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

ASI Advanced Sensors and Instrumentation

Linear Variable Differential Transformers (LVDTs)

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

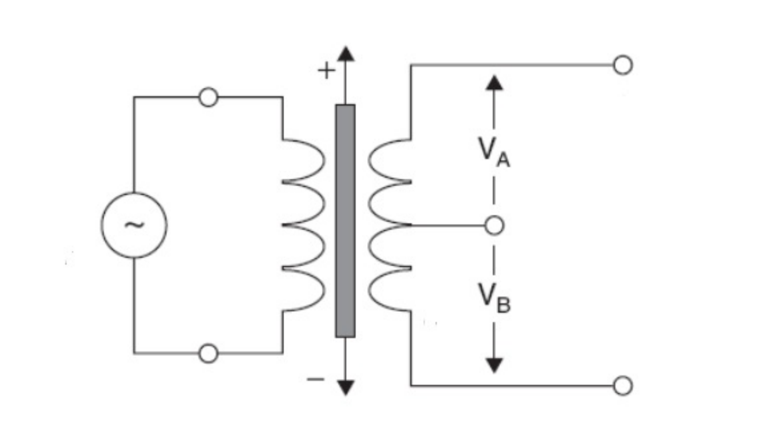
Principle Investigator: Kurt Davis

Idaho National Laboratory

Project Overview

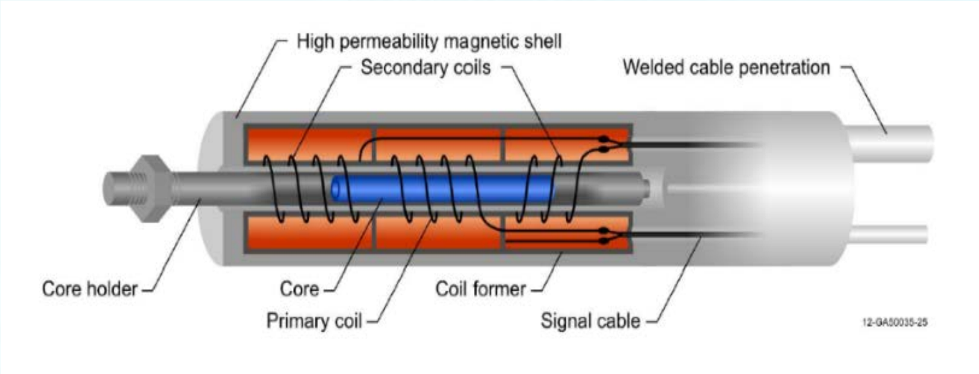
Background

- An LVDT (Linear Variable Differential Transformer) is an electromechanical transducer that converts object into a corresponding electrical signal. Submicron motions are resolvable.
- Many phenomena produce, or can be used to produce, length changes which in turn can be measured and converted into a measurement of the phenomenon (e.g., pressure, temperature).
- The commercial LVDT device has proved to be a robust and versatile sensor, but it falls short when used at elevated temperature or when irradiated because of the materials used in construction.
- Since 1965, IFE under the Halden Reactor Project has been developing irradiation resistant high-temperature LVDTs. They are the world leader when it comes to manufacturing LVDTs for irradiation testing.



$$D = (Va–Vb) / (Va+Vb)$$

Halden LVDT



Project Overview

Design of TREAT LVDT Experiment.

Zhangxian Deng (PI), Alex Draper (Student), and Joshua Poorbaugh (Student)

Wireless Transmission

Heng Ban (PI), William Spirnock (Student)

Commercial LVDT Evaluation

Kurt Davis (PI), Austin Fleming, and Malwina Wilding

BSU - Design of TREAT LVDT Experiment

Working Principle of the Sensor

Impulse neutron radiation → Fusion gas release → Pressure increment → Deformation of bellows → LVDT core displacement → Modulated voltage from LVDT

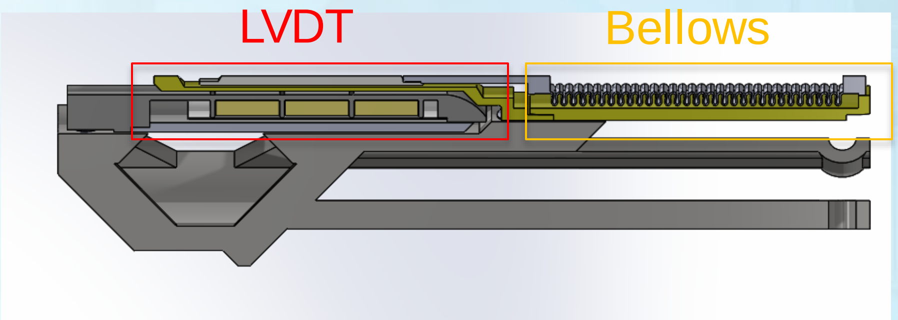
Problem

A pressure reading of 12.7 psi was observed immediately after the neutron radiation spike; fusion gas release from the fuel pellets becomes significant only after the first 2.5 seconds.

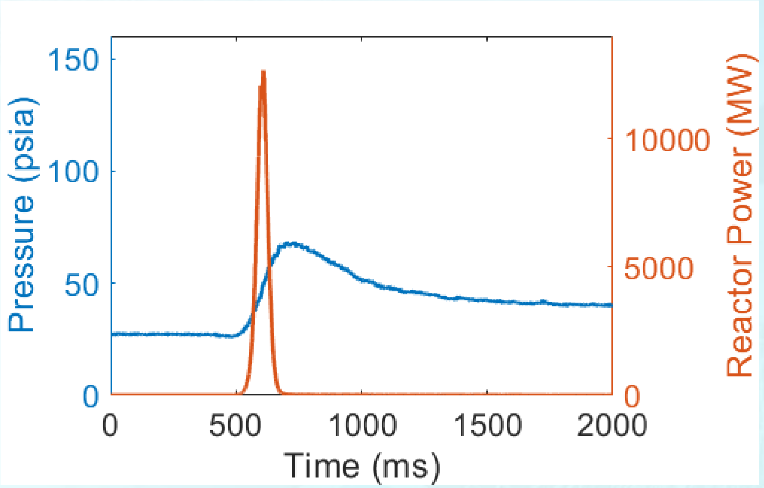
Hypothesis

The transient response and steady-state response are due to the thermal expansion of the pressure sensor.

LVDT+Bellows Pressure Sensor



Thermal Drift in TREAT

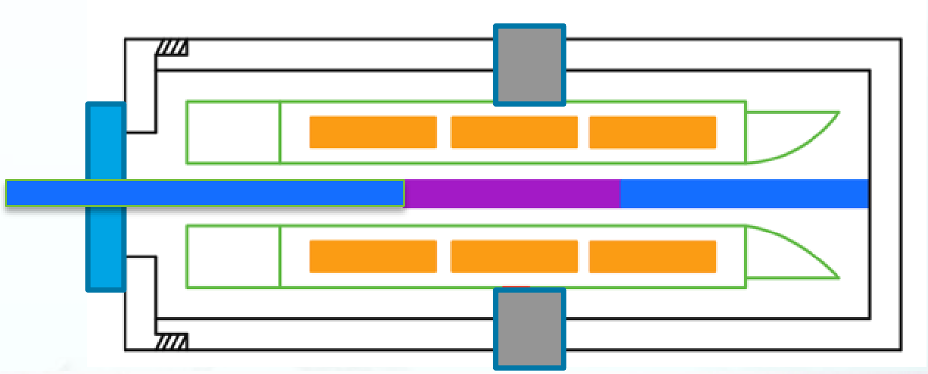


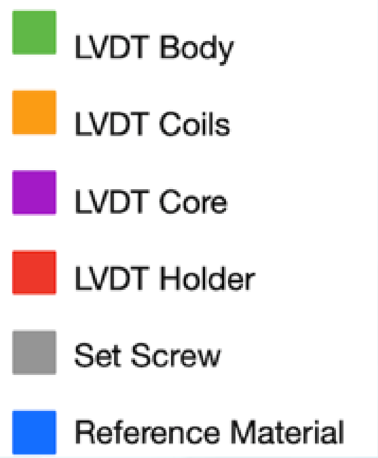
BSU - Design

Objective

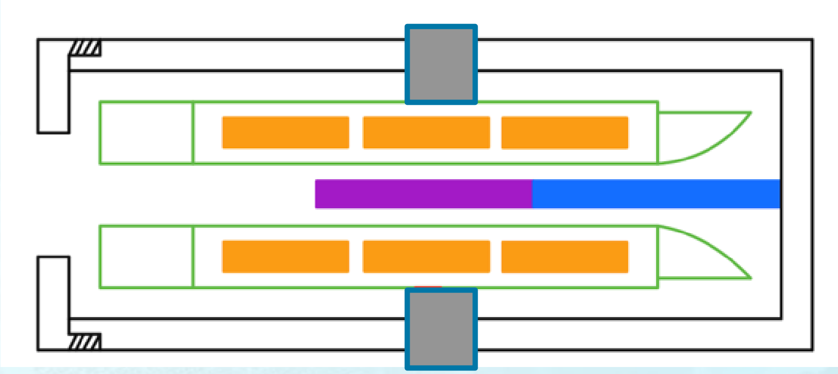
Design a test rig that can generate controllable thermal expansion in LVDT, especially the relative deformation between the LVDT core and coils.

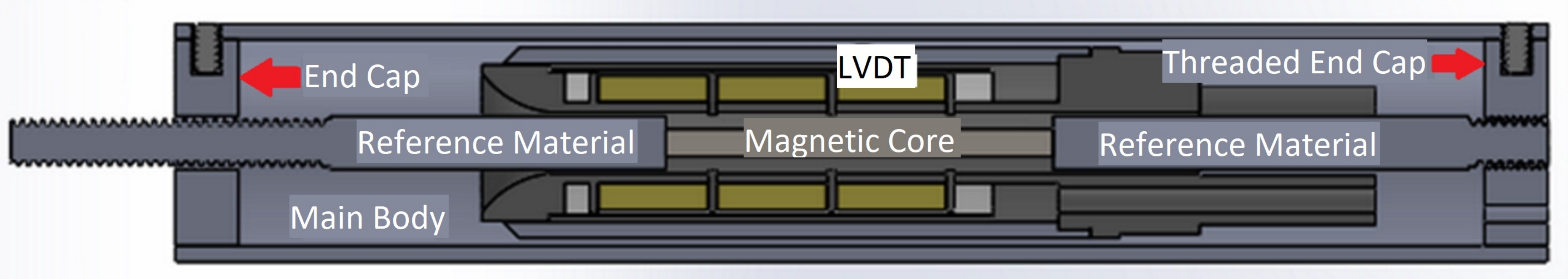
Setup #1





Setup #2



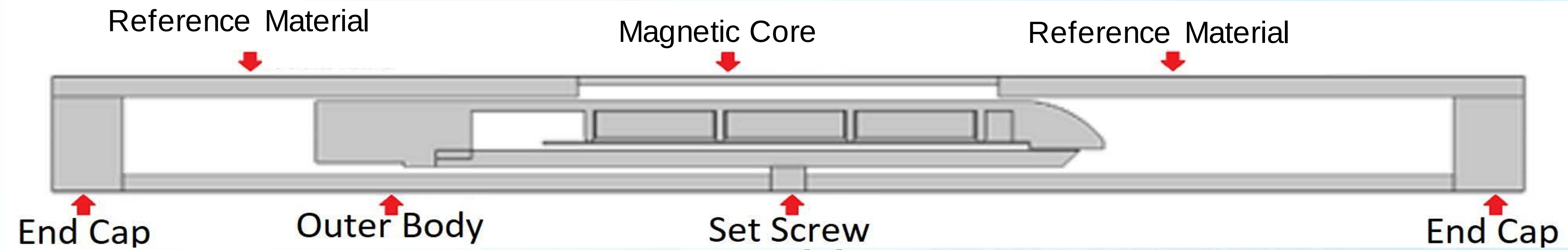


BSU - Finite Element Modeling

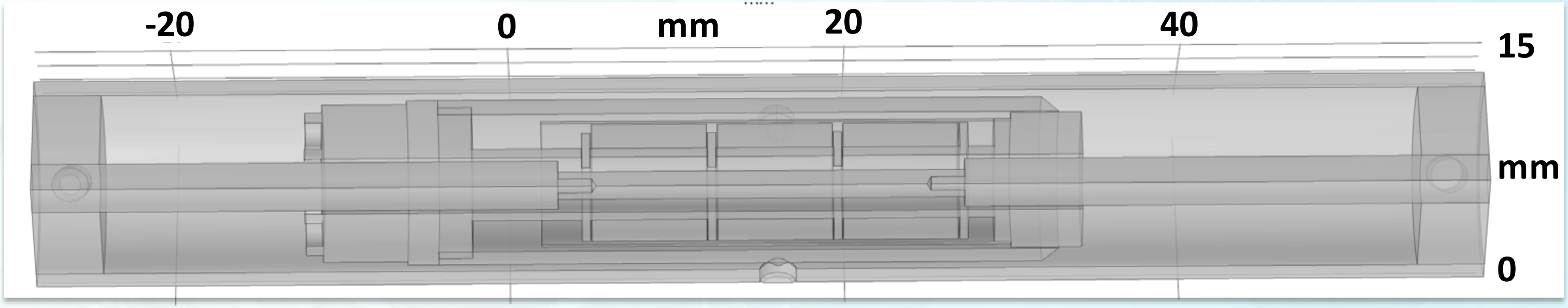
Objective

- Check if the set screw or the end cap can survive the thermal stress
- Check if the Setup #1 can hold the LVDT core in place

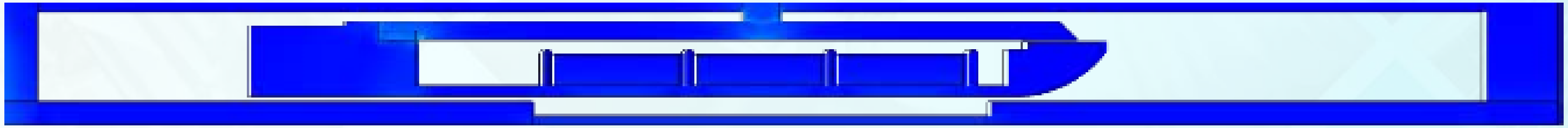
2D Model



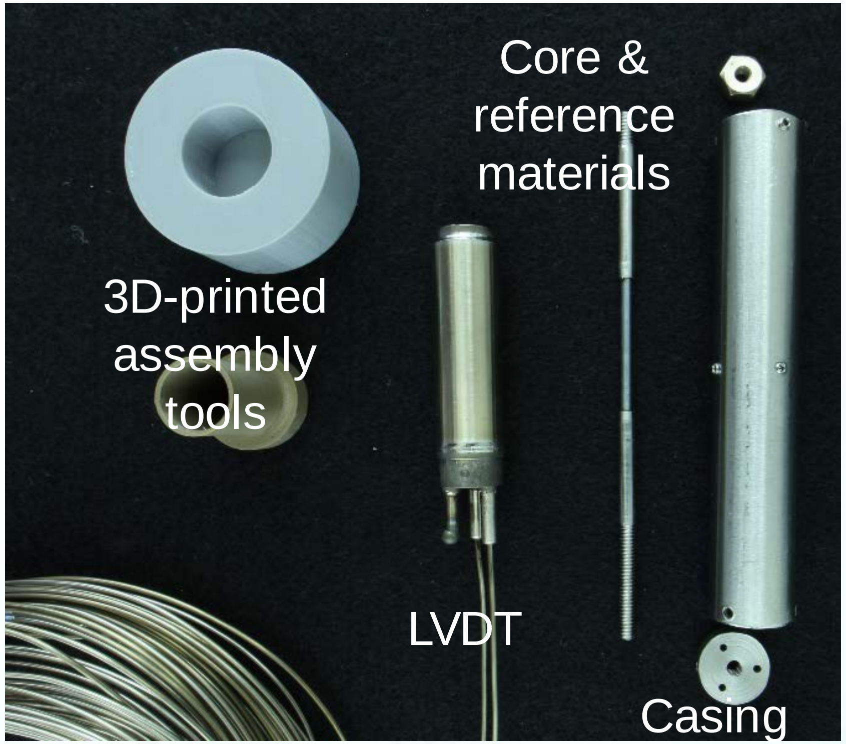
3D Model



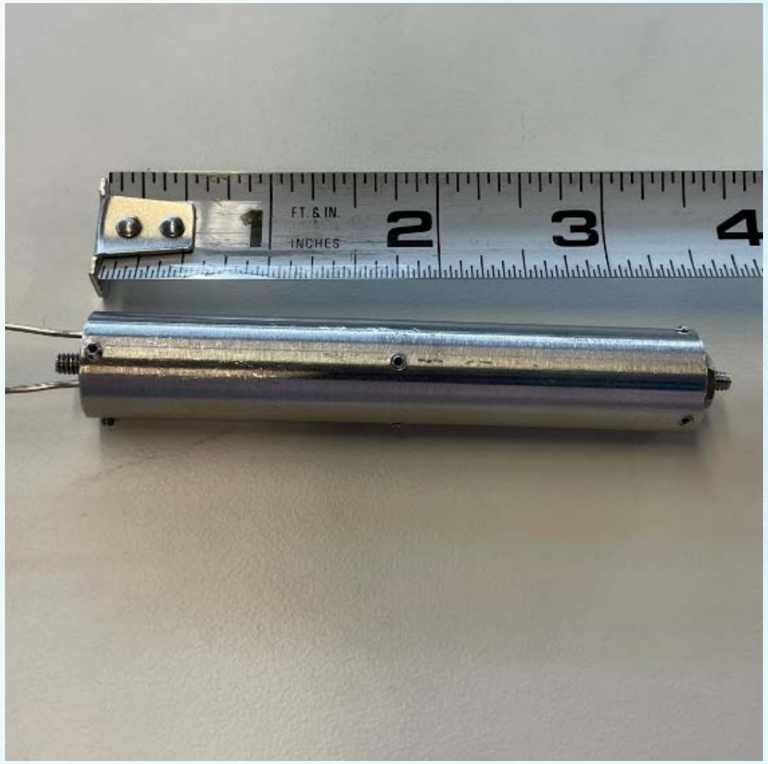
Thermal Stress



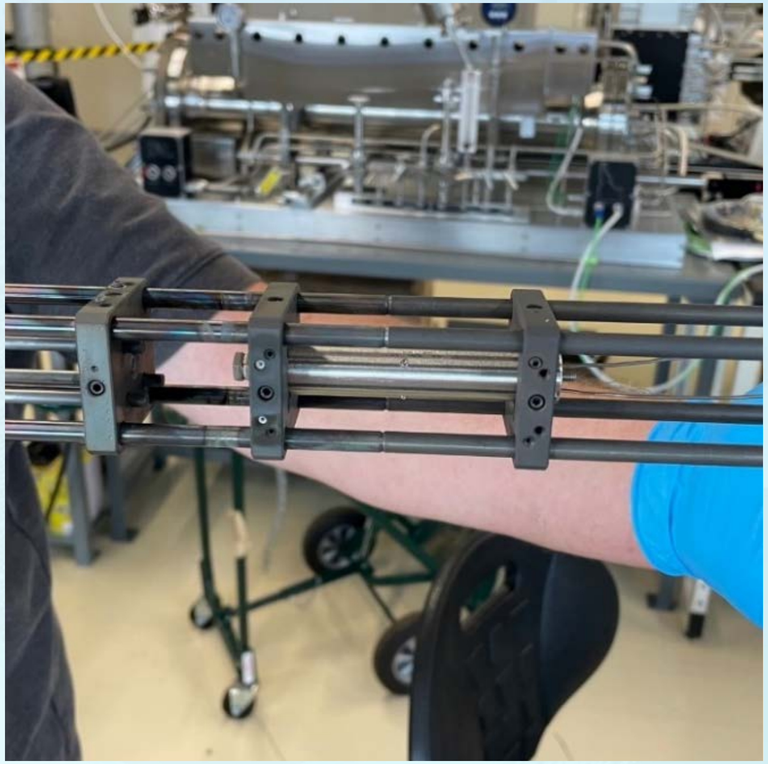
BSU - Assembly



Setup #1 actual assembly



Setup for tube furnace testing



BSU - Testing Procedures

Run #1

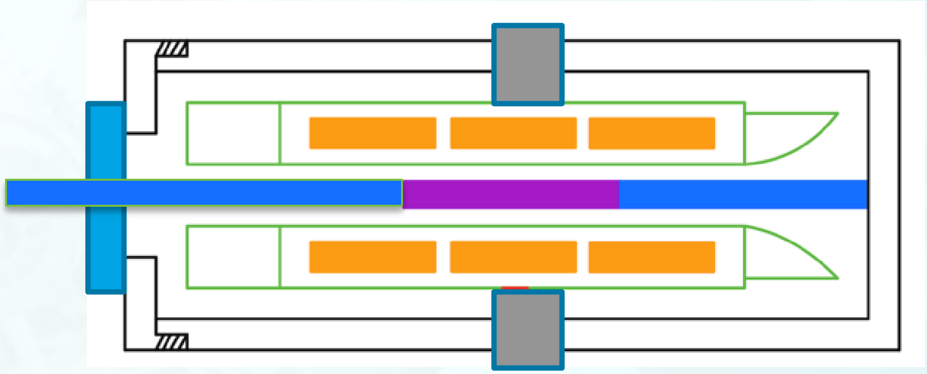
- Tested at 20, 200, 400, and 600°C
- Took 3-4 hours to reach thermal equilibrium between temperature settings
- Assembly was secured in two places in the support frame

Run #2

- Tested at 20,400, 600, and 700°C
- Took 3-4 hours to reach thermal equilibrium between temperature settings
- Assembly was secured in two places in the support frame

Run #3

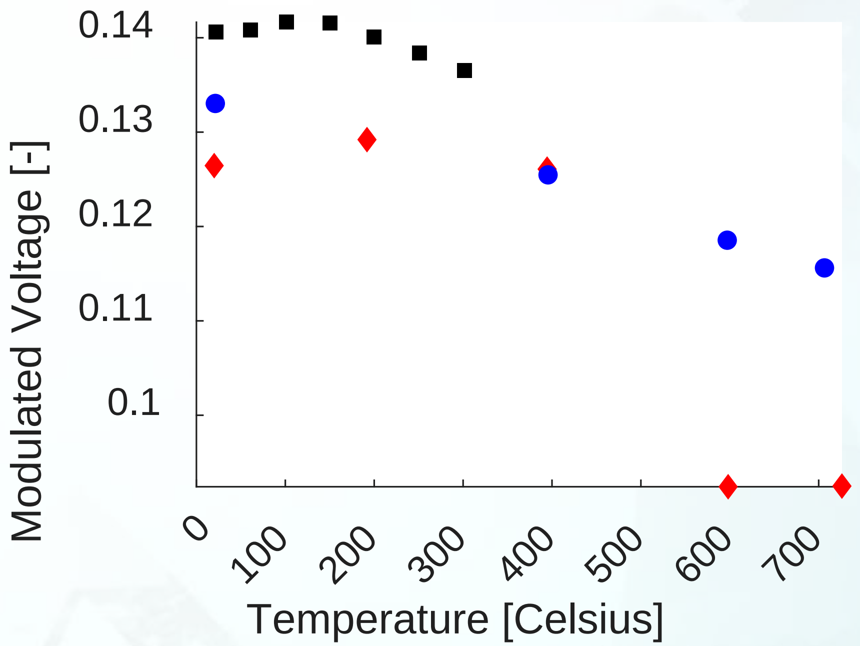
- Heated from 20 to 300°C, stopping at intervals of 50°C
- Did not wait to reach thermal equilibrium when collecting data
- Assembly was secured at one point

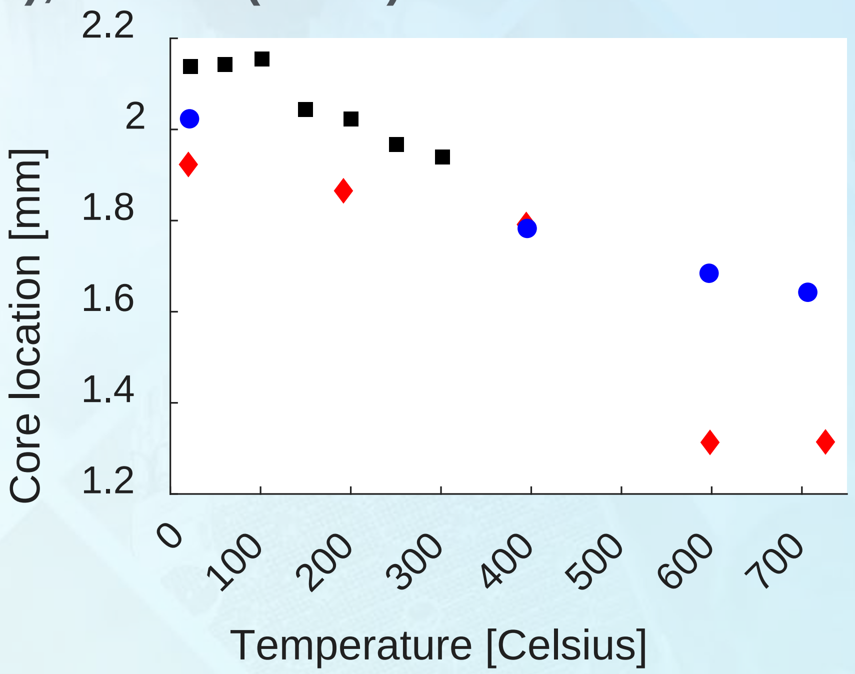


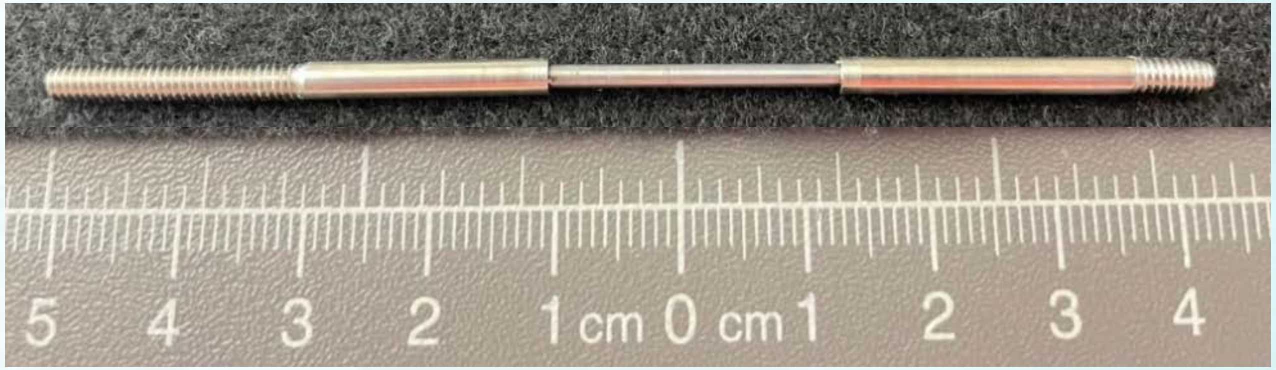
Tube Furnace Configuration

BSU - Results

Run #1 (Blue); Run #2 (Red); Run #3 (Black)







BSU - Conclusions and Future Work

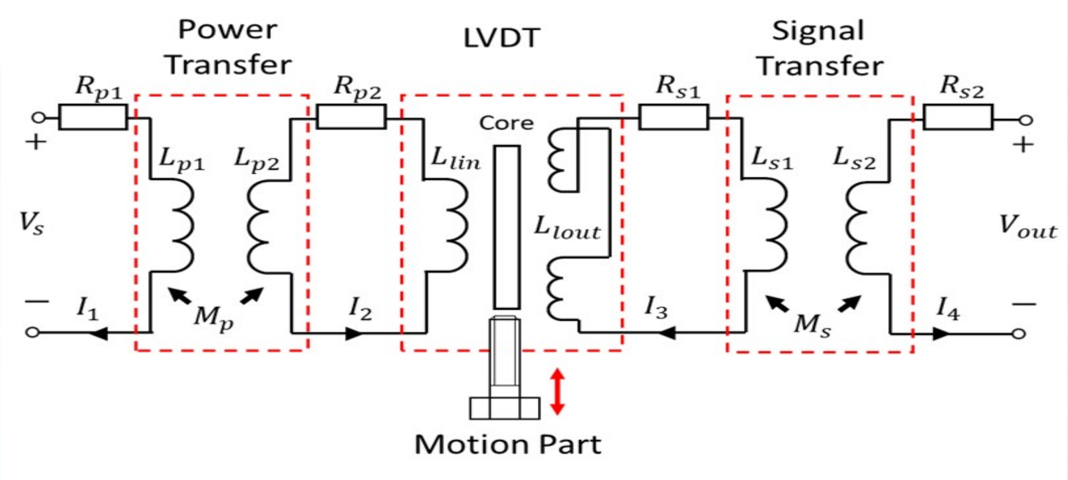
Conclusions

- Designed a test rig to study the thermal drift in LVDT
- Evaluated the test rig strength and feasibility at elevated temperature using COMSOL Multiphysics
- Collected preliminary results from the LVDT up to 700°C
- Thermal drift is severe in all three test runs especially beyond 150°C
  - ❑ Set screws might have failed. Only had 1-2 threads engaged
  - ❑ Inaccurate temperature readings
  - ❑ Magnetic core was attached at an angle

Future Work

- Increase wall thickness to improve number of threads engaged
- Create hole and room inside testing assembly for thermocouple installation
- Enhance alignment of magnetic core
  - ❑ Thread reference material and core
  - ❑ Use only one reference material rod

Theoretical Modeling



$$V_{out} = j\omega M_s \frac{M_1 - M_2}{L_{lout} + L_{s1}} \frac{M_p}{\frac{(M_1 - M_2)^2}{L_{lout} + L_{s1}} + L_{p2} + L_{lin}} \frac{1}{j\omega L_{p1} + R_{p1} - \frac{j\omega M_p^2}{\frac{(M_1 - M_2)^2}{L_{lout} + L_{s1}} + L_{p2} + L_{lin}}} V_s$$

- Developed theoretical models (i.e., transfer function) to incorporate the LVDT with the wireless transmission coils
- Enables us to predict the output of the system, which can be verified through computational modeling and experimentation

Pitt

Increase 5%

Input Voltage	Output Voltage
Parameters	**Result Max Value Change**
Mutual Inductance coefficient	10.65%
Frequency	3.00%
All Resistors	-3.02%
All Inductors	3.00%

Input Current	Output Voltage
Parameters	**Result Max Value Change**
Mutual Inductance coefficient	10.25%
Frequency	5.00%
All Resistors	**<0.01%**
All Inductors	5.00%

Input Voltage	Output Current
Parameters	**Result Max Value Change**
Mutual Inductance coefficient	12.29%
Frequency	-1.91%
All Resistors	1.83%
All Inductors	-1.91%

Input Current	Output Current
Parameters	**Result Max Value Change**
Mutual Inductance coefficient	11.88%
Frequency	**<0.01%**
All Resistors	5.00%
All Inductors	**<0.01%**

- Performed sensitivity analysis on LVDT/wireless transfer system to explore how parameters influence results at different inputs and outputs
- Gives insight to system performance and design optimization
- Tells us that the coupling coefficient has the largest overall affect on the system

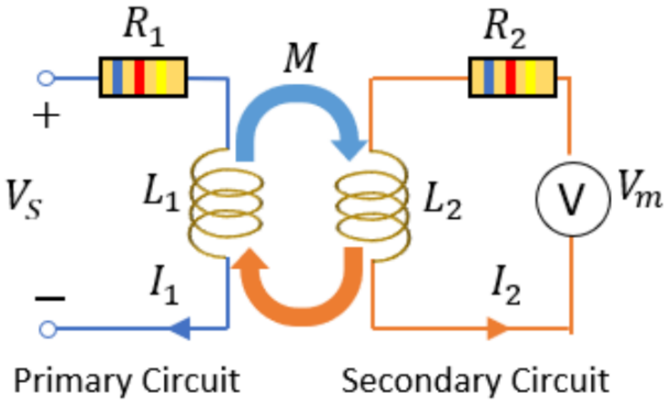
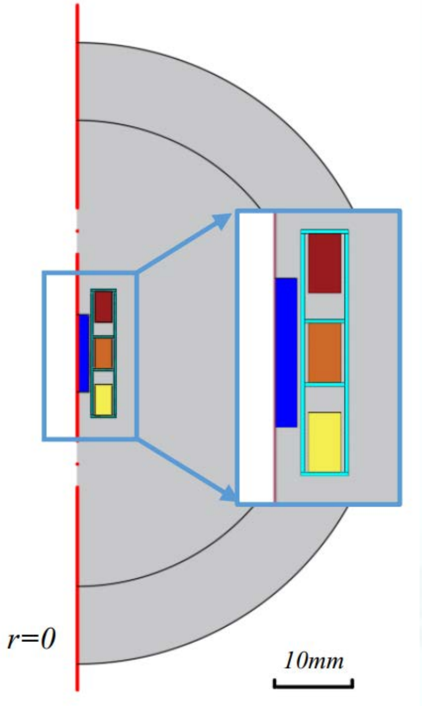


Figure 5: Signal Transfer Circuit

$$V_s = 0 = (2\pi f j L_1 + R_1)I_1 + 2\pi f j M I_2$$
$$0 = 2\pi f j M I_1 + (2\pi f j (L_2 + L_m) + R_2)I_2$$
$$M = k\sqrt{L_1 L_2}$$

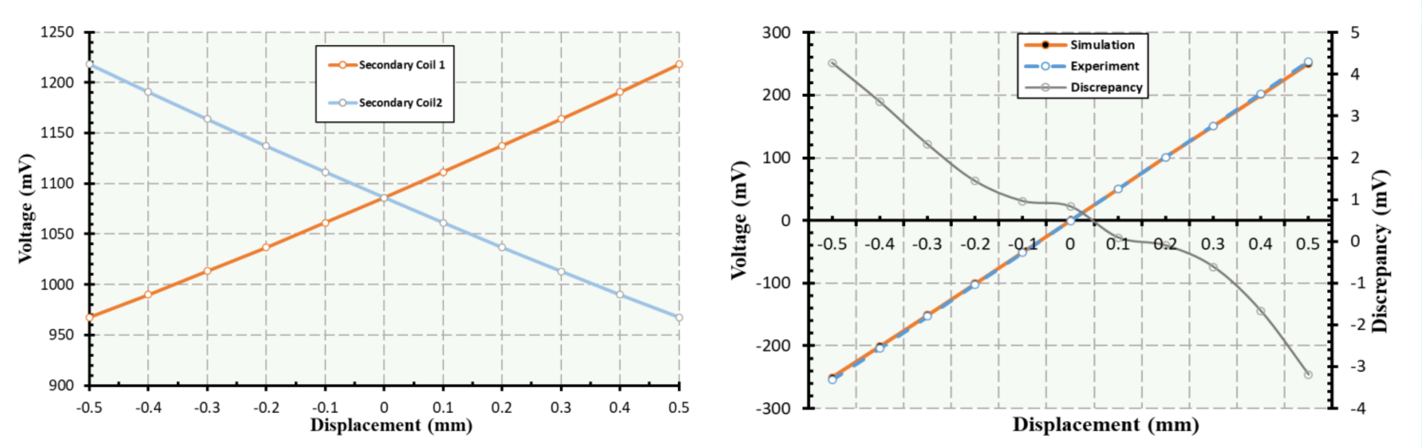
- Performed similar analysis on the interaction of two coils for the wireless transfer system for various inputs and outputs
- Based on the results, we were able to determine the most effective input and output combination that results in the least variation of the coupling coefficient (current input, voltage output)

LVDT Computation Modeling



Parameters	Value
Magnetic core radius	1.5mm
Magnetic core length	10mm
Coil outer radius	4.5mm
Primary coil length	4mm
Secondary coil length	4mm
Gap between coils	2mm
Turns of primary coil	1000
Turns of secondary coil	1000
Working frequency	1000
Power voltage	3V

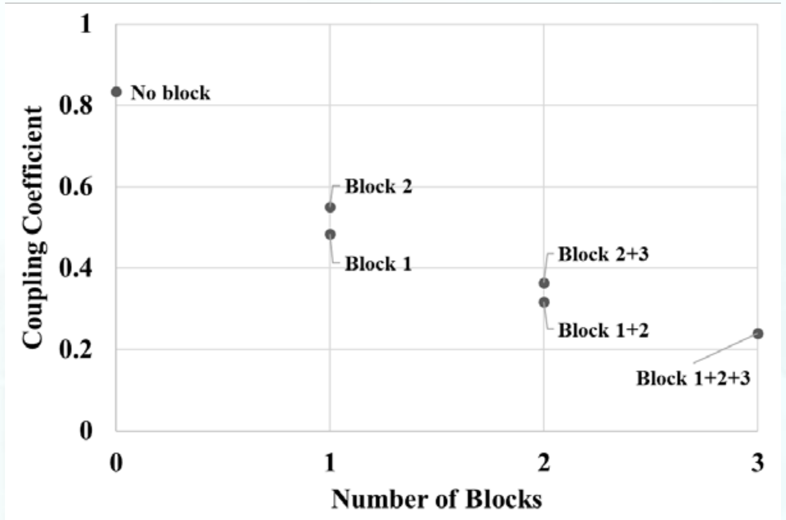
- Modeled an LVDT in COMSOL to simulate performance based on parameters from a published journal article
- This was done to acquire data for design optimization purposes without extensive experimentation
- This model can also be used to verify the accuracy of the transfer function for a LVDT/inductive coupling assembly



- The plots to the right show the results of the simulation and the discrepancy between the simulation and experiment
- The simulation and experiment results have a low discrepancy making the model quite accurate

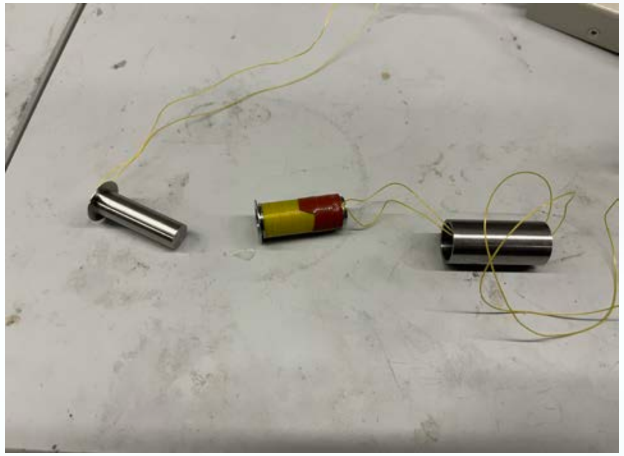
Stainless Steel Shielding Experiments

- Stainless steel shielding experiments were performed to simulate cladding conditions and determine how shielding layer position and thickness affects the coupling of the power/signal transfer coils
- A ferrite core wound with copper wire separated by three layers of stainless steel shielding with another coil wound around a plastic bobbin



- The largest coupling coefficient occurs with no shielding applied
- Results show that multiple layers of shielding produce adequate power/signal transmission
- Multiple layers of cladding within a nuclear reactor will not result in extreme signal attenuation

High-Temperature Wireless Transfer Model



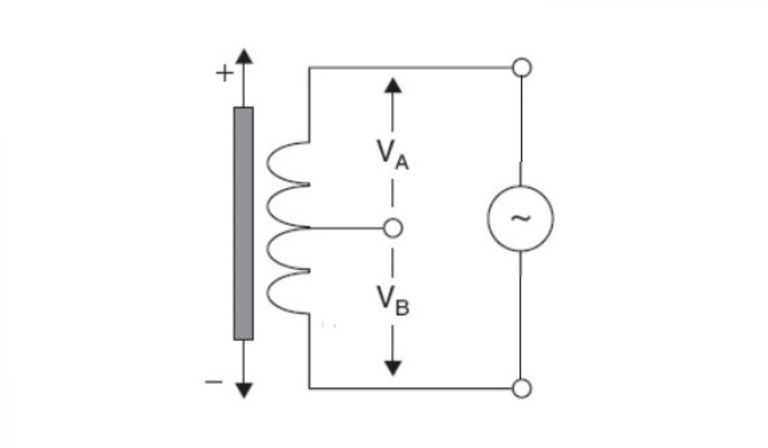
- Designed a high-temperature model composed of two coils, a highly permeable inner bobbin, two layers of stainless steel, and an outer layer of carbon steel
- This model is tested at room and high temperatures inside of a tube furnace to simulate reactor-like conditions
- Model will be tested up to 500°C
- Goal is to analyze the affect of a high-temperature environment on the coupling of the system

Conclusions

- Use of theoretical, computational modeling capabilities prove effective to analyze how various parameters affect the system without extensive experimentation
- Sensitivity analysis indicate that the current input and voltage output combination produces accurate results
- Stainless steel experiments show that this theory can be applied in reactor conditions in which several layers of cladding are present
- High-temperature model will provide insight on how temperature affects the coupling of the system

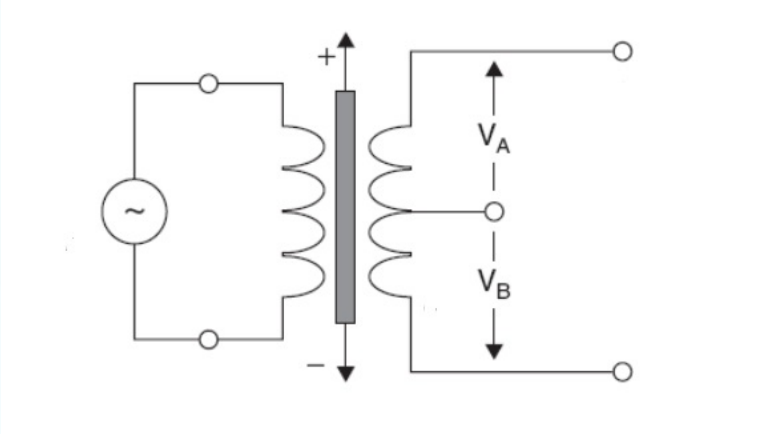
INL - Commercial LVDT Evaluation

RDP Group elongation sensor

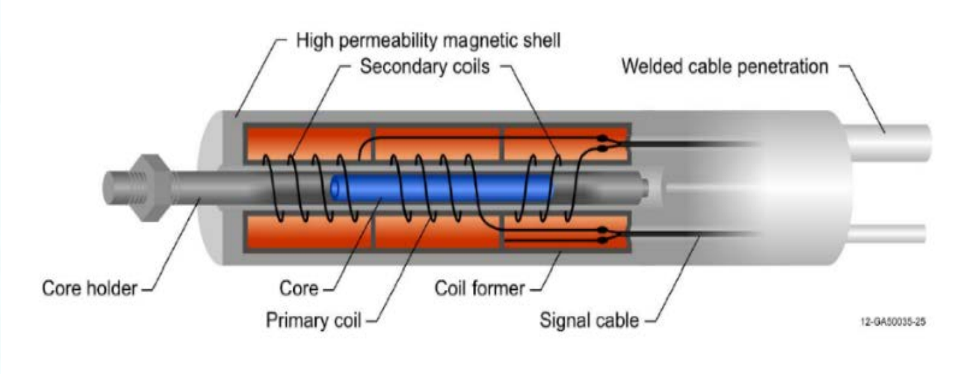


$D = Va / Vb$

IFE Halden LVDT

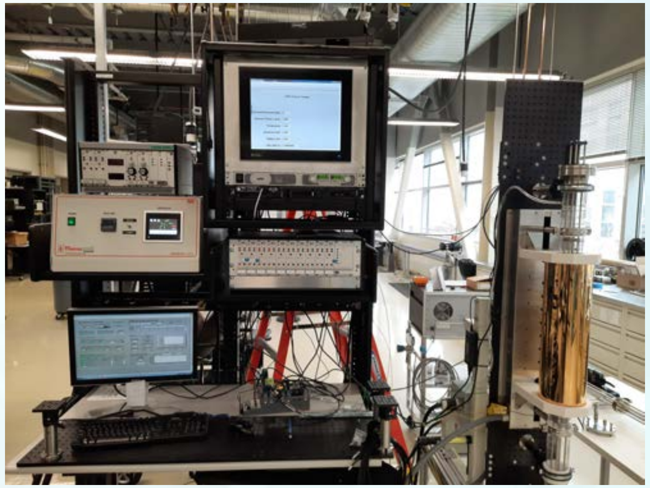


$D = (Va–Vb) / (Va+Vb)$



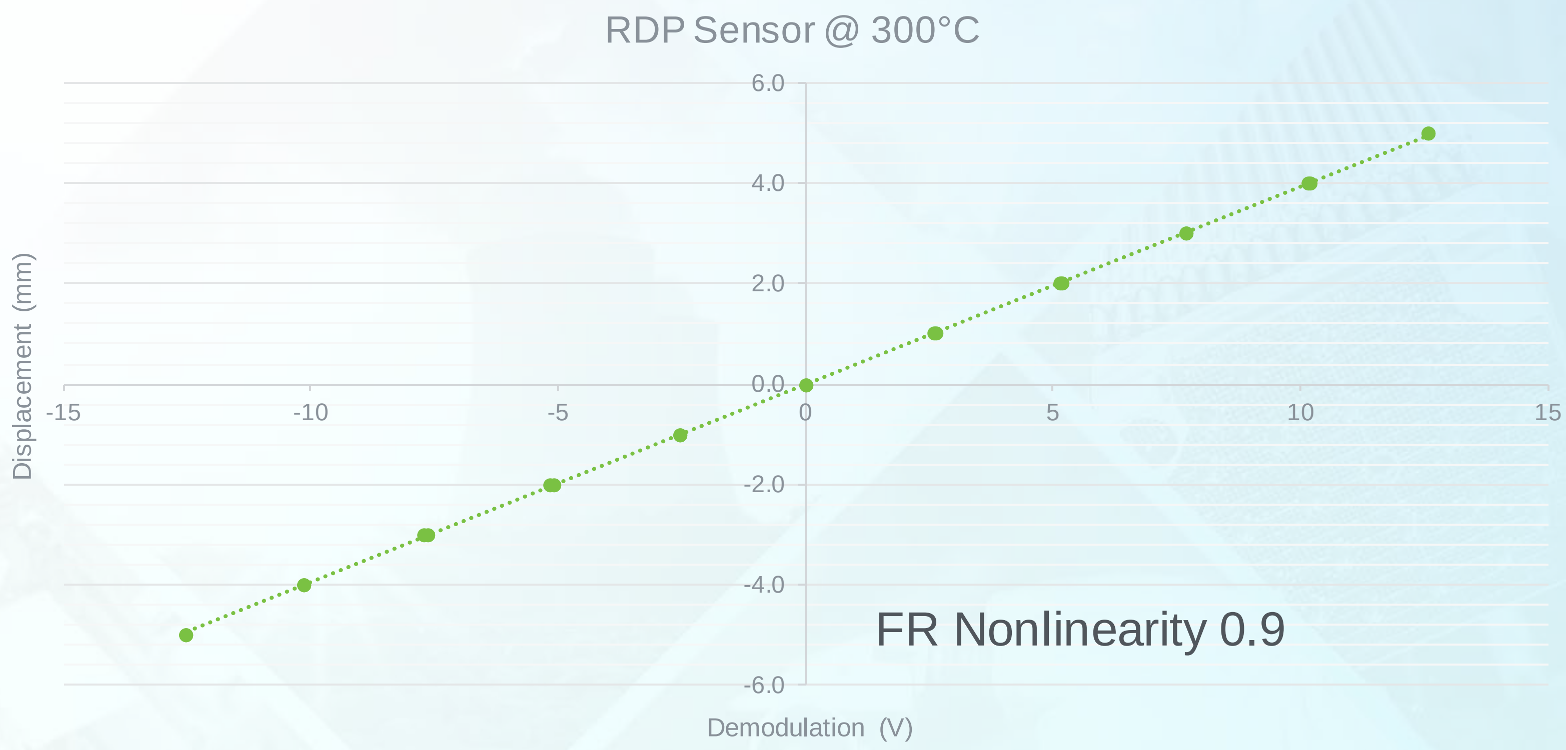
INL - Commercial LVDT Evaluation

Testing of RDP Group elongation sensor

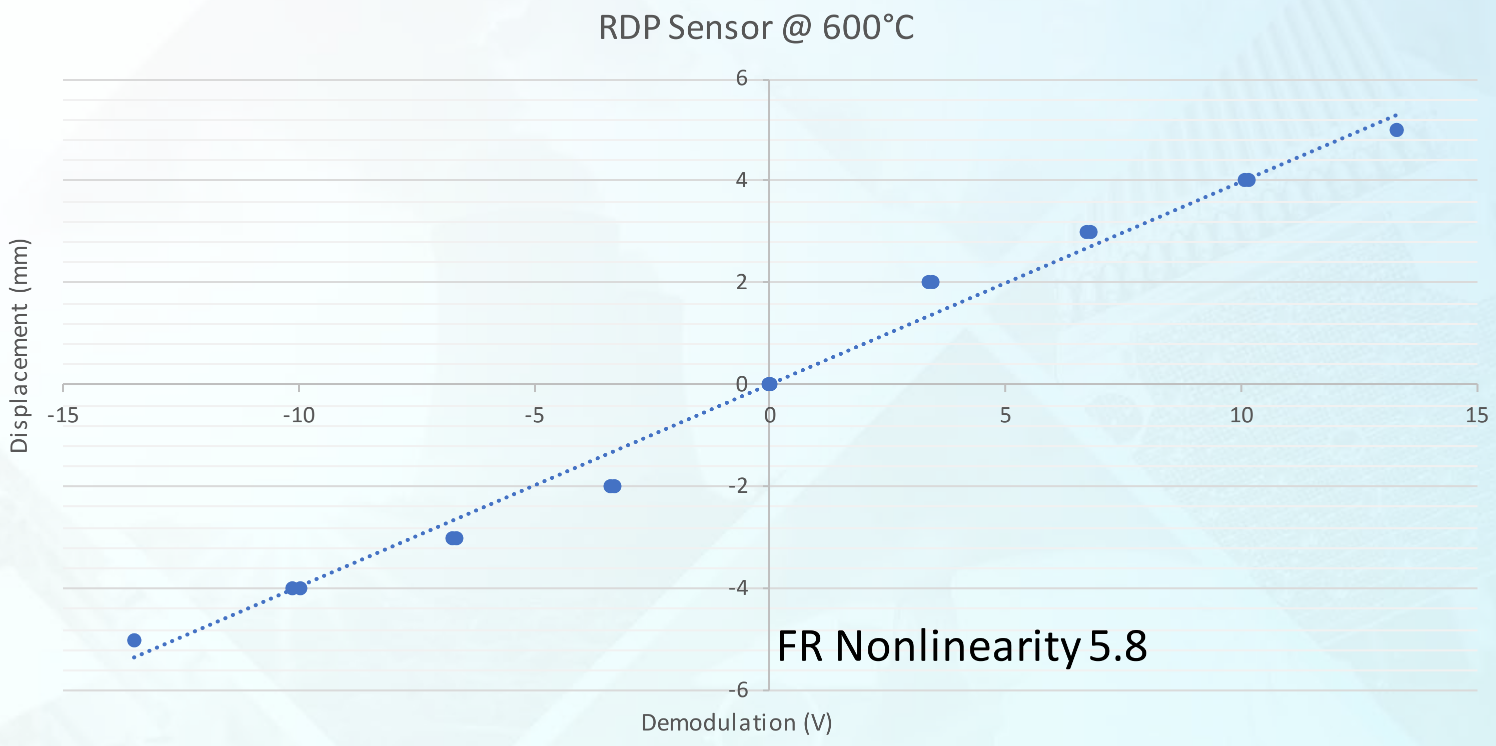


- Vertical orientation
- Test temperature 20, 300, 600°C
- Ultra pure argon @ 2 l/m
- Full range of motion +/- 5 mm

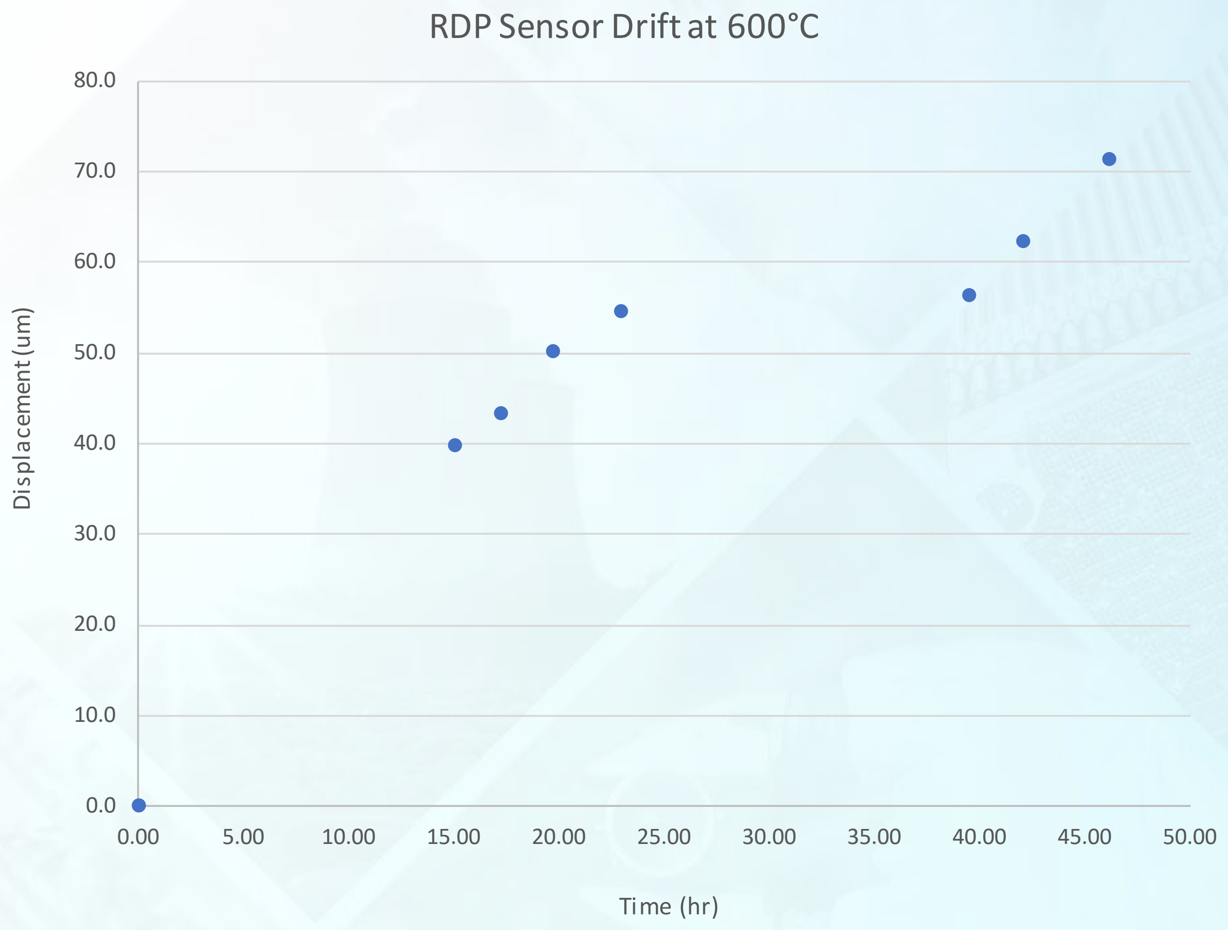
INL - Commercial LVDT Evaluation



INL - Commercial LVDT Evaluation



INL - Commercial LVDT Evaluation



INL – Conclusion

- LIN56 transducer performed well 20-300° C (FR nonlinearity 0.7-0.9)
- The LIN56 sensor may be viable for in-pile instrumentation
- 600° C temperature limit, sensor drift, FR nonlinearity 5.8
- FY23 - Investigation into the cause of the sensor failure
- FY23 - Testing LIN56 sensors, limiting temperature, drift, sensitivity, performance

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Thank You