U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Advanced Sensors and Instrumentation

An Innovative Monitoring Technology for Reactor Vessel of Micro-HTGR

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar
October 24 – 27, 2022

PI: Lesley Wright, Texas A&M University, Mechanical Engineering
Collaborators: Penn State, ANL, BWXT

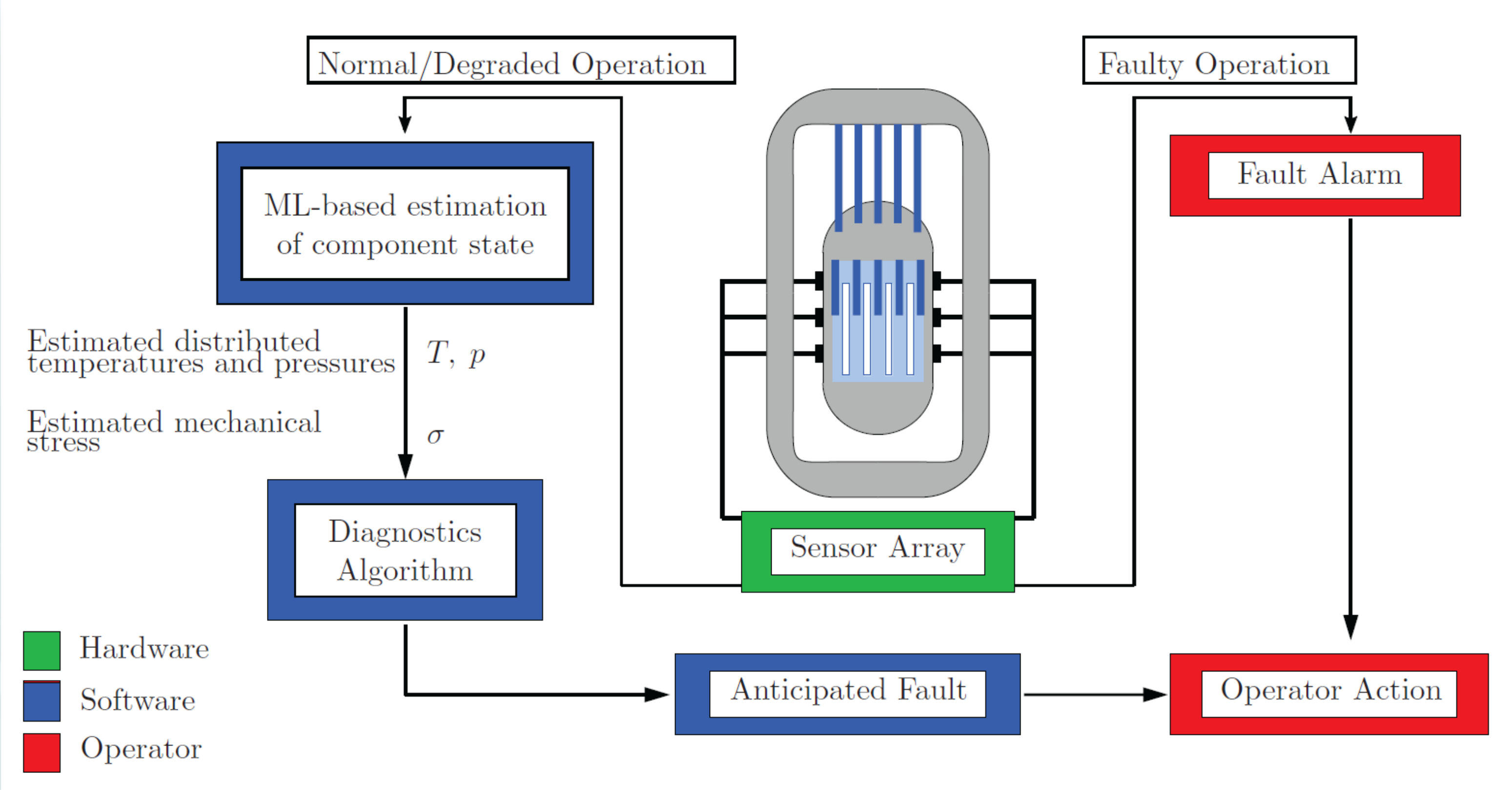
Project Overview

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

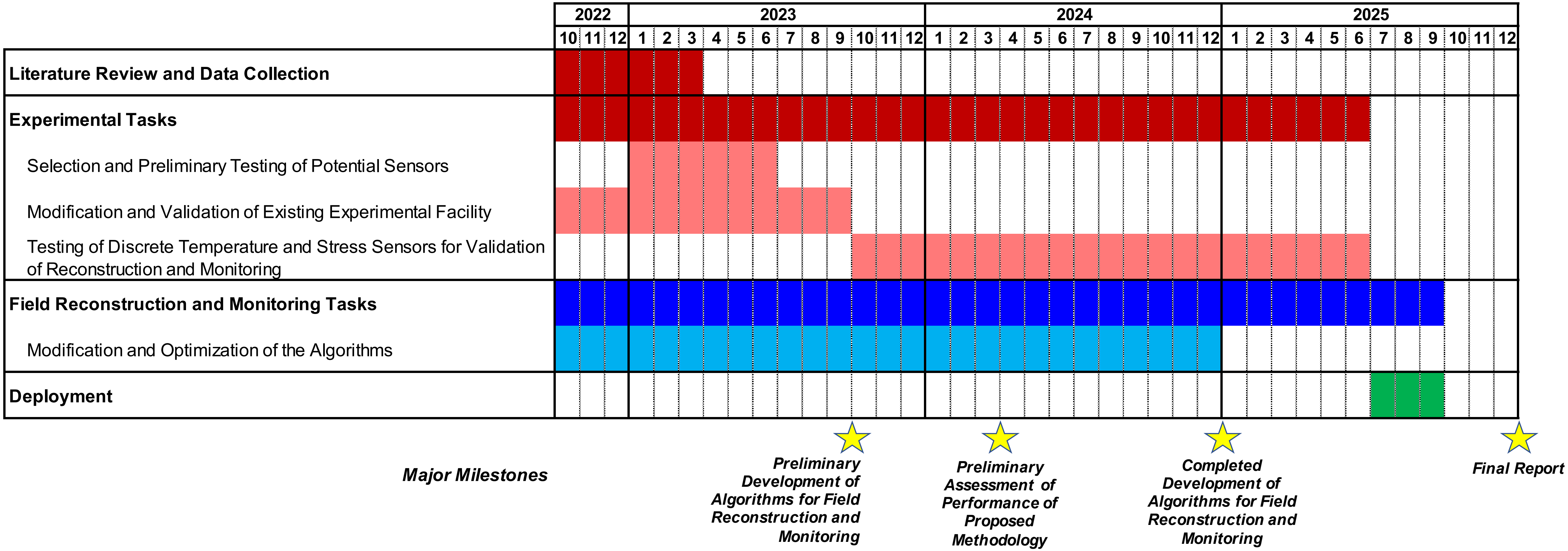
1. **Real-Time, Reliable, and Cost-Effective Monitoring Methodology**

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 - Participants

- **Texas A&M University**
  - *Laboratory Testing for Simulation and CNN Validation*
    - Lesley Wright, Mechanical Engineering
    - Rodolfo Vaghetto, Nuclear Engineering
    - Hanlin Wang, PhD Candidate Mechanical Engineering
    - Pramatha Bhat, MS Student, Nuclear 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

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.**

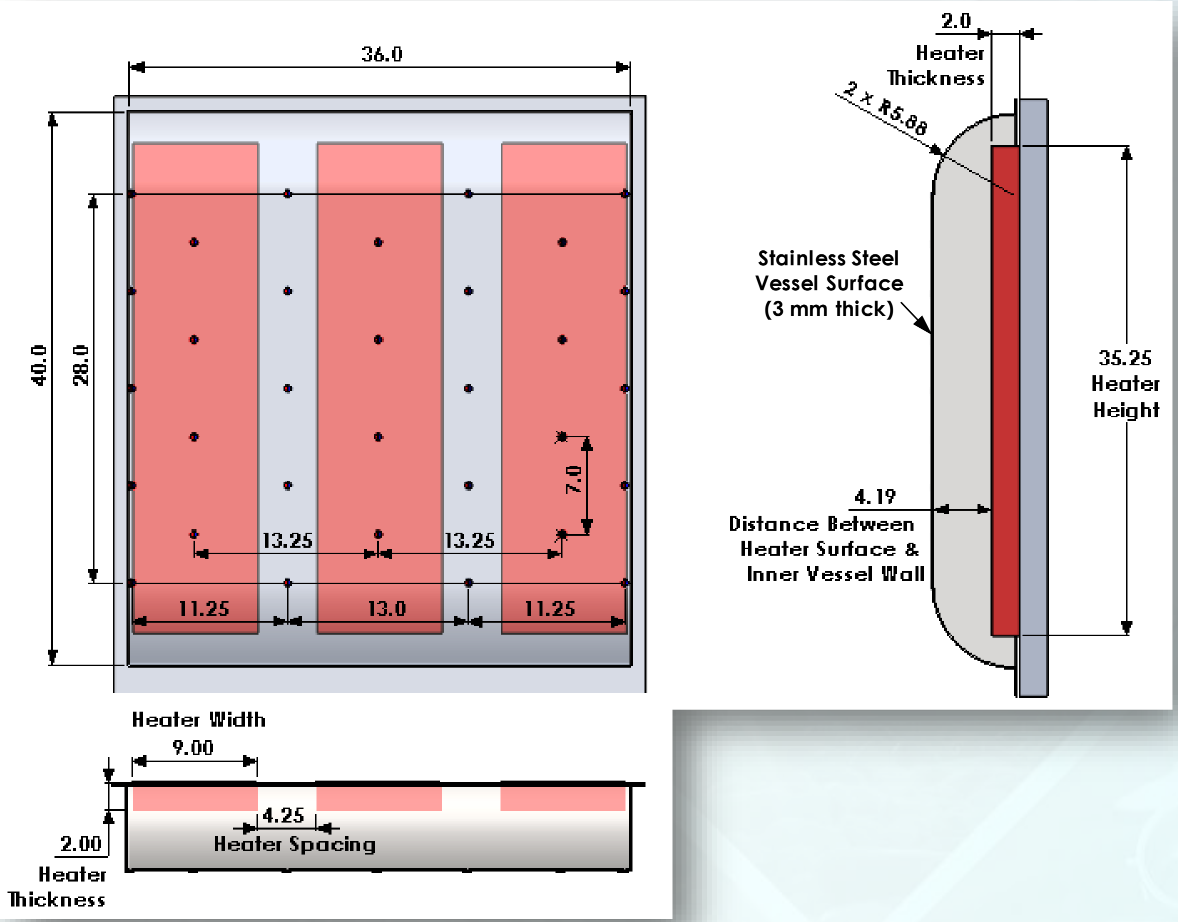
- **The proposed method removes the need for penetrations through the pressure boundaries and is suitable for other advanced micro-reactors technologies.**

- **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 – Project Accomplishments

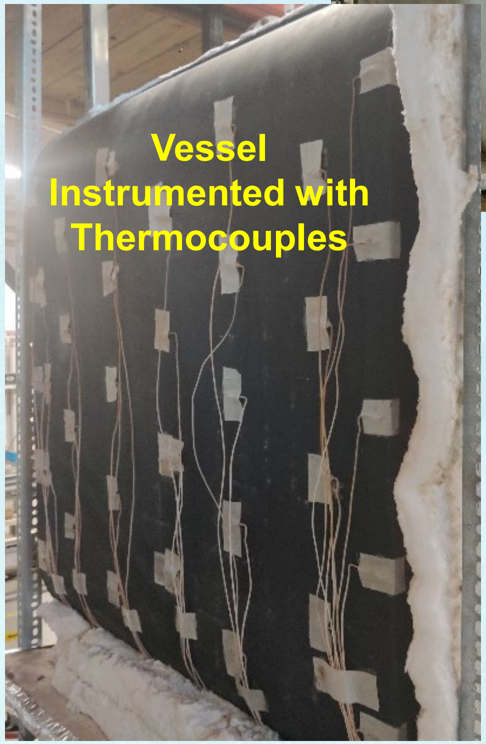
- **Experimental Testing**
  - *Existing experimental facility modified and brought to operational*
    - Radiant heating of reactor vessel model
    - Outer surface instrumented with thermocouple array
    - Benchtop testing of high temperature strain gauges is on-going
- **Numerical Simulations**
  - *Preliminary CFD simulations have been completed*
    - Validation of ray tracing algorithms
    - 3D simulations of TAMU experimental vessel
- **Application and Customization of the Convolutional Neural Network (CNN) Approach**
  - *CNN has demonstrated promising performance with the numerical datasets*

Results and Accomplishments – Experimental Validation

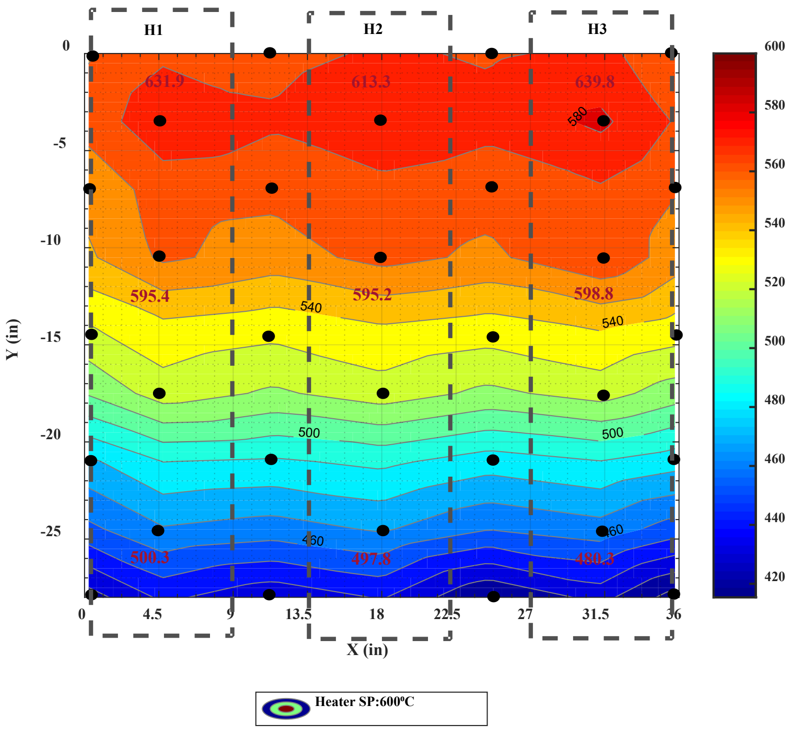


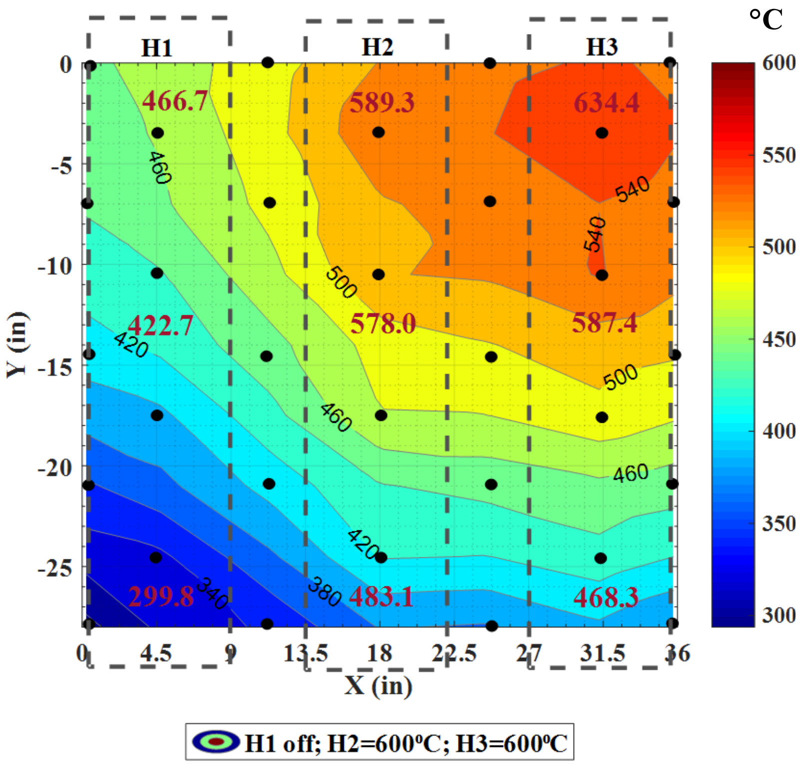
Three Radiant Heaters

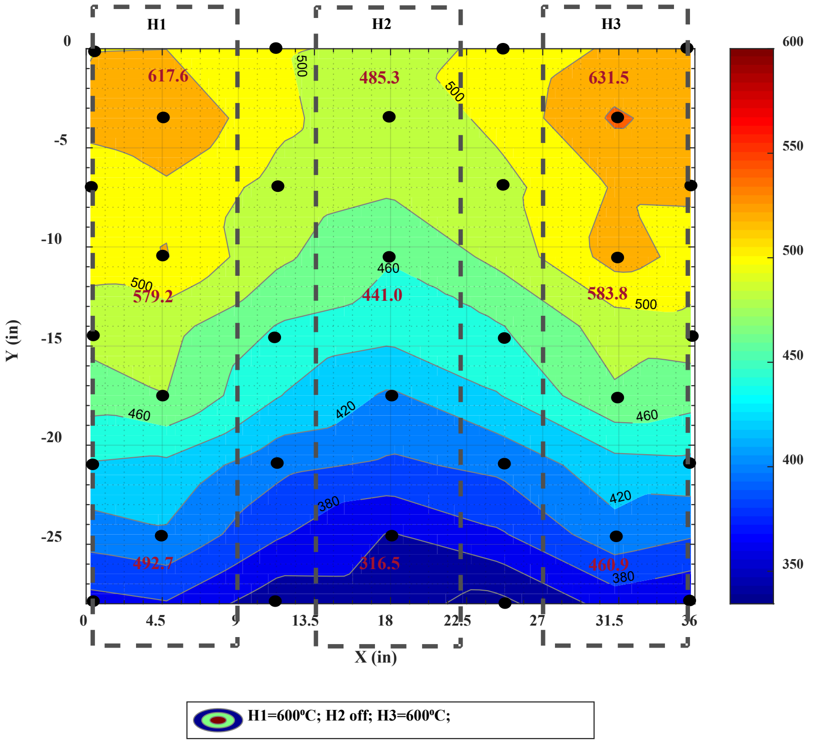
Outer Surface Fully Insulated for Testing



Results and Accomplishments – Experimental Validation







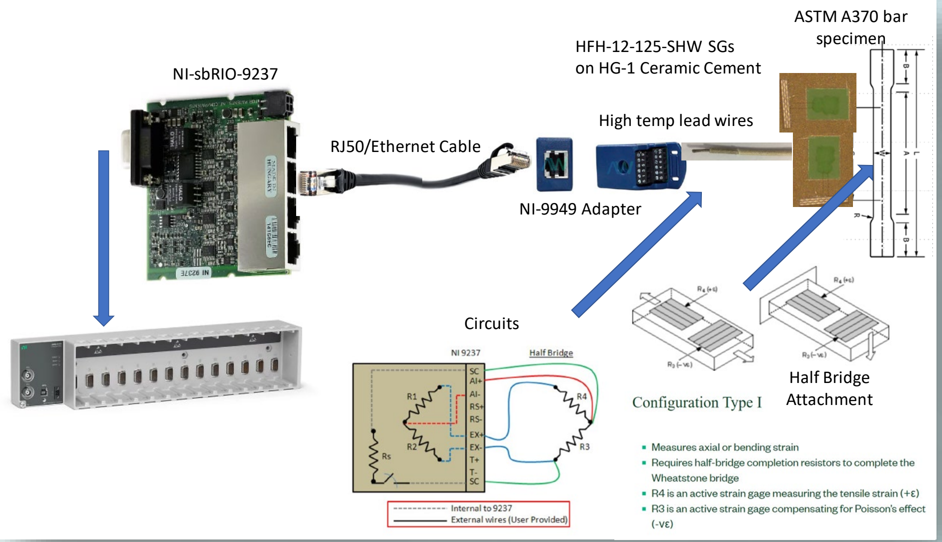
Heater 1 [Left] → Off

$T_{H2} = T_{H3} = 600°C$

Results and Accomplishments – Experimental Validation

- **Strain Gauge Testing**
  - *HBK (Hottinger Bruel, and Kjaer) nickel-chrome alloy gauges*
  - *HPI (Hitec Products, Inc.) high temperature strain gauges*

- **Heat Flux Gauge Selection**
  - *Huskeflux IHF01 and IHF02 heat flux gauges*
  - *FluxTeq HTHFS gauges for extreme environments (rated to 1000C)*



Results and Accomplishments – Numerical Simulations

- **Radiative Heat Transfer using MOOSE Framework**
  - *Mulitphysics Object Oriented Simulation Environment (MOOSE) Developed at Idaho National Laboratory (INL)*
    - Ray Tracing and Heat Conduction Modules

MOOSE's Ray Tracing Module

View Factor for 3D Geometry

$$F_{ij} = \frac{1}{A_i \pi} \sum_{l=1}^{L} \sum_{k=1}^{K} \omega_l \omega_k (\widehat{\Omega}_k . \vec{n}_l) H_j (\vec{r}_l, \widehat{\Omega}_k)$$

Net Radiation Method

Heat Flux

$$q_r''(\vec{x}) = J(\vec{x}) - H(\vec{x})$$

Radiosity

$$J(\vec{x}) = \epsilon(\vec{x})\sigma T^4 + (1 - \epsilon(\vec{x}))H(\vec{x})$$

$$J_i = \epsilon_i \sigma T_i^4 + (1 - \epsilon_i) H_i$$

Irradiation

$$H_i = \sum_{j=1}^{n} F_{ij} J_j$$

Heat Flux

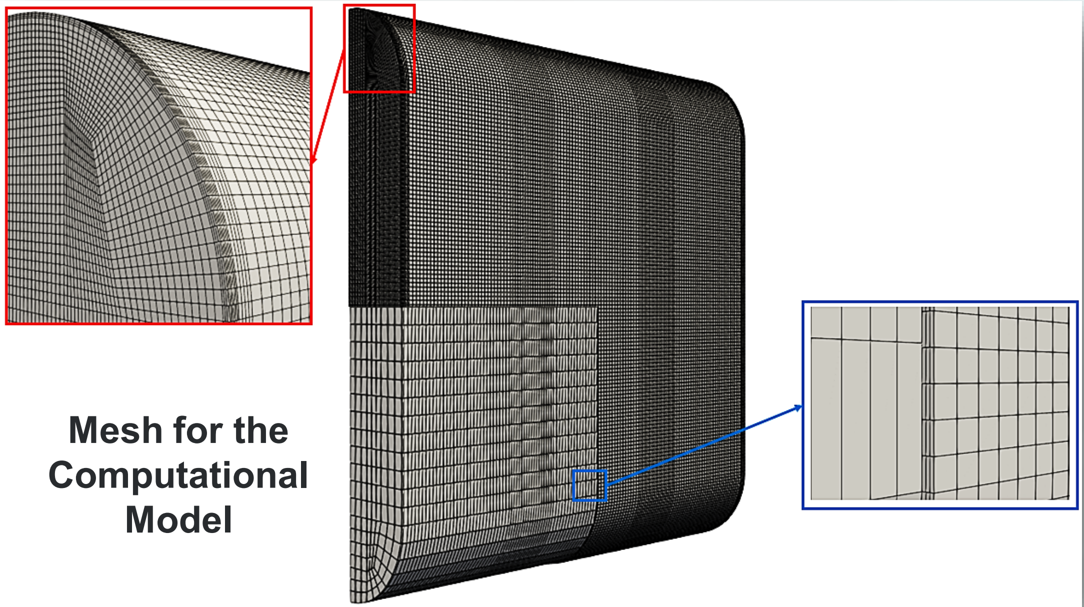
$$q_i'' = \sum_{j=1}^{n} (\delta_{ij} - F_{ij}) J_j$$

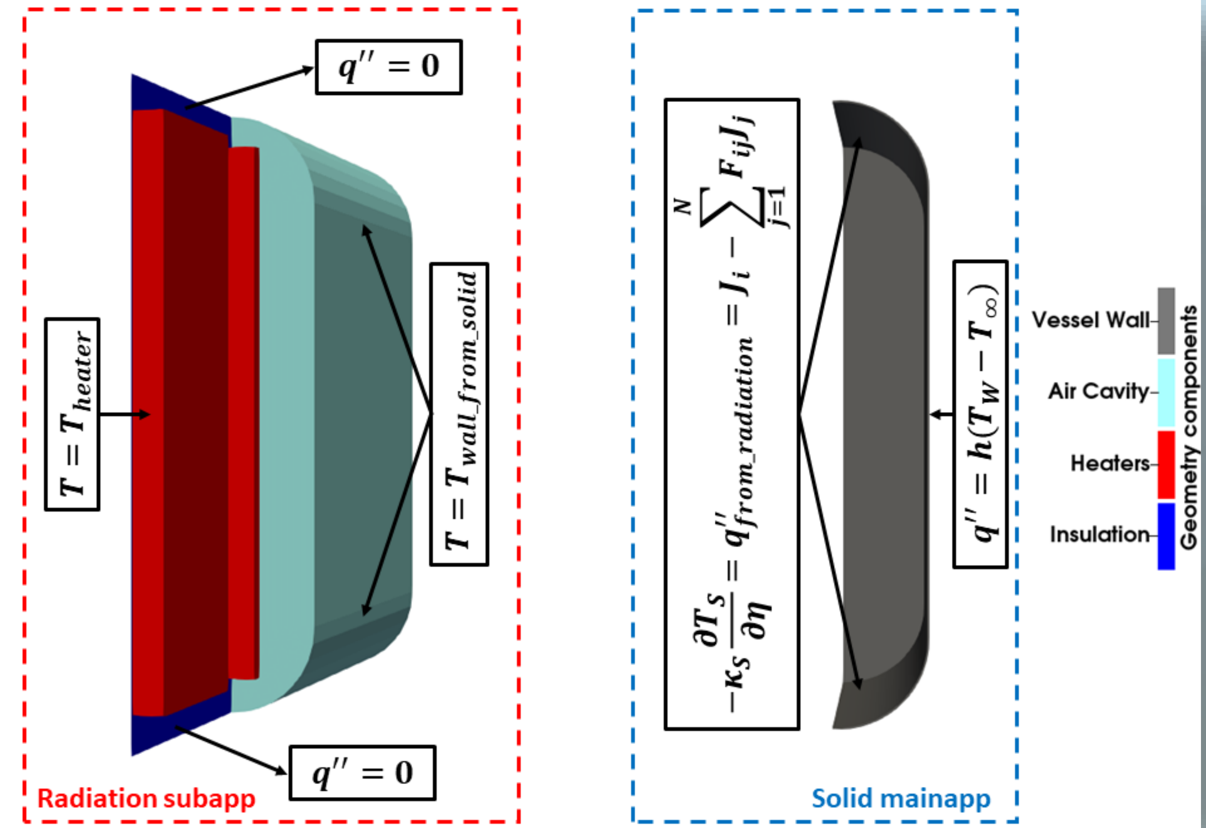
$$\sum_{j=1}^{n} (\delta_{ij} - F_{ij}) J_j = 0$$

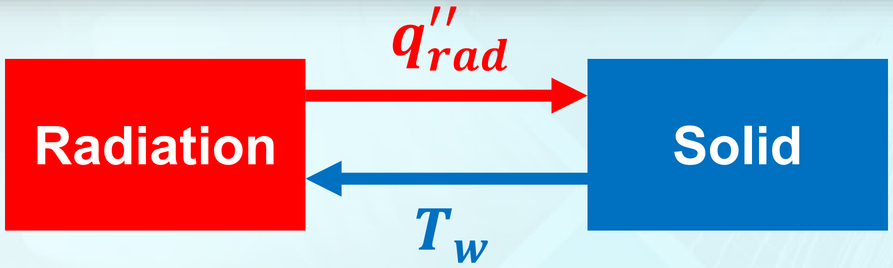
$$\sum_{j=1}^{n} (\delta_{ij} - (1 - \epsilon_i) F_{ij}) J_j = \epsilon_i \sigma T_i^4$$

Results and Accomplishments – Numerical Simulations

- **Model Development of the TAMU Vessel Experiment**

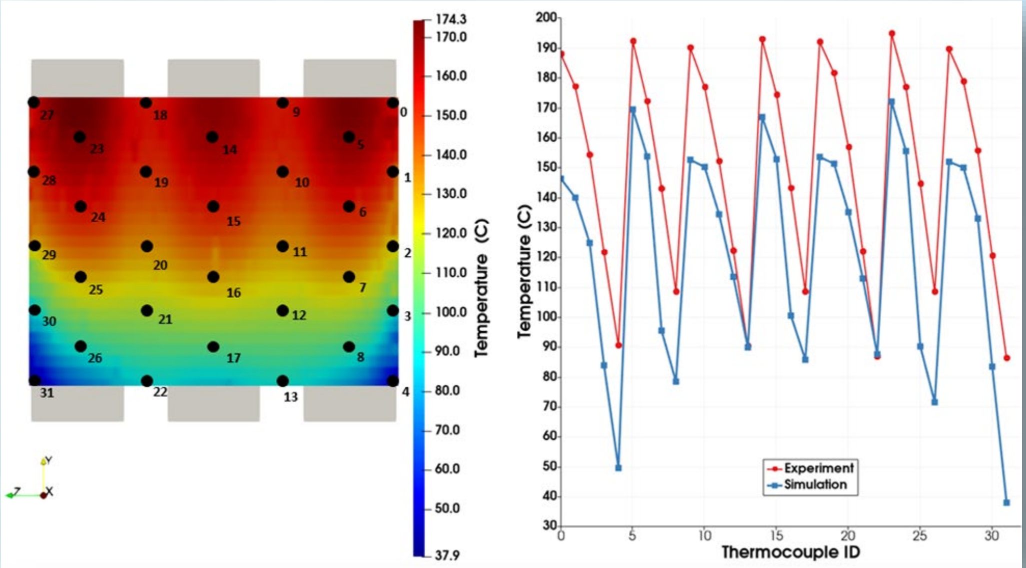


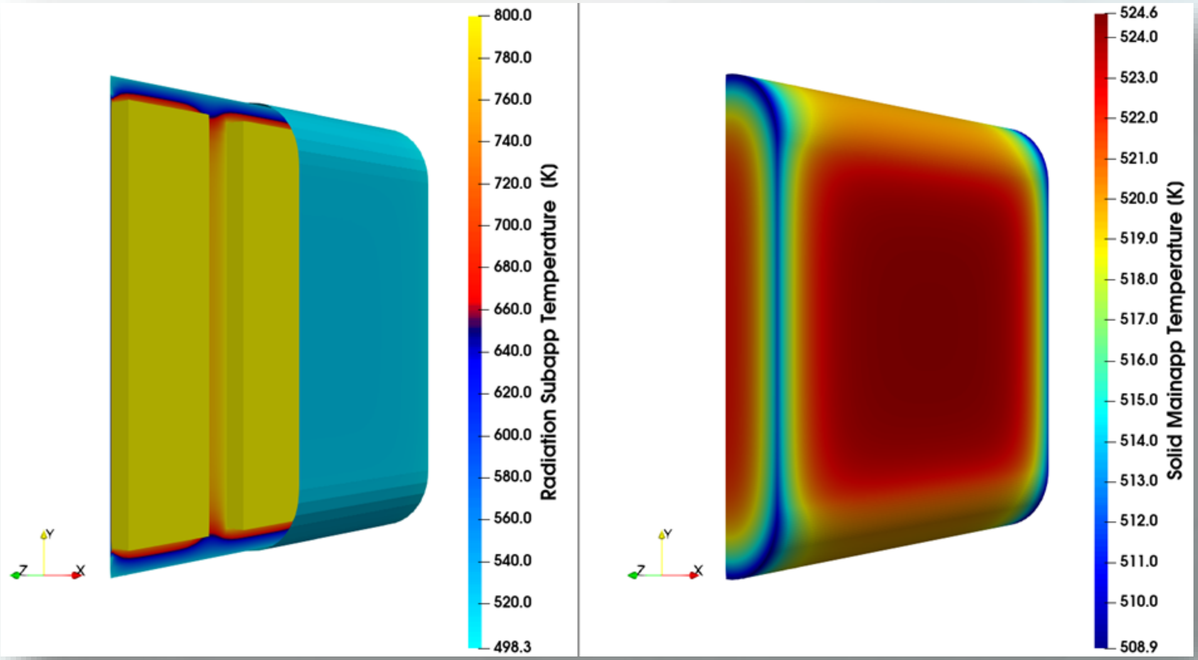




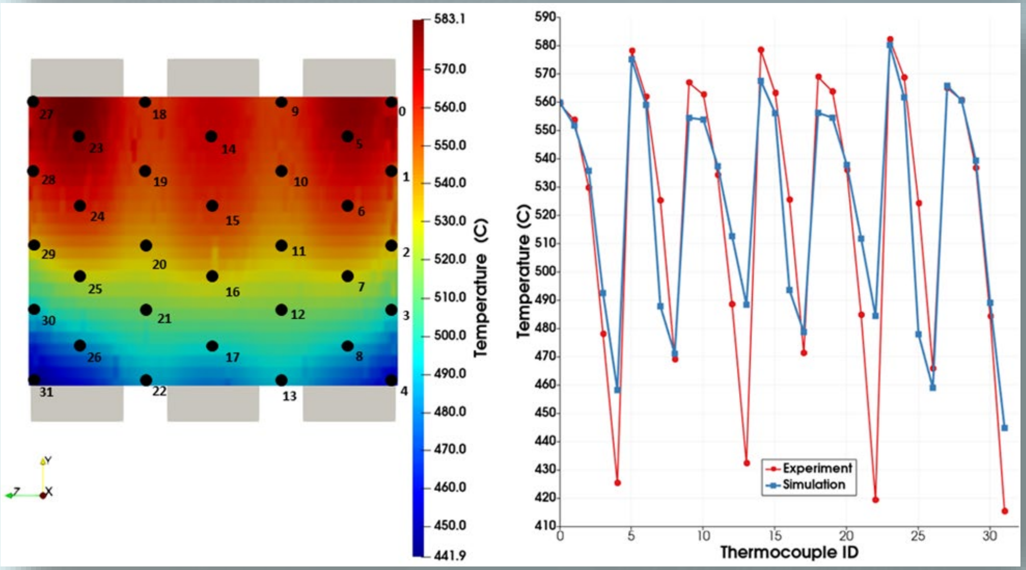
Results and Accomplishments – Numerical Simulations

Non-uniform Heating (200°C Setpoint)





Uniform Heater Temperatures



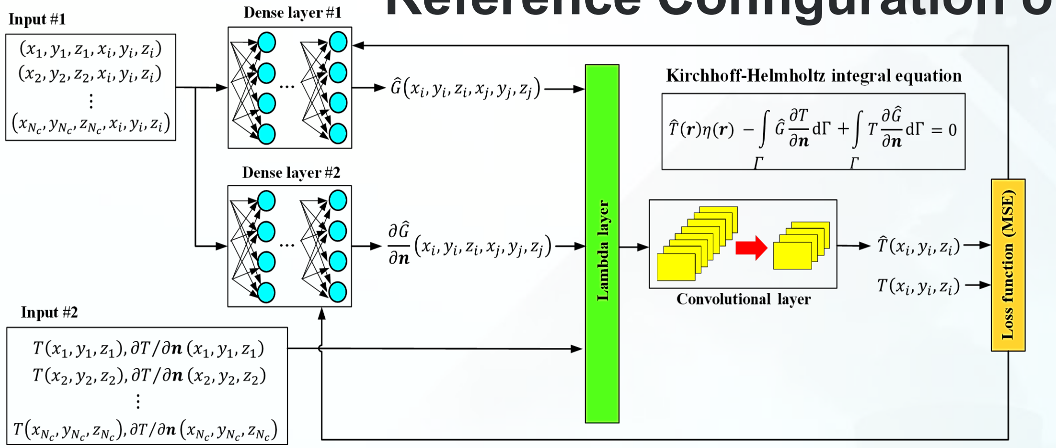
Non-uniform Heating (600°C Setpoint)

Results and Accomplishments – CNN Algorithm Development

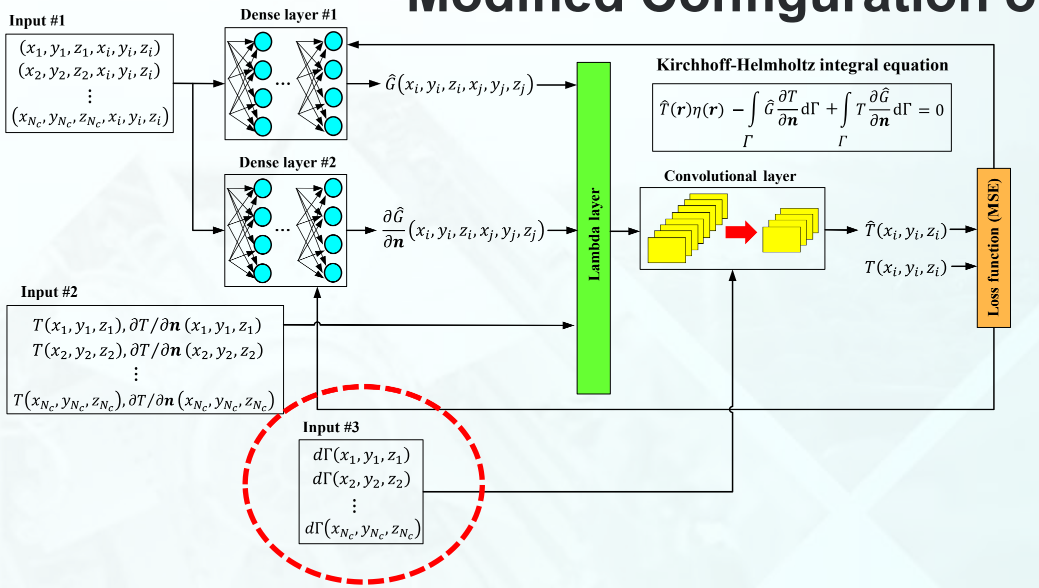
- **Develop a CNN Model to Reconstruct Temperature Fields**
- **Couple Tensor Mechanics Module of MOOSE with CFD Predications to Assess Thermal-Mechanical Stresses within the Vessel**
- **Determine if the Inferred Temperature Distribution Represents Normal or Degraded Operating Temperatures**
- **PRO-AID Will Be Leveraged for Diagnostic Capabilities**
- **Technology Will Provide**
  - **Real-time, cost-effective monitoring system**
  - **Quantification of the lifetime and integrity of the pressure vessel**
  - **Means to improve the economics of the microreactor system**

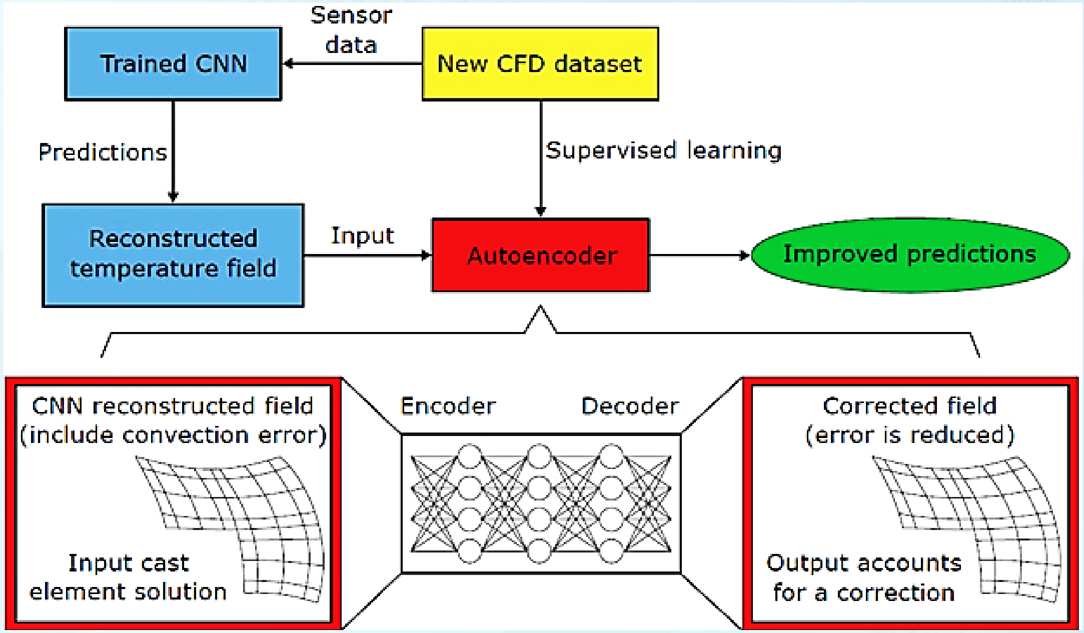
Results and Accomplishments – CNN Algorithm Development

Reference Configuration of the CNN



Modified Configuration of the CNN





Autoencoder Layer

Concluding Remarks

Experimental Testing

- Vessel model was put into operation and instrumented with a thermocouple array
- Temperature distributions were obtained under several heating conditions
- Installation of benchmarked strain gauges and further testing of heat flux gauges

Numerical Simulations

- Preliminary CFD simulations have been carried out including MOOSE's Ray Tracing Module
- Excellent agreement with initial testing at TAMU
- Initial training of CNN using preliminary results
- Continue to generate simulated data sets for CNN training

CNN Algorithm Development

- CNN has so far demonstrated promising performance with the numerical datasets
- Preliminary CNN for diagnostics has been proposed
- Validation of the proposed algorithm is underway

Lesley Wright

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Publications

[1] Victor Coppo Leite (Penn State), April Novak (ANL), Elia Merzari (Penn State), Roberto Ponciroli (ANL), Lander Ibarra (ANL), "Application of a Physics-Informed Convolutional Neural Network for Monitoring the Temperature Field in Advanced Reactors", Proceedings of NURETH-20, Washington, DC, August 2023.

Thank You