An Innovative Monitoring Technology for Reactor Vessel of Micro-HTGR

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Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar
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Project Overview

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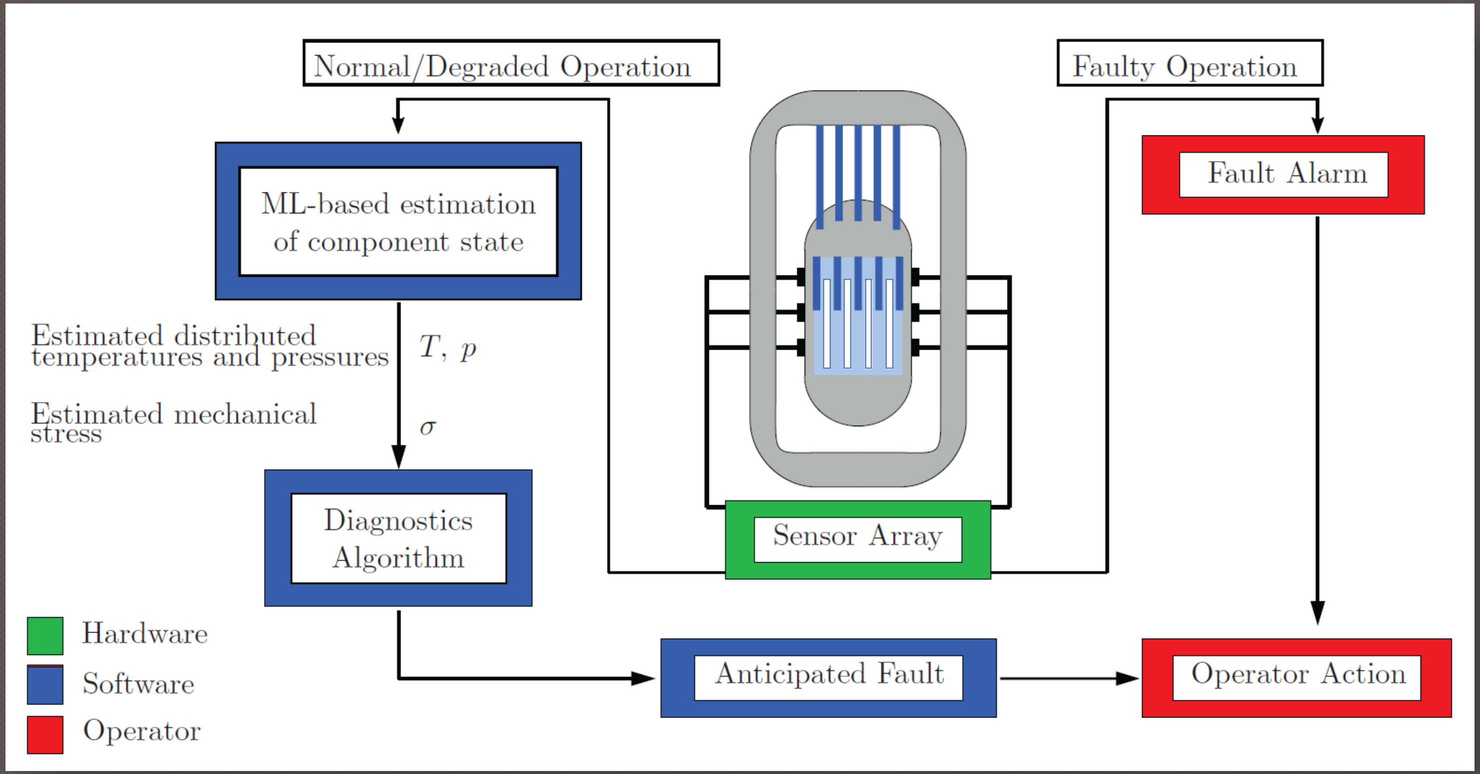
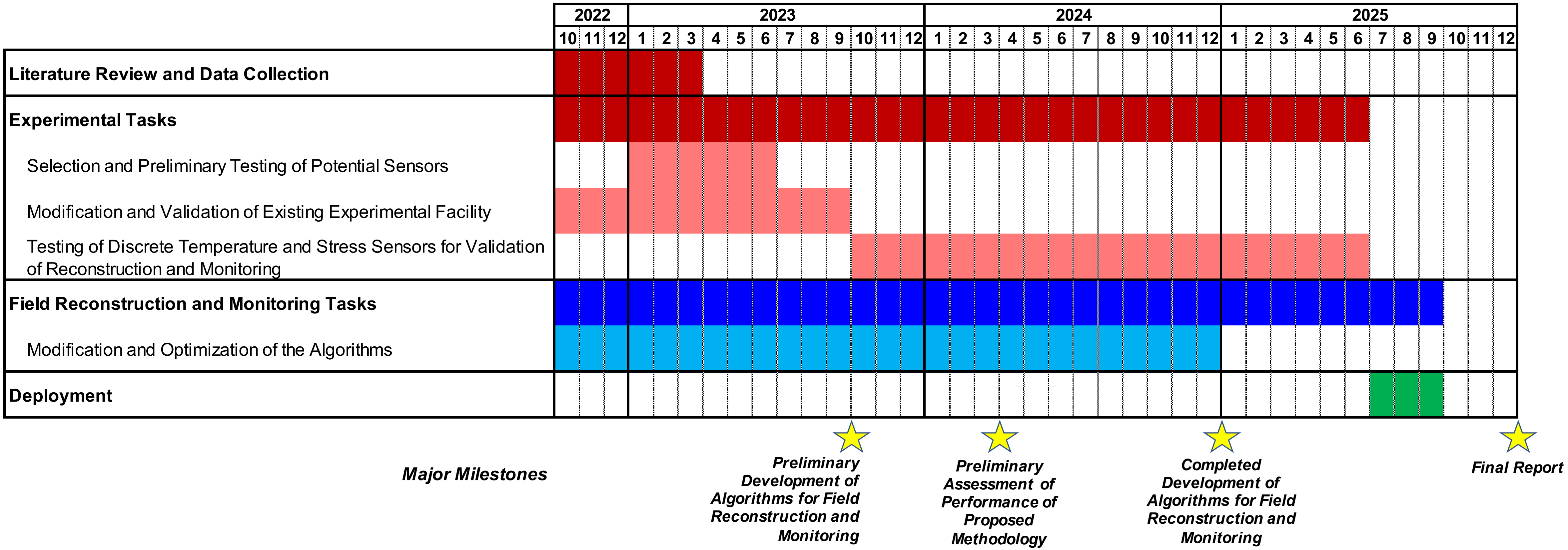
Develop & Demonstrate Integrated Sensor Technology for Real-Time Monitoring of Thermal-Mechanical Stresses of Reactor Vessel for Micro-High Temperature Gas Reactors (mHTGRs)

1. **Real-Time, Reliable, and Cost-Effective Monitoring Methodology**
2. **Quantification of the Lifetime and Integrity of the Pressure Vessel**
3. **Improve the Economics of MicroReactor Systems**



Project Overview

Schedule and Milestones



Project Overview

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Participants

- **Texas A&M University**
  - *Laboratory Testing for Simulation and CNN Validation*
    - Lesley Wright, Mechanical Engineering
    - Rodolfo Vaghetto, Nuclear Engineering
    - Pramatha Bhat, PhD Candidate, Nuclear Engineering
    - Hanlin Wang, PhD Candidate Mechanical Engineering
- **Penn State University**
  - *Numerical Simulations and Algorithms*
    - Elia Merzari, Nuclear Engineering
    - Victor Coppo Leite, PhD Nuclear Engineering
    - Luiz Aldeia Machado, PhD Candidate, Nuclear Engineering
- **Argonne National Laboratory**
  - *Machine Learning Algorithms and Capabilities*
    - Roberto Ponciroli
    - Lander Ibarra
- **BWXT, Inc.**
  - *Industry Perspective*
    - Erik Nygaard

Technology Impact

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We will develop & demonstrate integrated sensor technology for real-time monitoring of thermal-mechanical stresses of reactor vessel for micro-high temperature gas reactors (mHTGRs).

- **Development of a novel combined software/hardware sensing technology capable of monitoring the health of reactor components.**
  - Field reconstruction algorithm tuned for vessel temperature and stress predictions
  - Methods to optimize sensor locations
- **Creation of a credible pathway for an innovative measurement system for a key component of gas-cooled micro-reactors (i.e., the pressure vessel). This will allow industry to assess the viability of the technology to realize economic benefits.**
- **The proposed method removes the need for penetrations through the pressure boundaries and is suitable for other advanced micro-reactors technologies.**
- **Development of a tool to facilitate the fault diagnostics with a measurement procedure than is less invasive than the current state-of-the- art sensor placement strategies.**
  - Integration of reconstruction algorithm with an actual sensor array and assessment of its accuracy
  - Demonstration on realistic HTGR applications

Results and Accomplishments

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Project Accomplishments

- **Experimental Testing**
  - *Thermal and strain distributions obtained under a variety of heating condition*
    - Radiant heating of reactor vessel model
    - Outer surface of vessel model instrumented with thermocouple and strain gauge arrays
    - Benchtop testing and validation of high temperature strain gauges
- **Numerical Simulations**
  - *CFD simulations for temperature fields have been completed and strain predictions are ongoing*
    - Validation of ray tracing algorithms
    - 3D, thermal simulations of TAMU experimental vessel
    - Preliminary simulations of thermal strains have been acquired
- **Application and Customization of the Convolutional Neural Network (CNN) Approach**
  - *CNN has been demonstrated using CFD simulations and validated with experimental data*

Results and Accomplishments

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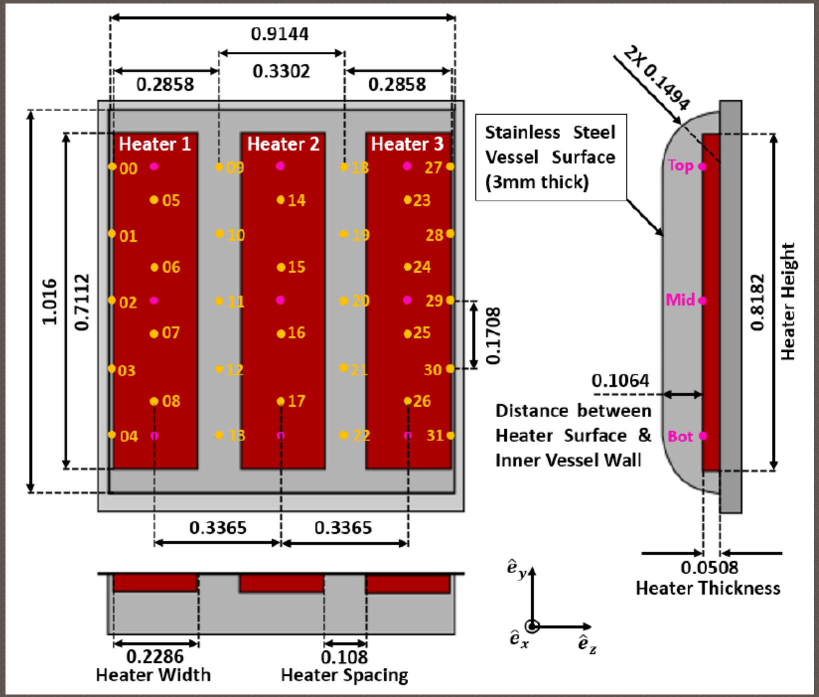
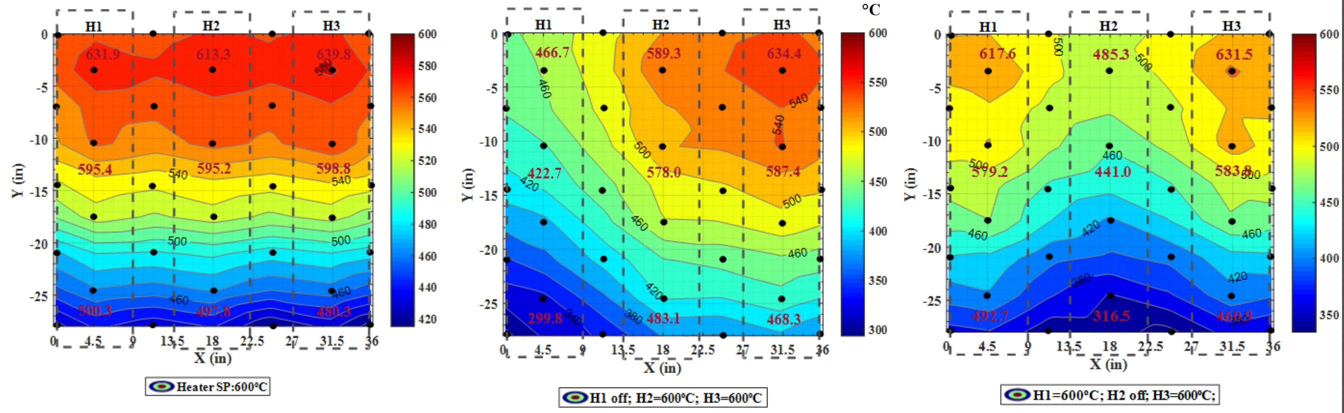
Thermal Testing





Heater 1 [Left] → Off

$T_{H2} = T_{H3} = 600°C$

Results and Accomplishments

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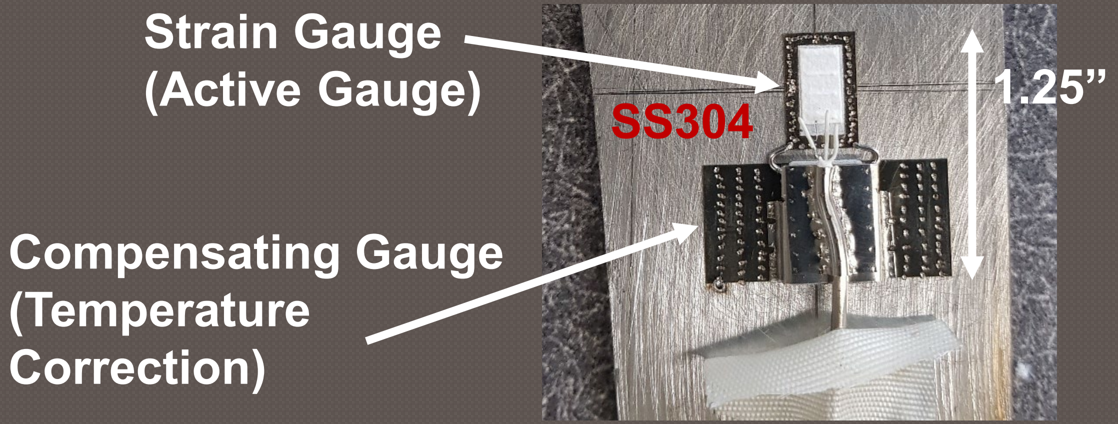
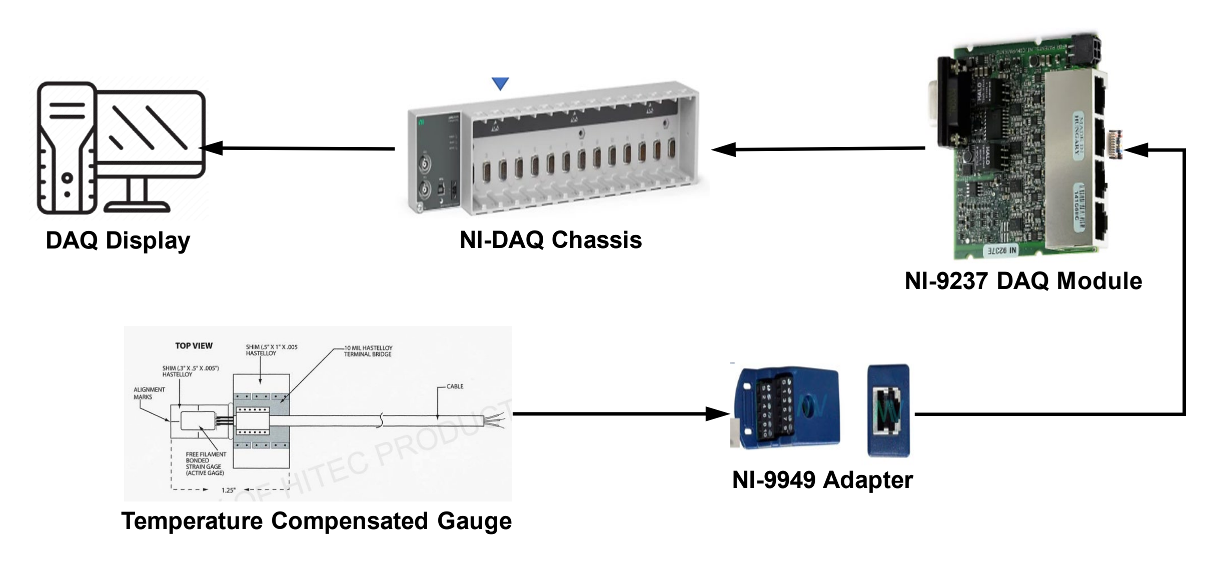
Strain Gauge Validation

Strain Gauge Details

- **HPI Strain Gauges**
  - HBWAH-12-250-6-MG-HB
  - Rated for 980ºC
  - QuarterBridge-II (Modified Half-Bridge) configuration that helps eliminate zero drift error, temperature effects, lead wire resistance, etc.
    - One active element and one compensating element, unstrained on coupon
  - Robust build and connections
  - Easy application by spot welding





Results and Accomplishments

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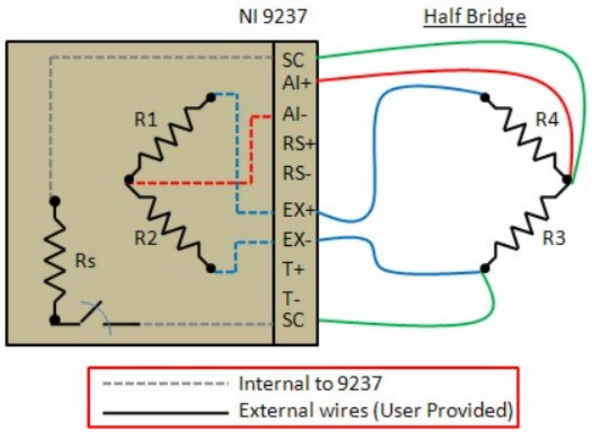
Strain Gauge Validation

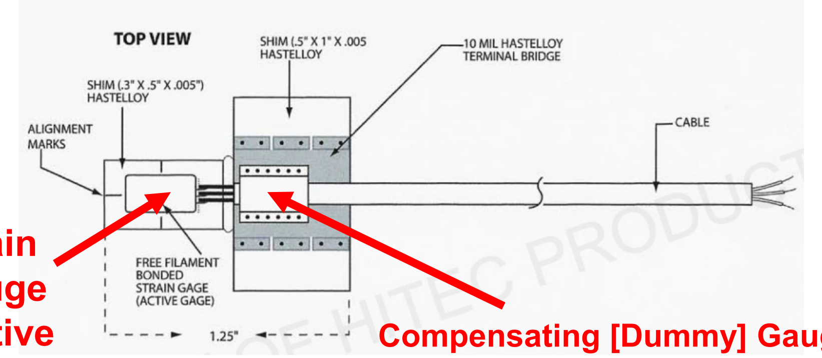
Strain Gauge Details – Temperature Compensation

- Resistive type sensor (R4) – The output is sensitive to temperature changes. This leads to:
  - Change in the resistance of gauge itself
  - Zero drift or datum shifts
  - Change in lead-wire resistance

- Temperature compensation is provided physically using a similar dummy gauge (R3), which is not attached to the substrate material, but is affected by similar conditions as R4. This negates any change in resistance due to temperature.
  - R1 and R2 are part of the NI module.



$$\frac{V_o}{V_s} = \frac{1}{4}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \overbrace{\frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}}^{0}\right)$$

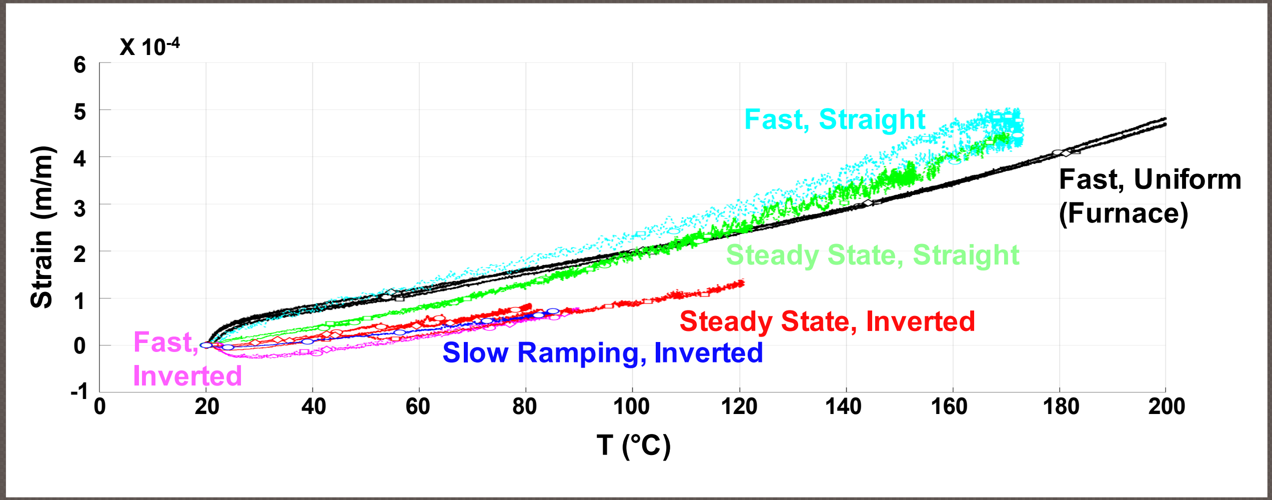


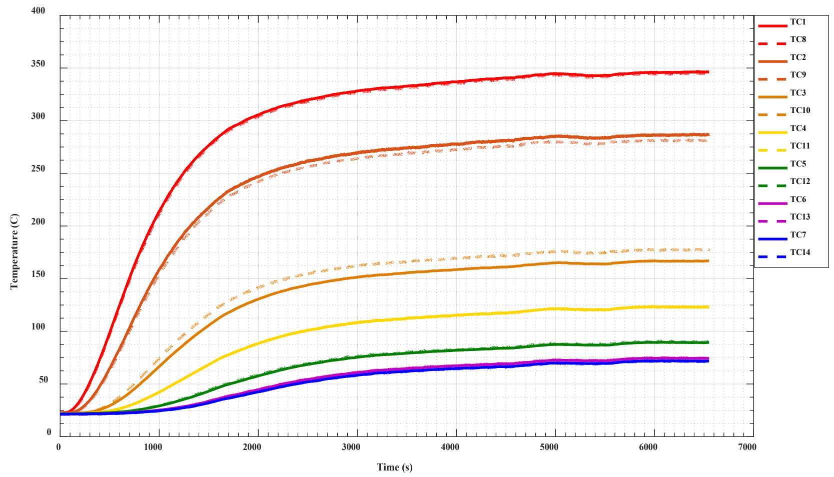
Results and Accomplishments

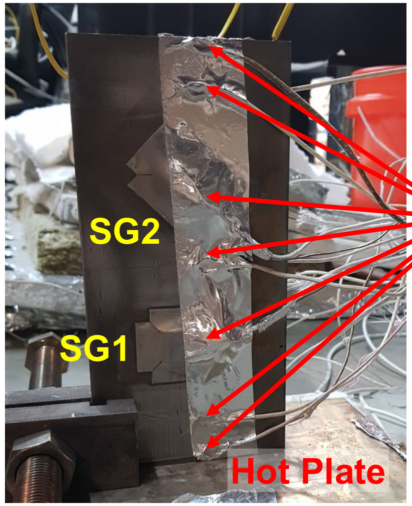
Strain Gauge Validation

Benchtop Validation – Thermal Strain Measurements

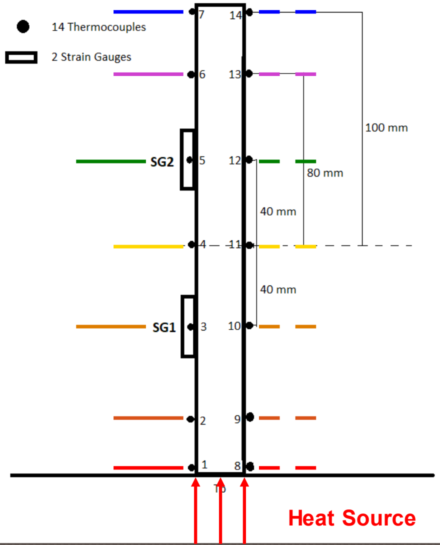
- “Fin-type” 1-Dimensional Heating
  - Stainless steel specimen
    - Temperature and Thermal Gradient Variation along the fin length







Front Side



Results and Accomplishments

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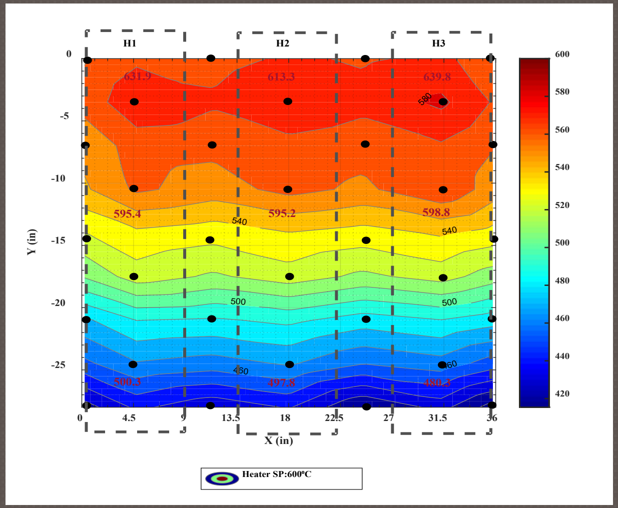
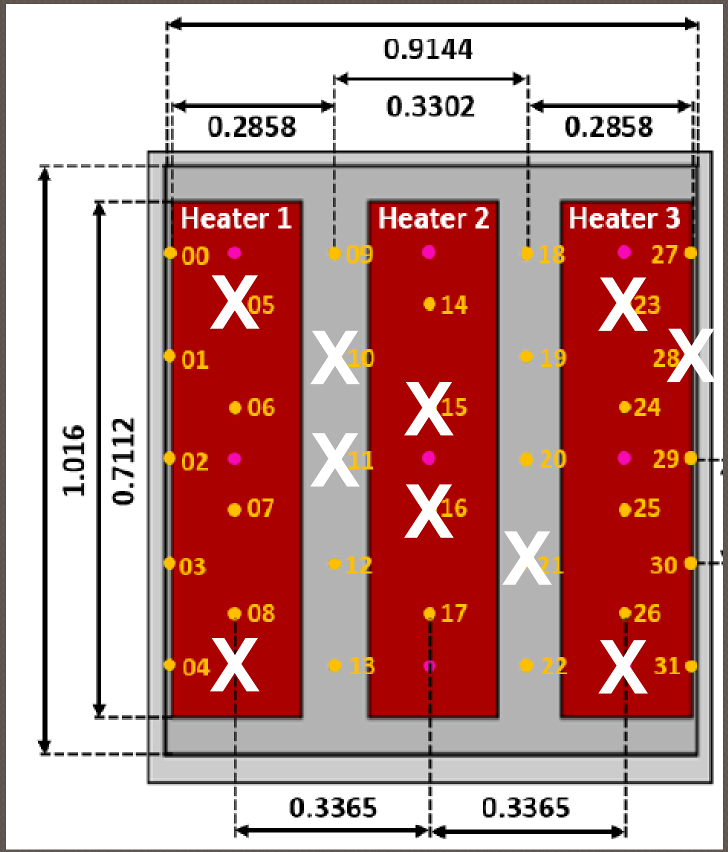
Strain Testing

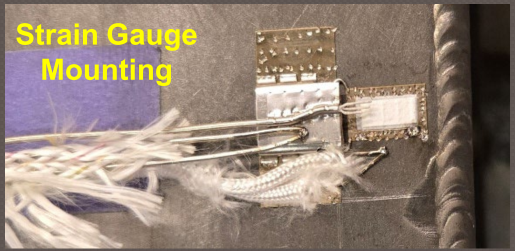
Vessel – Thermal Strain Measurements

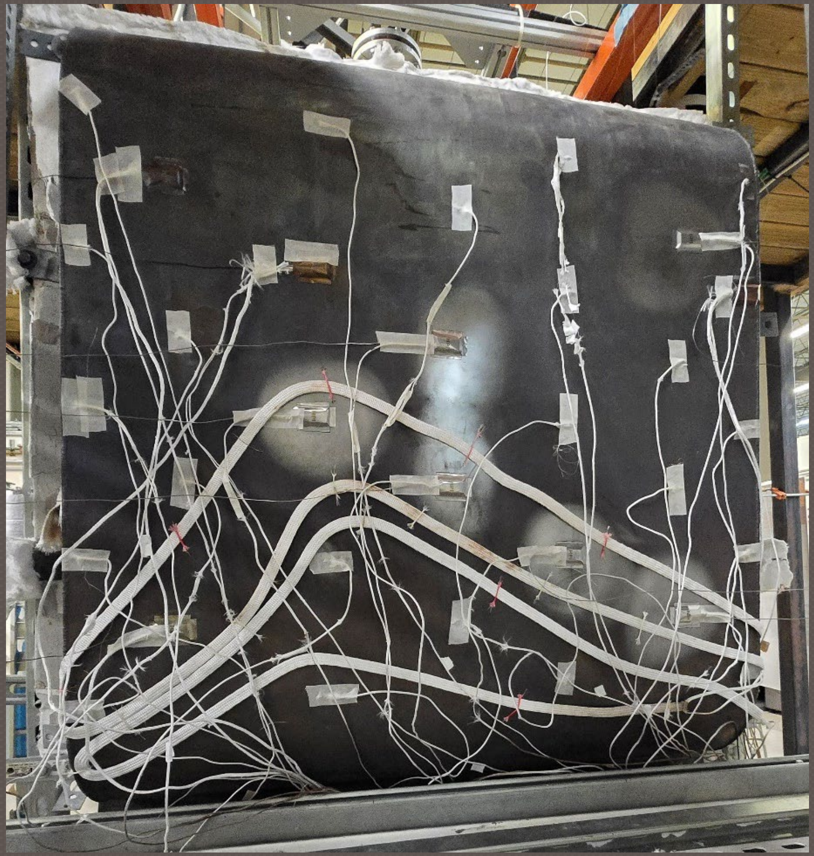
- **Vessel Instrumentation**
  - 10 Strain gauges
  - 32 Thermocouples



Strain Gauge Locations



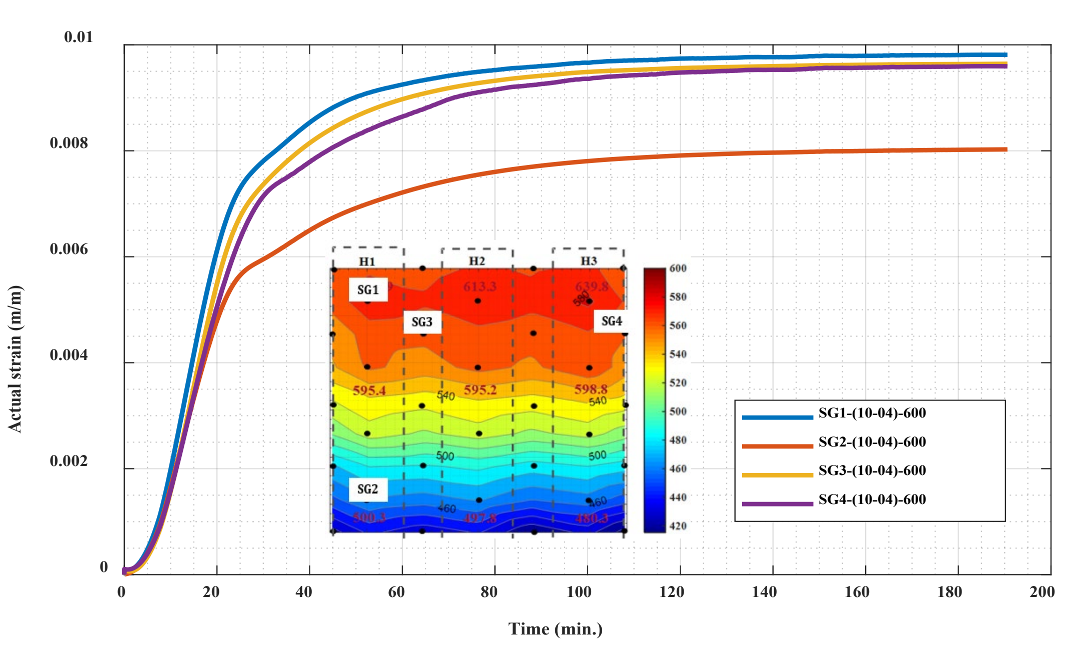


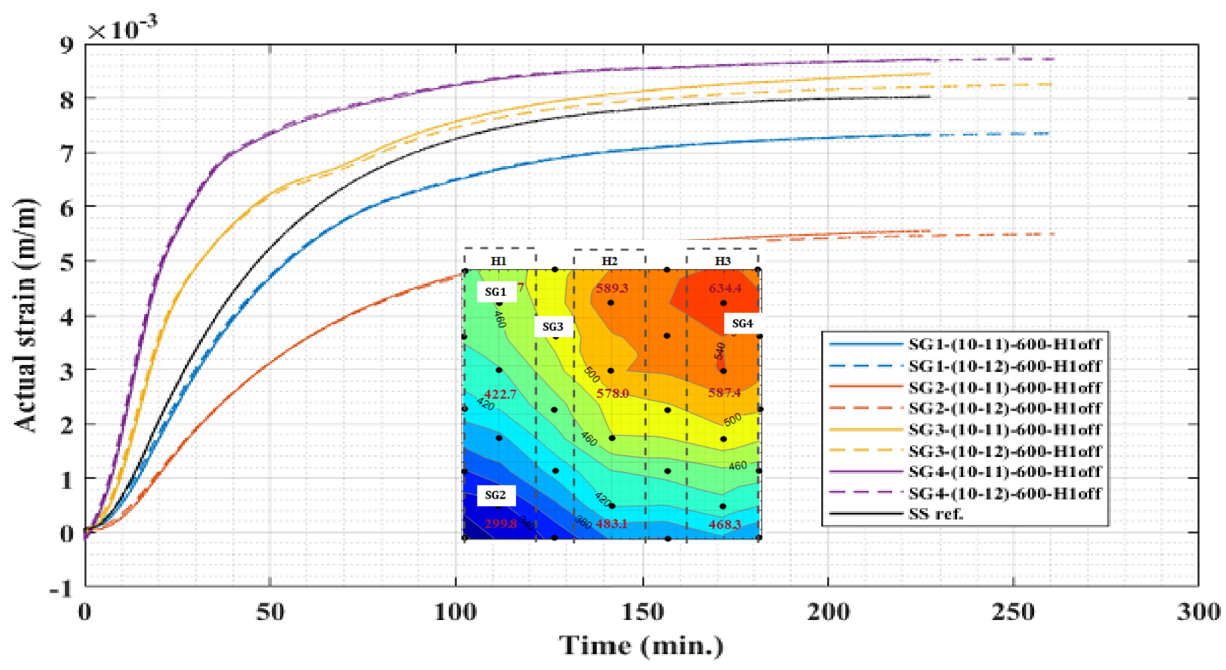


Results and Accomplishments

Strain Testing

Vessel – Thermal Strain Measurements





Results and Accomplishments

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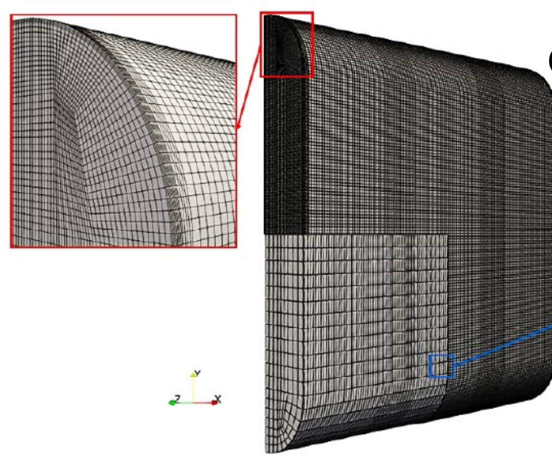
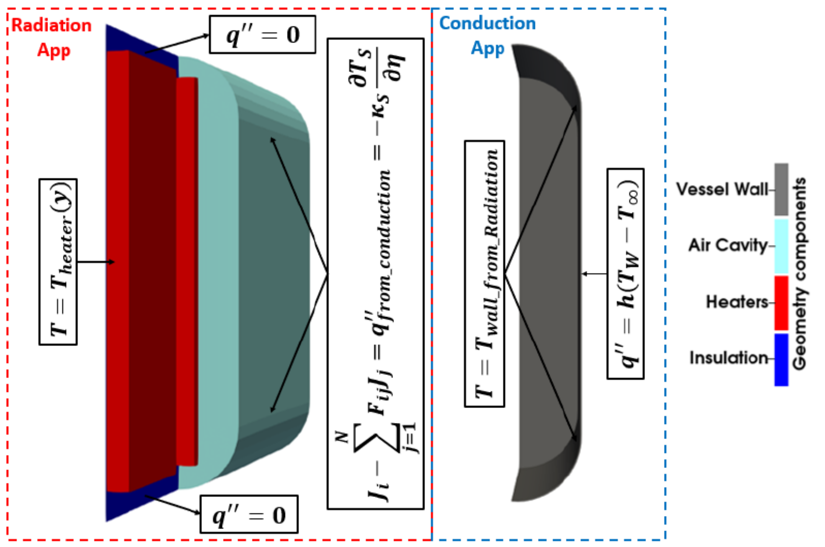
Numerical Simulations

Model Development with MOOSE

	# Elements (Gmsh)	Boundary Conditions
Radiation App *(Between Heaters and Vessel Inner Surface)*	33,288	Heater Temperature Distribution
Conduction App *(Through Vessel Wall)*	145,170	Inner Wall Temperature from Radiation App Outer Vessel Temperature – Convective Heat Flux (variable h)



Mesh for Computational Model



Boundary Conditions for Computational Model

Results and Accomplishments

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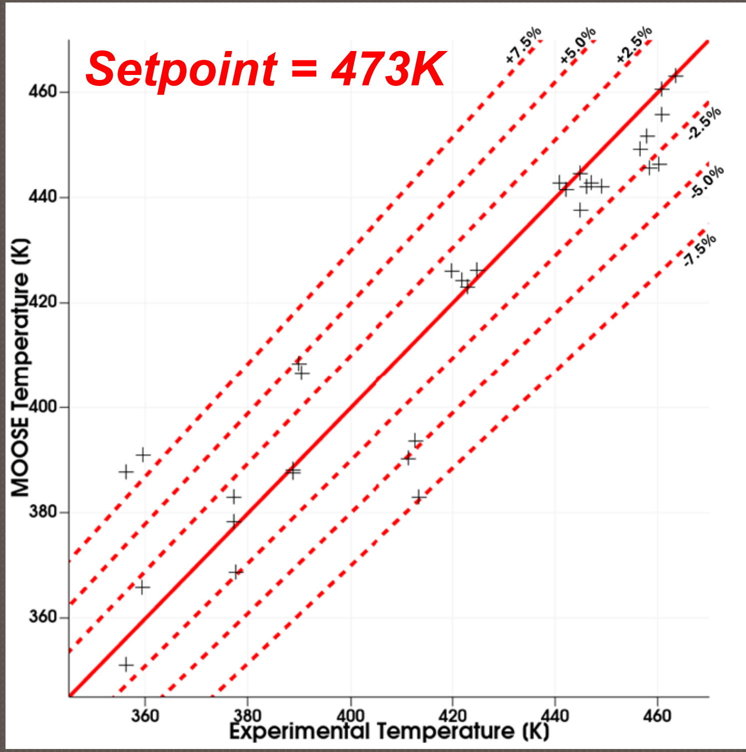
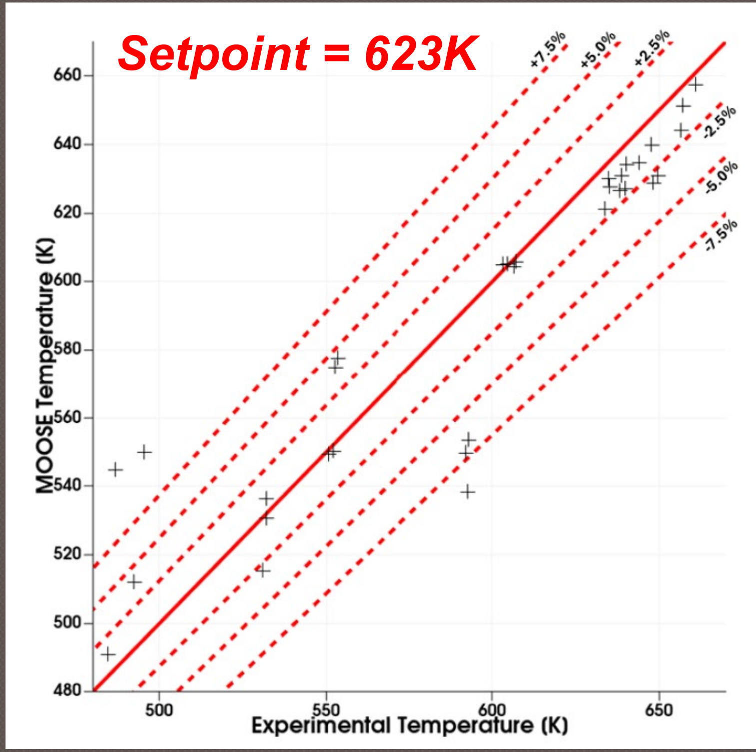
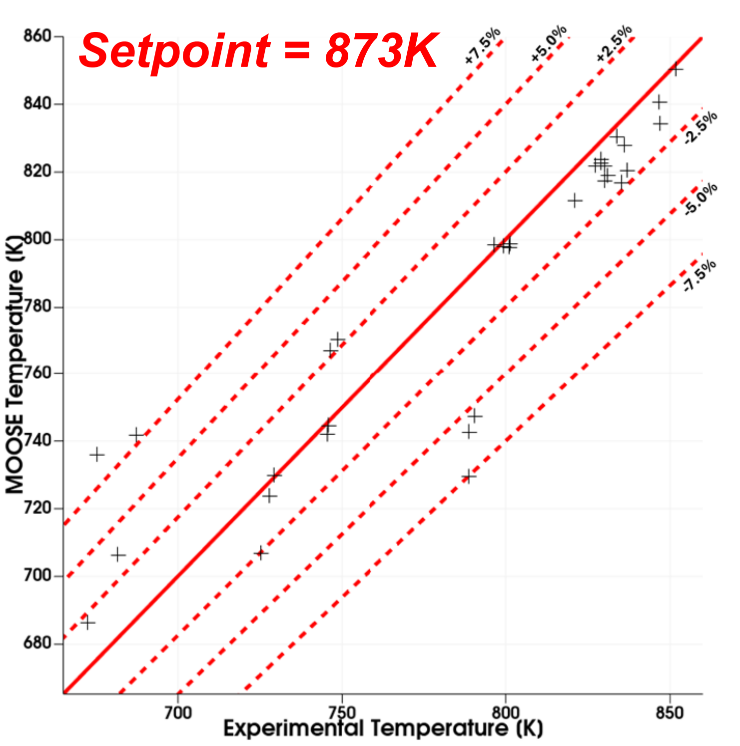
Numerical Simulations

MOOSE Prediction and Comparison with Experimental Data







Results and Accomplishments

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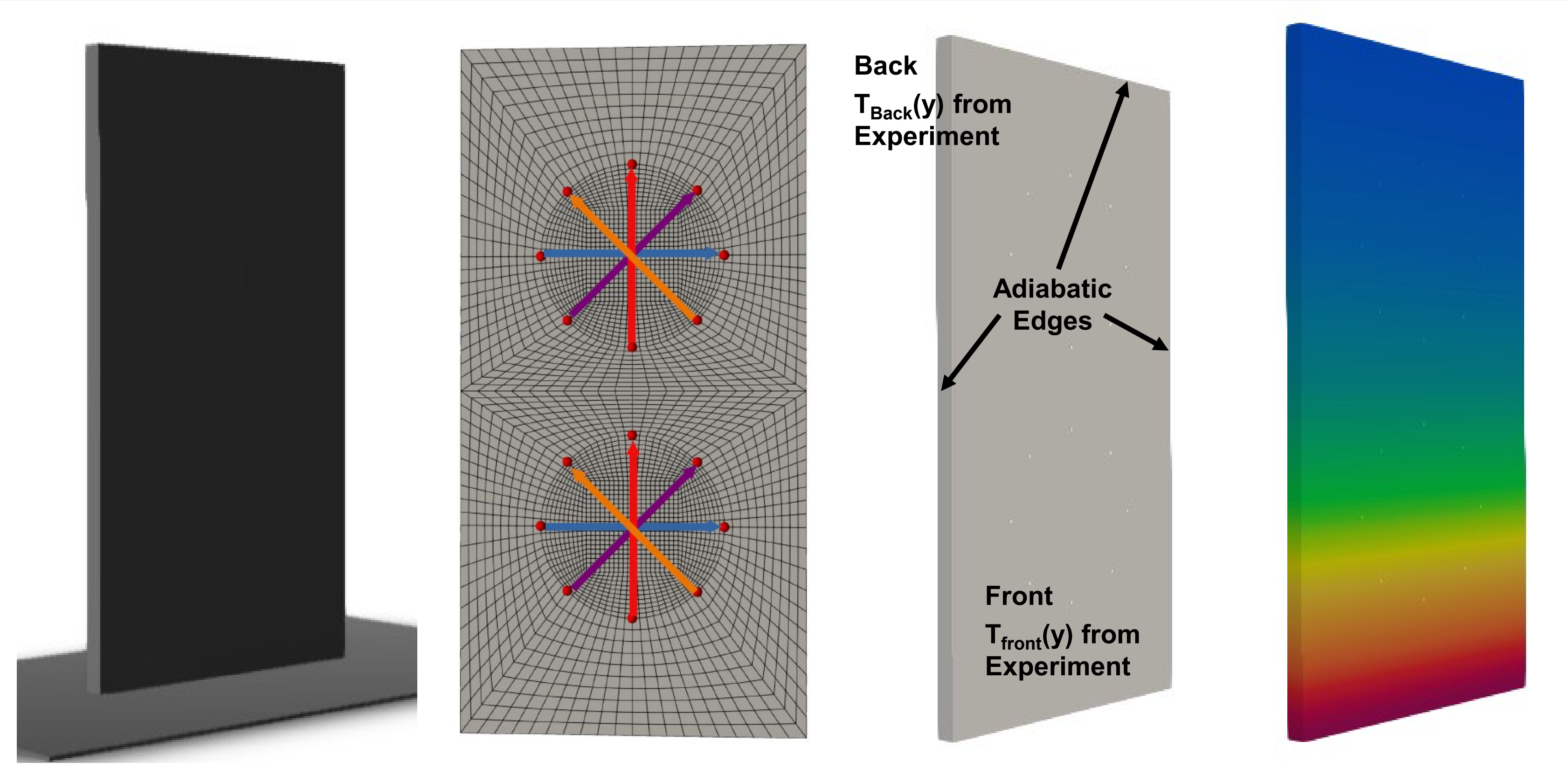
Numerical Simulations

MOOSE Prediction of Thermal Strains in Benchtop Tests



Model for Numerical Simulations

Preliminary Mesh and Target Regions Based on Strain Gauge Placement

Thermal Boundary Conditions

Results and Accomplishments

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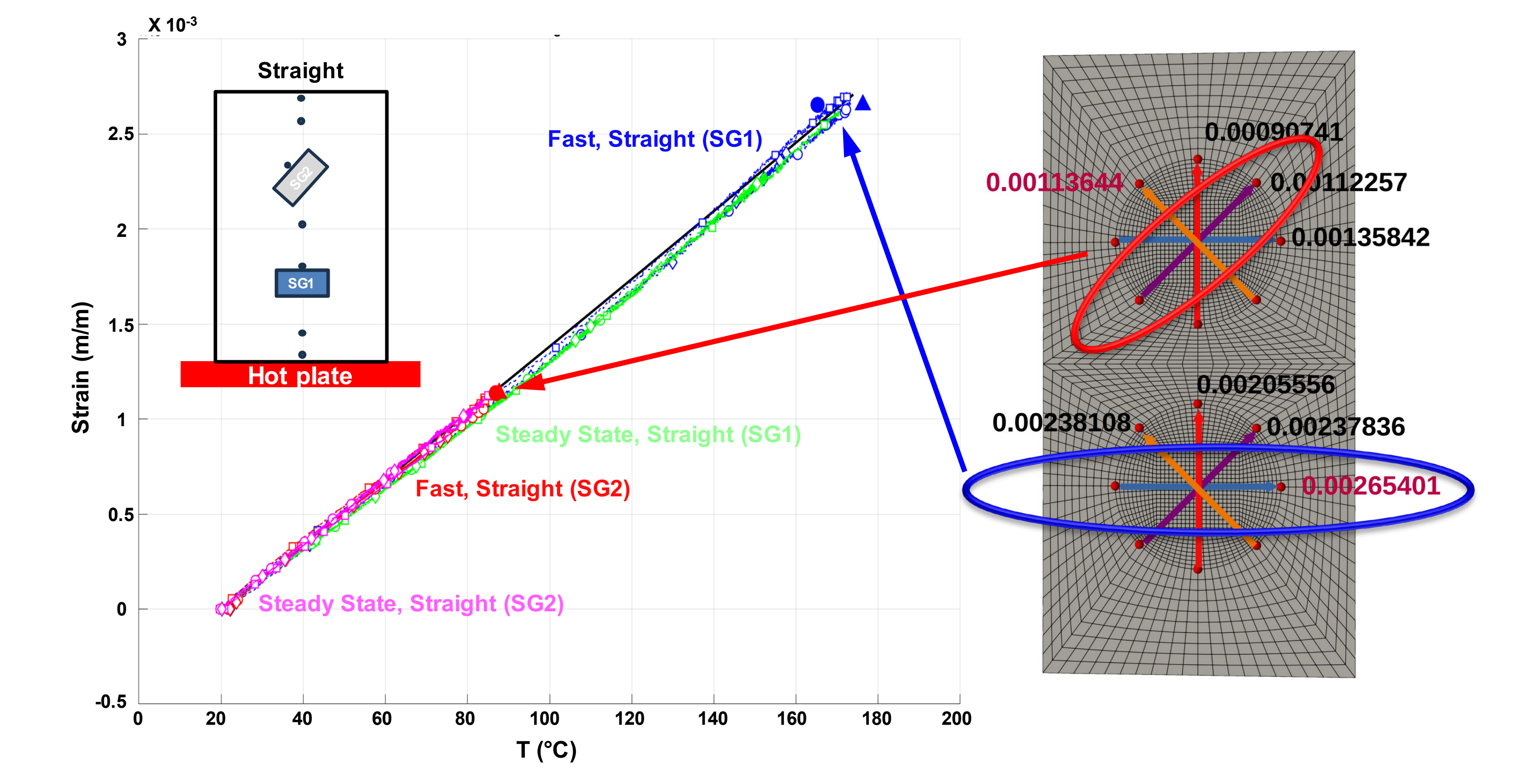
Numerical Simulations

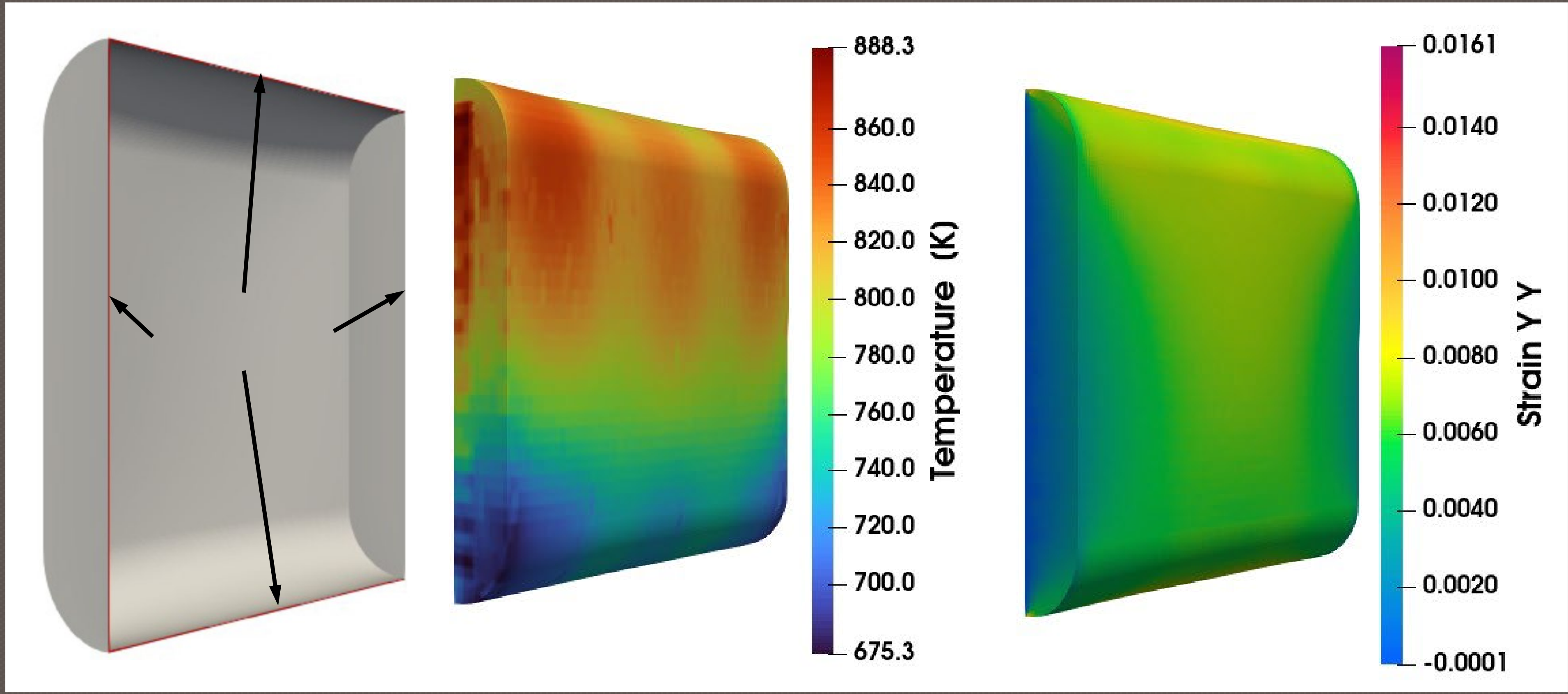
MOOSE Prediction of Thermal Strains in Benchtop Tests



Results and Accomplishments

Numerical Simulations

Preliminary Strain Predictions on Vessel Wall



Vessel Model | **Predicted Temperature Distribution (600°C Setpoint)** | **Preliminary Predicted Strain Distribution in Y-Direction for Given Temperature Distribution**

Results and Accomplishments

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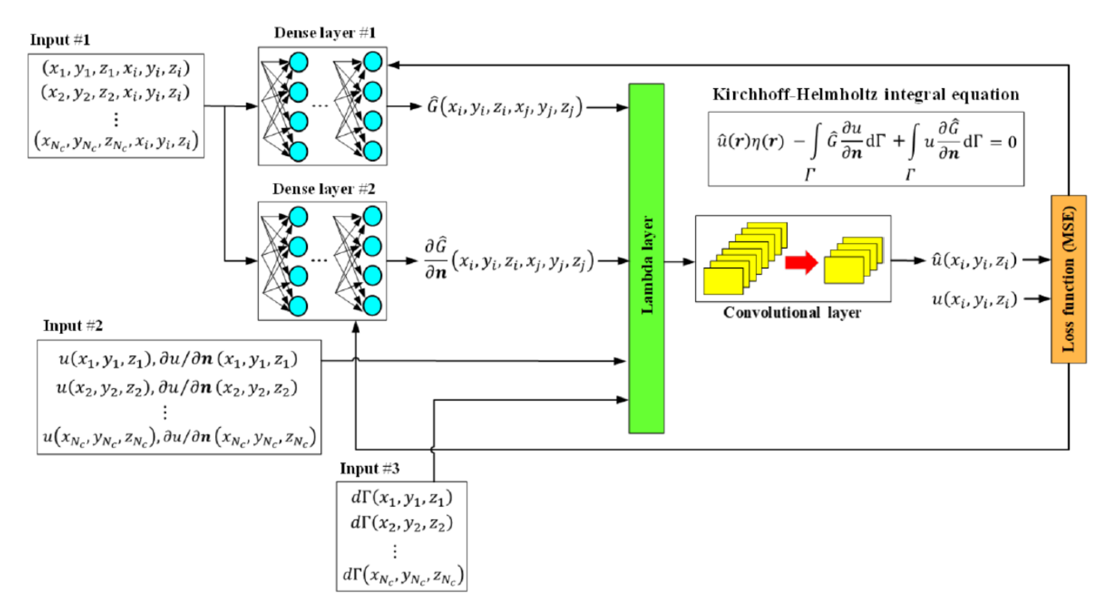
CNN Algorithm Development

CNN for Restructuring a Spatial Field Distribution



Set-Point Temperature (K)						
Training	873	823	723	623	523	473
Validation	773	573				
Testing	673					

Reconstruct the temperature distribution within the vessel wall based on minimal temperature measurements.

2 Approaches to Generate CNN Data Set

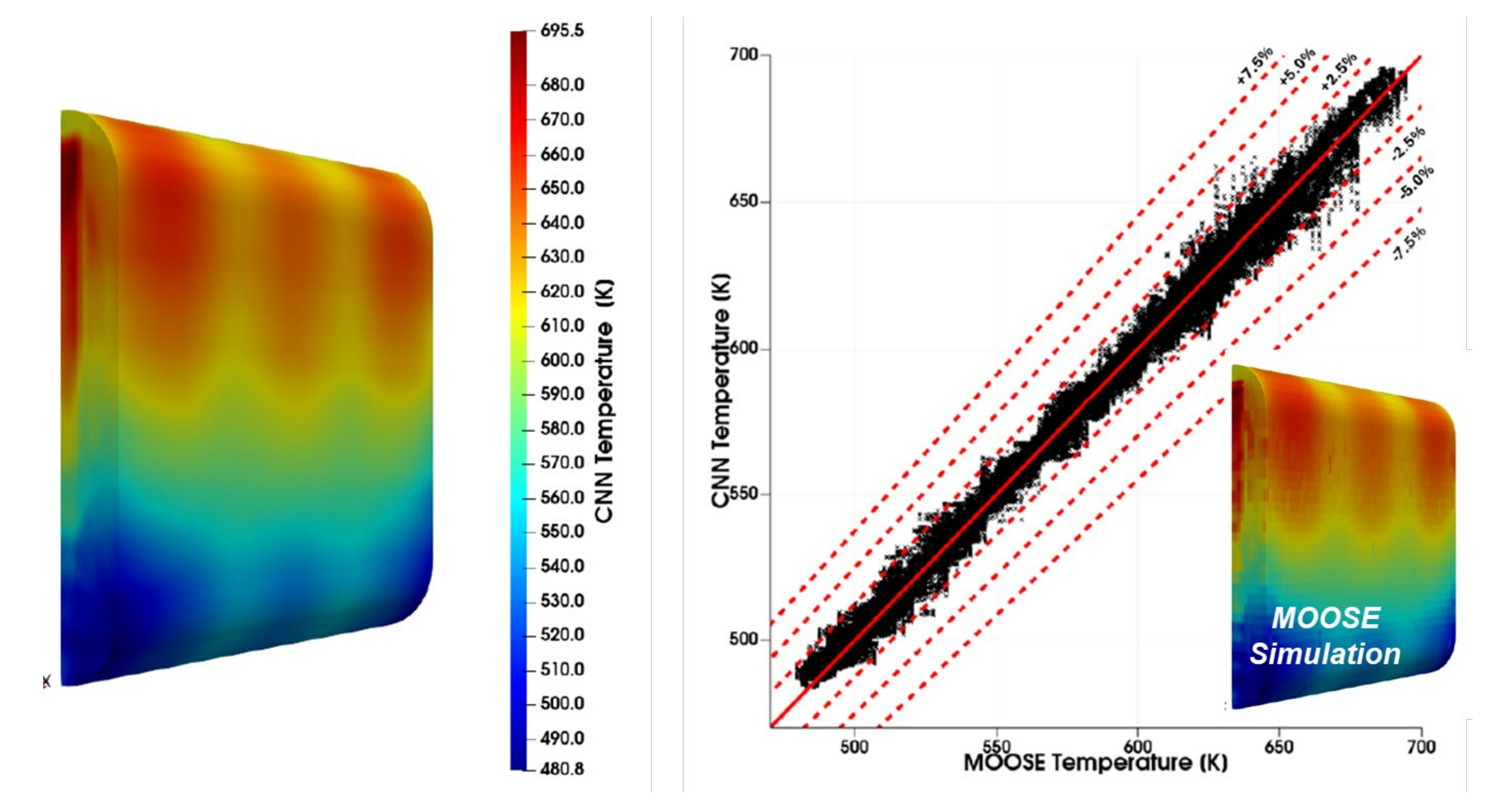
1. **Conventional Model – Collect Temperature and Heat Flux from MOOSE at TC Locations to Construct Data Sets**

2. **Newton-Cooled Based Model – Temperature from MOOSE at TC Locations; Heat Flux Calculated within CNN from Convection Equation**

Results and Accomplishments

CNN Algorithm Development

Temperature Comparison between CNN Reconstrued Field and MOOSE Model



Results and Accomplishments

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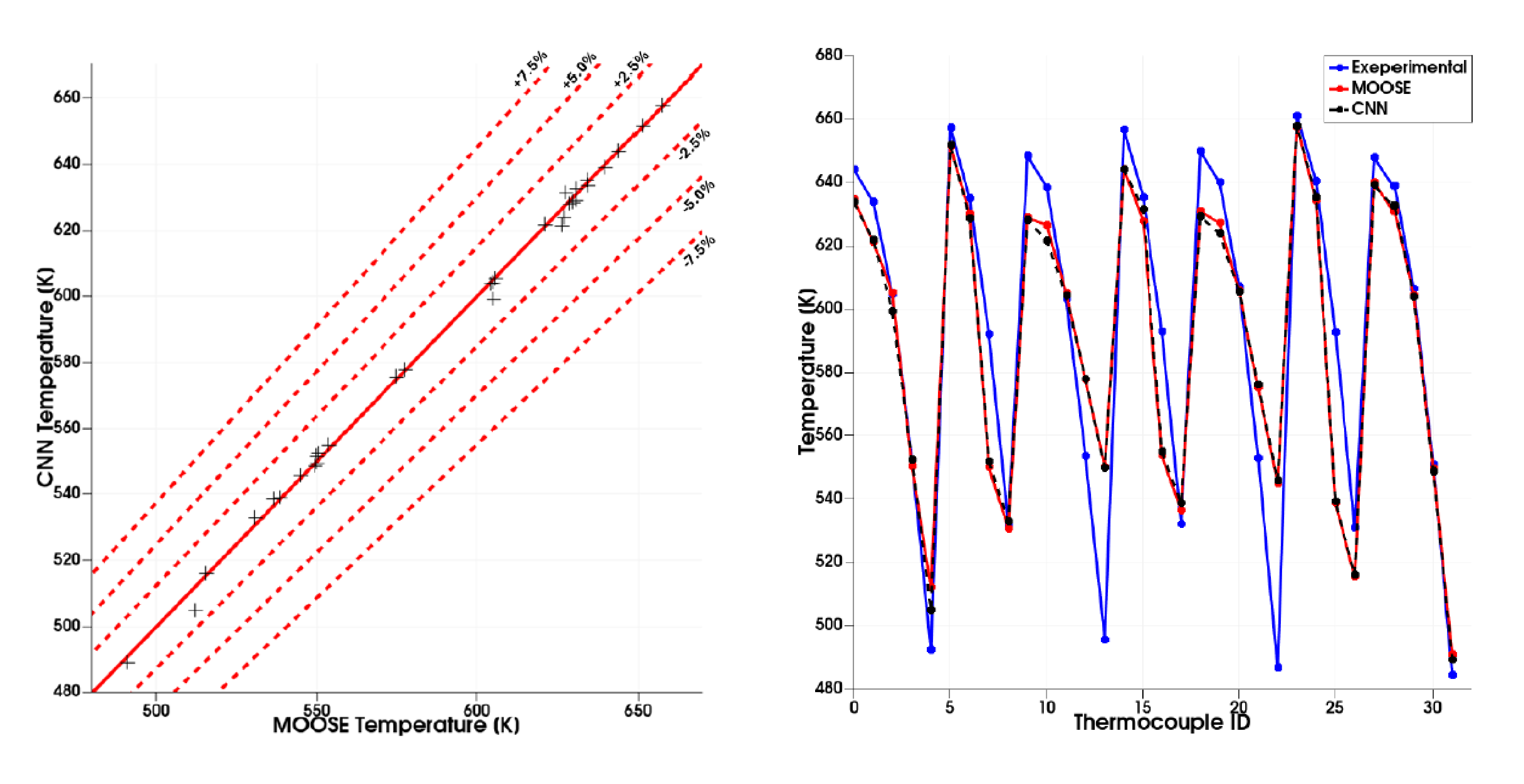
CNN Algorithm Development

Temperature Comparison between Measurements, MOOSE, and CNN



Concluding Remarks

Project Accomplishments

- **Experimental Testing**
  - *Benchmark testing and validation of high temperature strain gauges completed*
  - *Strain gauges installed on vessel wall*
  - *Strain distributions have been obtained under several heating conditions*
- **Numerical Simulations**
  - *CFD simulations have been completed including MOOSE's Ray Tracing Module*
  - *Excellent agreement with experimental data*
  - *Thermal simulations used as training data for CNN*
  - *Validation of thermal strain measurements using benchtop test data*
  - *Preliminary prediction of strain distributions in vessel wall*
- **Application and Customization of the Convolutional Neural Network (CNN) Approach**
  - *CNN has been demonstrated for temperature distributions using CFD simulations and validated with experimental data*

Publications

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1. Coppo Leite, V., Novak, A., Merzari, E., Ponciroli, R., Ibarra, L., 2023, "Application of a Physics-Informed Convolutional Neural Network for Monitoring the Temperature Field in Advanced Reactors", Proceedings of NURETH-20, Washington, DC, August 2023.

2. Aldeia Machado, L.C., Coppo Leite, V., Merzari, E., Wright, L.M., Bhat, P., Hassan, Y., Ibarra, L., and Ponciroli, R., 2024, "Temperature Field Reconstruction of Surfaces Heated Through Radiative Heat Transfer Using Convolutional Neural Networks," ASME Paper No. HT2024-130465, 2024 ASME Summer Heat Transfer Conference, July 15 – 17, 2024, Anaheim, California.

3. Pramatha Bhat, "Assessing Strain Gauges for Real-Time Health Monitoring of High Temperature Gas-Cooled Reactor Vessels," 2024, TAMU (Nuclear Engineering) – MS Thesis.

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