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

Advanced Sensors and Instrumentation

Nuclear Thermocouples

CT-23IN070204

10:30AM-10:50AM EDT

Oct 31st, 2023

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

October 30 – November 2, 2023

PI: Richard Skifton, PhD

Idaho National Laboratory

Project Overview

Nuclear Thermocouple Technology:

- The thermocouple element implements R&D activities to develop nuclear instrumentation that addresses critical technology gaps for monitoring and controlling existing and advanced reactors and supporting fuel cycle development. For temperature measurements, thermocouple instrumentation is typically composed of one or more sensing element, interrogation systems, data acquisition system as well as processes and procedures to collect, analyze and calibrate data. Temperature instrumentation is utilized to measure process parameters (i.e., such as **temperature, fluid flow, and water level**) independent of the experiment, component, or process in which it is deployed.
- In FY22 R&D activities are carried out in the following technical areas:
  - M3CT-23IN0702043-Develop a calibration process for intrinsic junction thermocouples for surface temperature measurement
  - M3CT-23IN0702044-Characterize performance of commercial thermocouples for nuclear applications
- In FY23 R&D activities are carried out in the following technical areas:
  - M3CT-23IN0702046-Complete assessment of HTIR-TC testing results using the different heat treatment methods
  - M4CT-23IN0702048-Complete assessment of uncertainty quantification of multi-point measurement

Personnel:

- PI: Richard Skifton, PhD, Idaho National Laboratory
- CO-PI: Brian Jaques, PhD, Boise State University
- PhD Candidate: Scott Riley, Boise State University

Project Overview

Schedule:

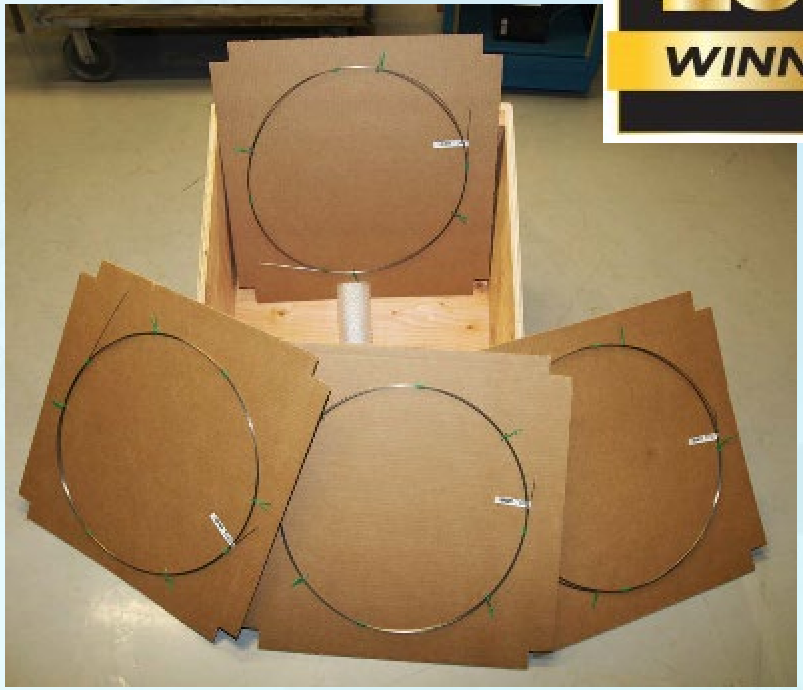
FY 2023 FY 2024 FY 2025 FY 2026 FY 2027 FY 2028

		2023											
Milestone / Activity	**STI**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
ActivityCT-23IN0702041-Intrinsic junction thermocouples for surface temperature measurement													
M3CT-23IN0702043-Develop a calibration process for intrinsic junction thermocouples for surface temperature measurement	Yes	M3											
ActivityCT-23IN0702042-Performance assessment of commercial thermocouples for nuclear applications													
M3CT-23IN0702044-Characterize performance of commercial thermocouples for nuclear applications	Yes	M3											
ActivityCT-23IN0702045-HTIR heat treatment optimization method													
M3CT-23IN0702046-Complete assessment of HTIR-TC testing results using the different heat treatment methods	Yes												
ActivityCT-23IN0702047-Uncertainty quantification of multi-point measurement													
M4CT-23IN0702048-Complete assessment of uncertainty quantification of multi-point measurement	Yes												M4

Technology Impact

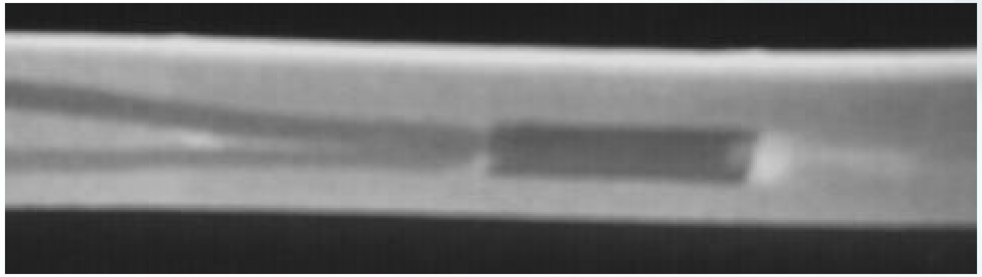
Table 1: Summary of performance parameters for the HTIR-TC

Performance Parameter	Performance Metric
Temperature Range	Room Temperature - 1600°C
Accuracy	Not Specified
Drift	-3% for 4.5×10^{21} nvt (thermal)
Life	4.5×10^{21} nvt (thermal)
Junction	Rugged mechanical junction design
Thermal Shock	5 sudden startups and 5 sudden shutdowns—each causing a thermal shock on the order of room temperature up to 1600°C
Response Time	<0.5 seconds



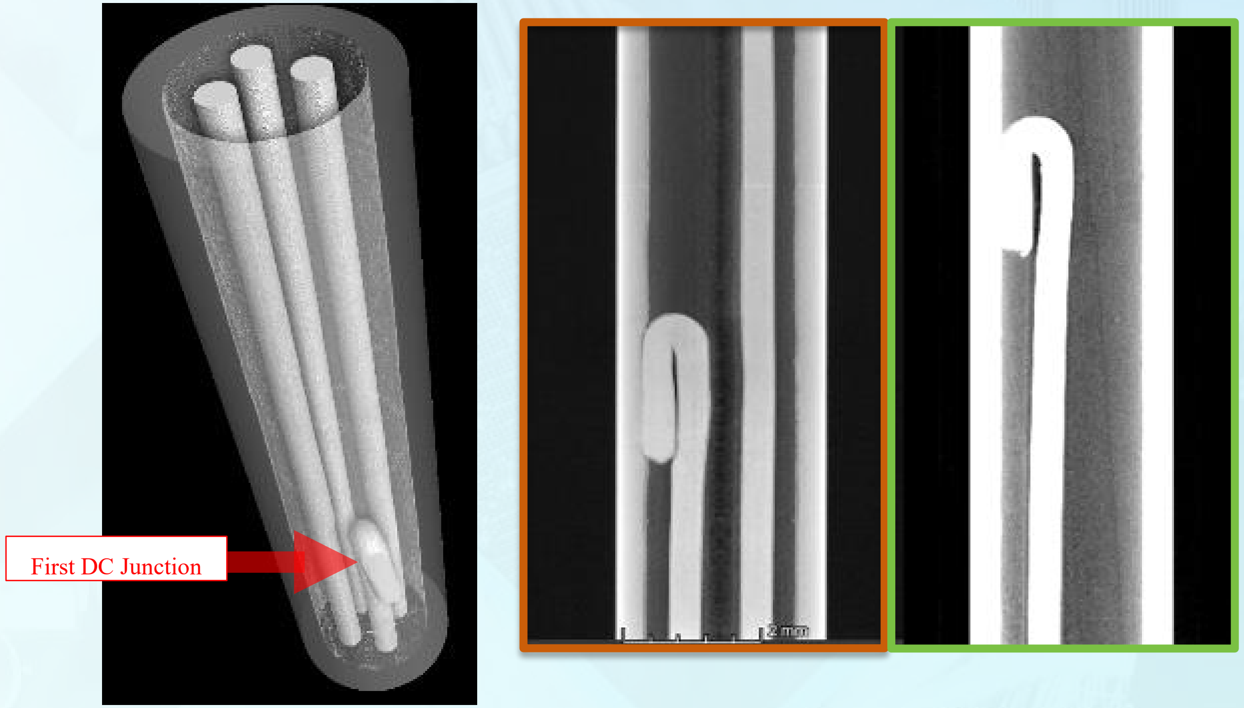
2019 R&D 100 WINNER

Technology Impact



HTIR-TC Traditional

HTIR-TC Coaxial



HTIR-TC Demicouple

Technology Impact

- Next generation reactors will make use of thermocouples for the temperature measurement of normal and abnormal operations–including fuel qualification tests

Thermocouple	Type K	Type B	Type N	HTIR-TC
Materials	Chromel vs Alumel	PtRh30% vs PtRh6%	Nicrosil vs. Nisil	Molybdenum vs. Niobium
Temperature Range	-270°C to 1260°C	250°C to 1700°C	-270°C to 1260°C	0°C to 1700°C
Cost	~\$30/ft	~\$250/ft	~\$50/ft	~\$250/ft
Radiation Tolerance as Compared to HTIR-TC	1/10th	~1/100th	1/4th	

- Temperature is one of the most fundamental measurements
- Other uses of TCs is the measurement of flow and water level using multi-point TCs or demicouples.

Technology Impact

The following are to be considered when using thermocouples. <u>Not a complete list.</u>

1.Environment
   a. Gas/Liquid/Solid/Two-phase
   b. Flow – natural or forced convection
   c. Reactive
   d. Transmutation
   e. Oxidizing

2. **Homogeneous wire(s)**
   a. Solid state diffusion (disassociated atoms traveling from sheath/insulators)
   b. Heat treated/damaged
   c. Isothermal

4. Temperature range(s)

5. TC construction
   a. Diameter
   b. Materials
      i. thermoelements
      ii. insulators
      iii. sheath(s)
   c. Exposed/Integral junction
   d. Loose pack vs. swaged
   e. Hard fired insulators vs. crushable
   f. Ungrounded vs. grounded

6. Number of thermal cycles

7. TC contact/junction point(s)
   a. Environmental error
   b. Observational error
   c. Heat sink/Fin Effect
   d. Noise
   e. Eutectics formed

7. Immersion depth—usually 10x the TC diameter

8. Time response (i.e. thermal diffusivity)

9. Thermal gradient zone—between 10% and 90% the reference to sensing temperature

10. **Common/Shared leg thermoelement**

11. TC Shunting – Voltage Leakage

12. Thompson Effect

13. Peltier Effect

14. Joule Heating

15.Gamma Heating

Results and Accomplishments

- Standardized the inhomogeneity tests using MSL's draw bench (Fig. 1). This transfers the UUT at a known rate through the heat source. Consistency of the inhomogeneity tests is accomplished.
- Initial before and after inhomogeneity tests of the effects of heat treatment with joule heating (at 30V 2A) show more power is needed to introduce change. (Fig. 2).

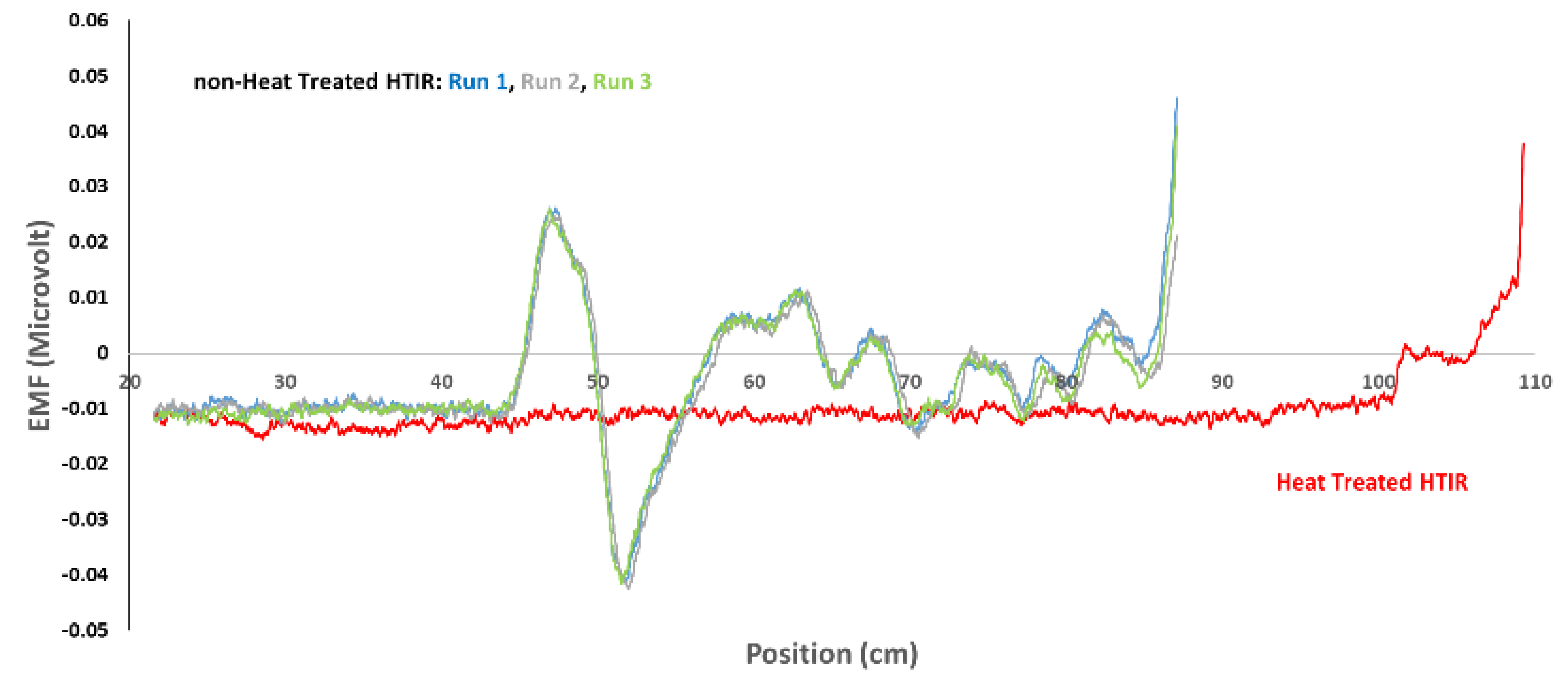


Figure 2: Inhomogeneity results for Joule heated HTIR-TC. Each run is after a 30-minunte cycle at temperature. Traditionally heat-treated HTIR (red) for comparison.

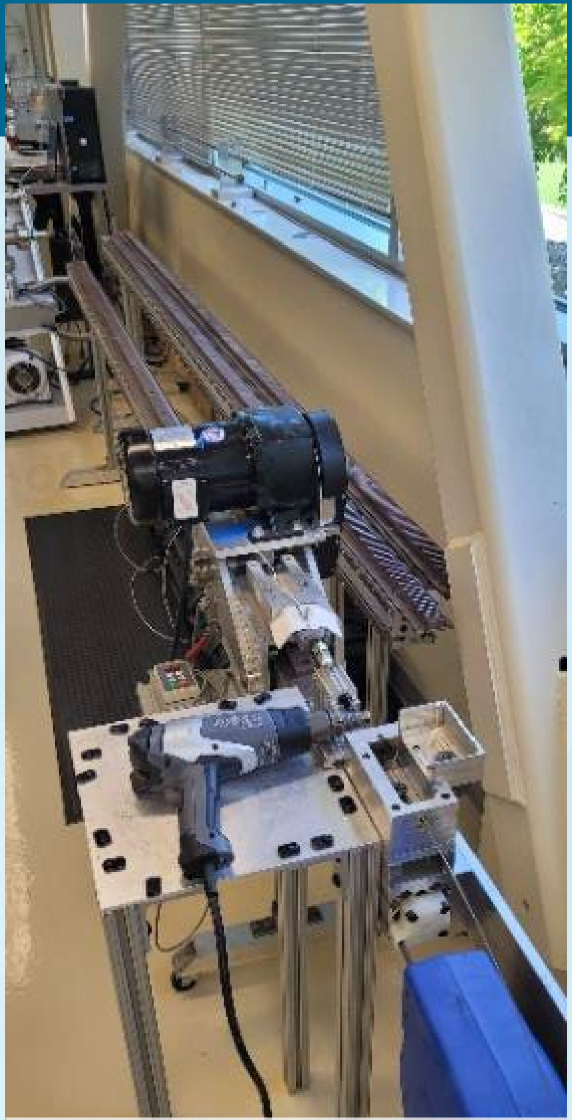


Figure 1: Inhomogeneity TC test setup. Heat gun used for high temperature.

Results and Accomplishments

- Ran tests in furnace on HTIR-TCs that were heat treated using resistance/joule heating at various amperage. (See Figure 3). Shows the heat treatment process can be successfully accomplished over the entire length of the TC at 2.25A for 30 minutes – down from 72hrs+ for only 3-4 ft.

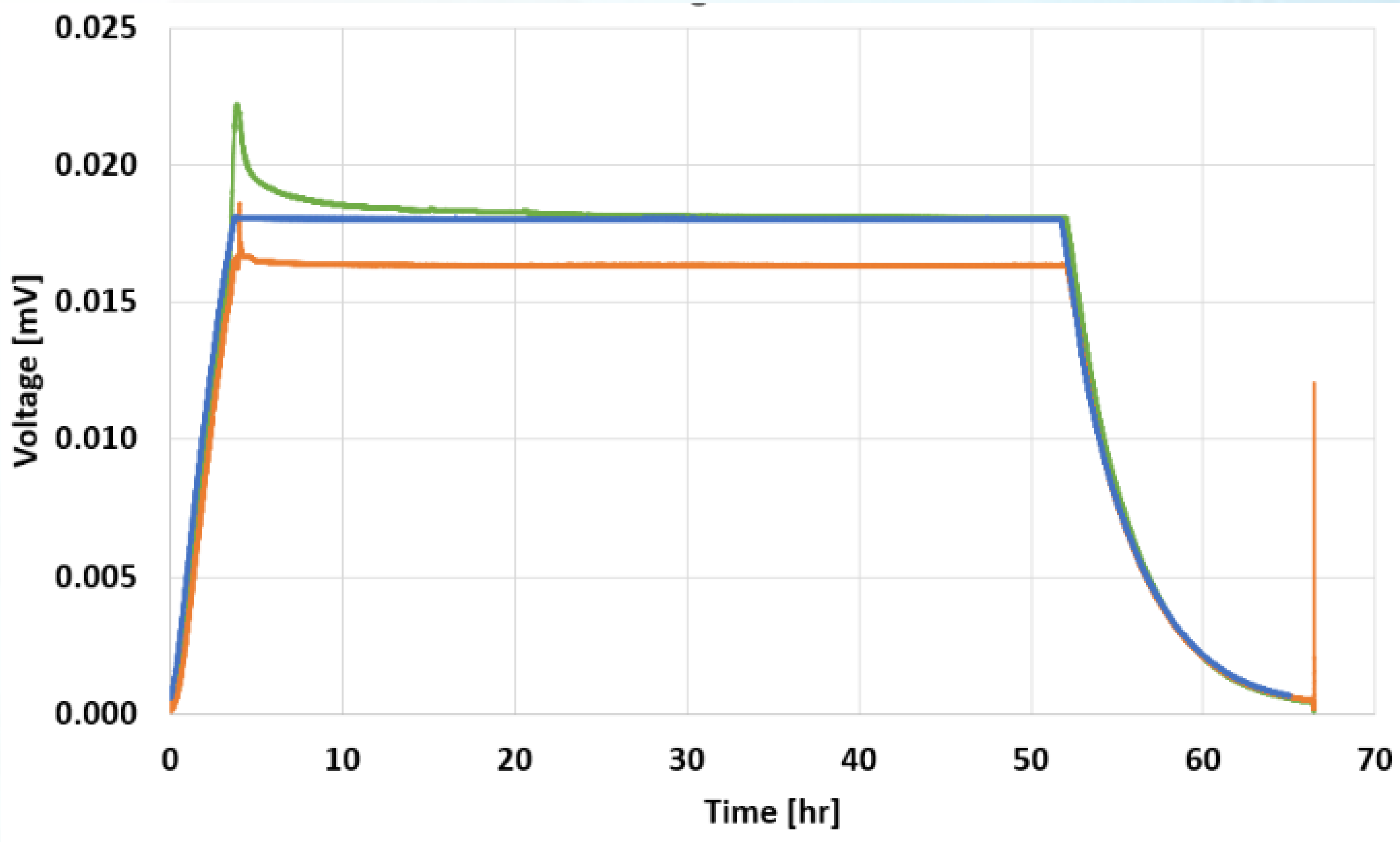


Figure 3: HTIR stability test in furnace after joule heating. Each was heated for 30 minutes at Blue: 2.25A, Orange: 2A, and Grean: 1.5A.

Results and Accomplishments

- Experimental data of common and separate leg thermocouples ran through a statistical analysis
- Data shows that real world data collected on common leg thermocouples will greatly reduce the noise inherent in the TCs.
- The uncertainty term will reduce this noise due to the form of the ΔV equations.

$$\Delta V_{SL} = V_{AB} - V_{CD} \quad (1)$$

$$U(x, \ldots) = 2\sqrt{\left(\frac{df}{dx_1}\sigma_1\right)^2 + \left(\frac{df}{dx_2}\sigma_2\right)^2} \quad (2)$$

$$\frac{d\Delta V_{SL}}{dV_{AB}} = 1 \qquad \frac{d\Delta V_{SL}}{dV_{CD}} = -1 \quad (3a, 3b)$$

$$U_{SL} = 2\sqrt{{b_{AB}}^2 + {b_{CD}}^2} \quad (4)$$

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$$\Delta V_{CL} = V_{AB} - V_{AD} \quad (5)$$

$$U(x, \ldots) = 2\sqrt{\sum_{i=1}^{N}\left(\frac{df}{dx_i}\sigma_i\right)^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{df}{dx_i}\frac{df}{dx_j}\sigma_{ij}} \quad (6)$$

$$\sigma_{ij} = \frac{1}{N}\sum_{i,j=1}^{N}\left[(x_i - \bar{x_i})(x_j - \bar{x_j})\right] = \rho_{ij}\sigma_i\sigma_j \quad (7)$$

$$U_{CL} = 2\sqrt{b_{AB}{}^2 + b_{AD}{}^2 - 2\rho_{ABAD}\sigma_{AB}\sigma_{AD}} \quad (8)$$

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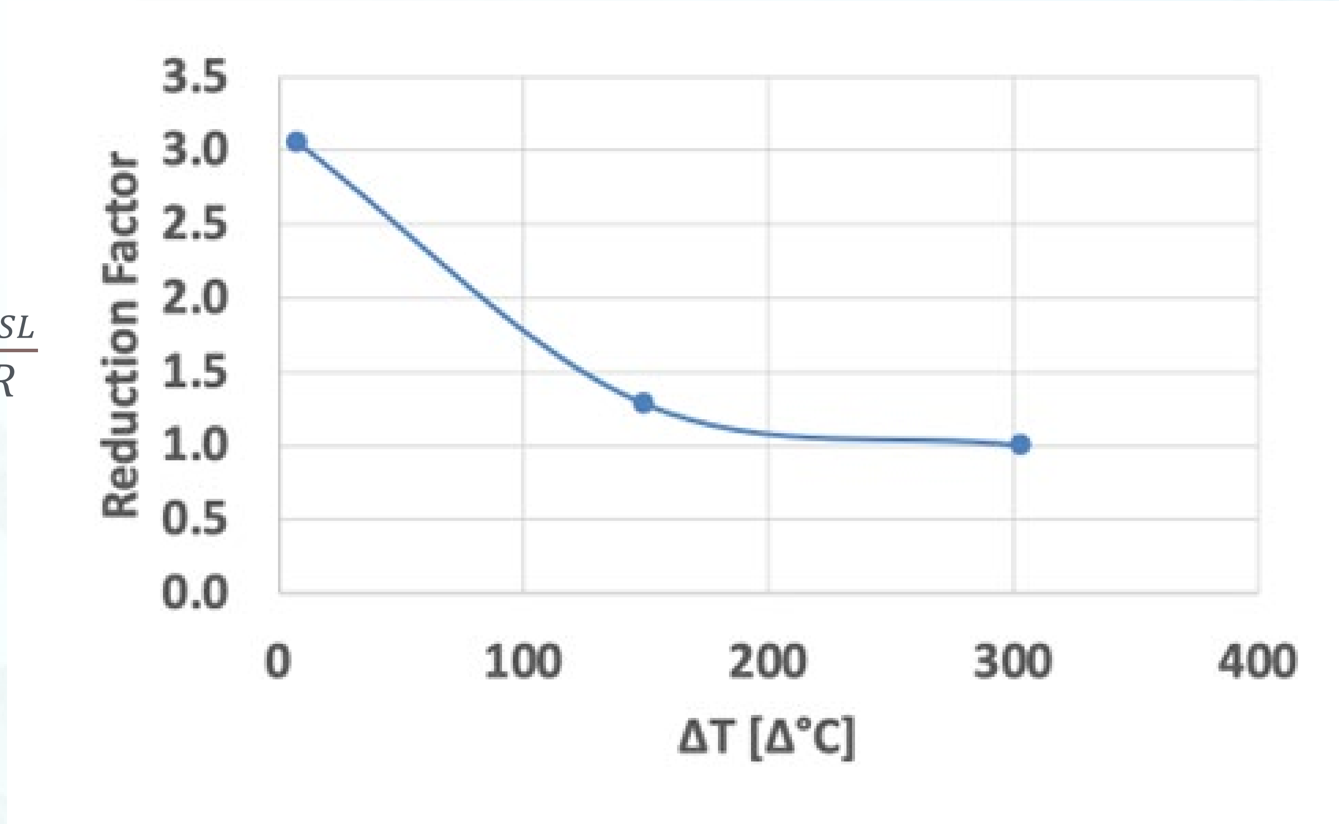
$$U_{CL} = \frac{U_{SL}}{R}$$



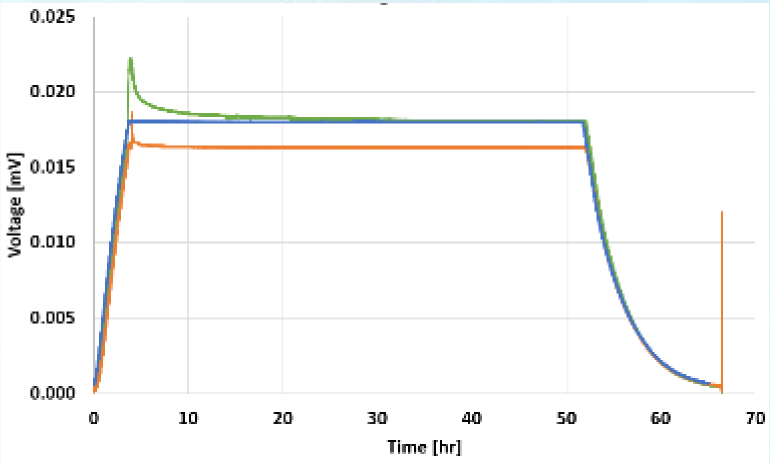
Concluding Remarks

Patents: STABILIZATION METHODS FOR THERMOCOUPLES USING OHMIC HEATING (elected by BEA, 09/2023, patent pending)

Papers: - Skifton, R. "Intrinsic Junction Thermocouples for Fuels Surface Temperature Measurement," ANIMMA 2023, Italy, 2023

- *Riley, S., Skifton, R., et. al., "Influence of Microstructure and Phase Morphology on the Stability of High Temperature Irradiation Resistant Thermocouples," International Journal of Refractory Metals and Hard Materials, VXX, 2023*

- Skifton, R., (2023) High-temperature irradiation-resistant thermocouple instability model for in-pile reactor use. Front. Energy Res. 11:1099584. doi: 10.3389/fenrg.2023.1099584



Idaho National Laboratory

Richard Skifton
Instrumentation Engineer | Measurement Sciences
richard.skifton@inl.gov | 208.526.2696 | 702.306.1258
Idaho National Laboratory | 1955 Fremont Ave. | Idaho Falls, ID | 83415

Thank You