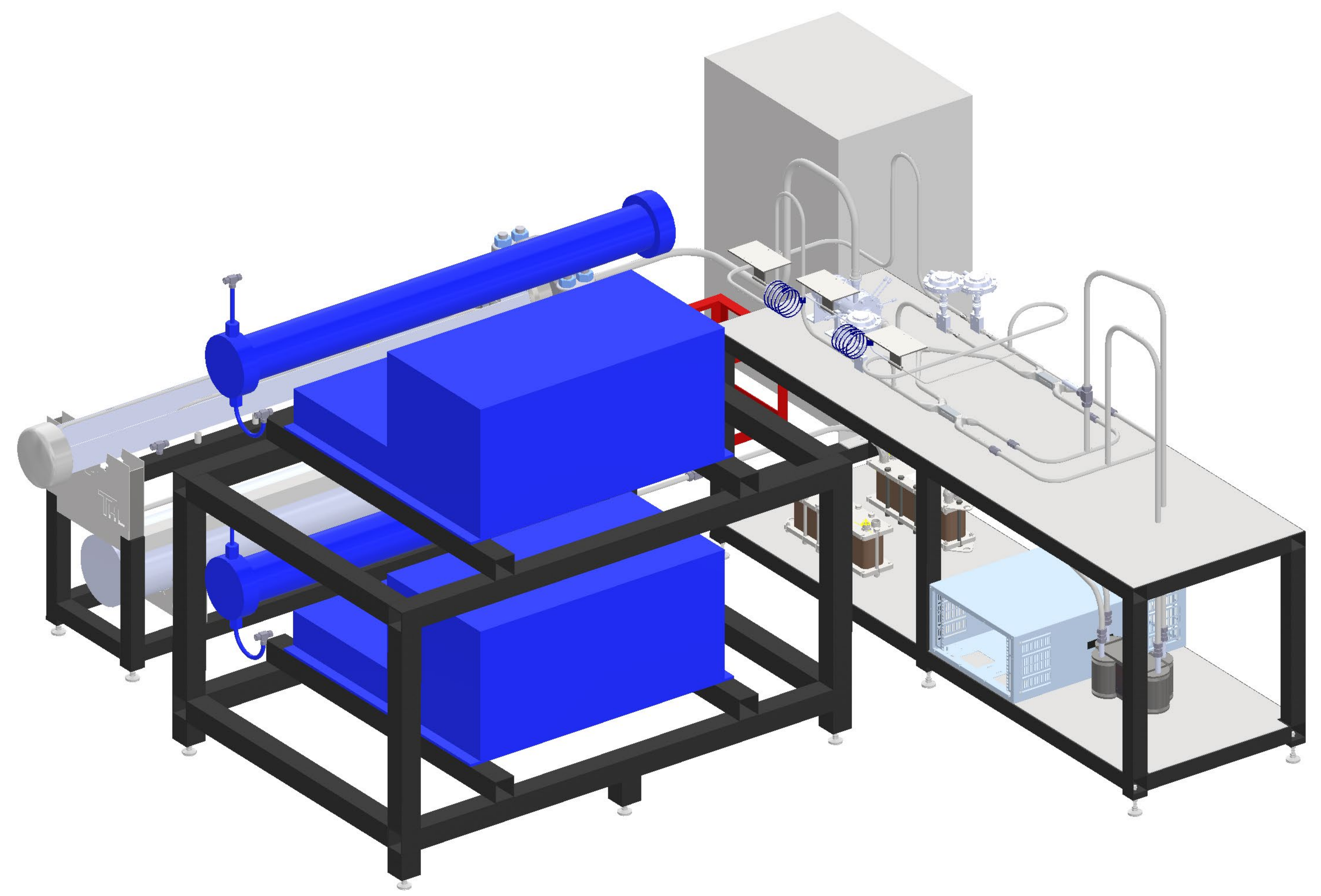
Conclusion

- Turbine test facility designed to achieve turbine inlet conditions of 800°C, 11 MPa, and 0.48 kg/s
- Facility delivers auxiliary flow requirements
- All components manufactured/procured
- Assembly of test facility underway
- Interesting challenges encountered related to high temperature and high speed operation
- Objective to validate performance novel turbomachinery as a step toward high-temperature, high efficiency power cycles of the future



Thank you
Questions?





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