ORNL/TM-2021/1960
CRADA/NFE-20-08041

Testing of Instrumentation and Control Sensors and Cables for Small Modular Reactors

Nesrin Cetiner
Robert Duckworth
David Felde
Edwin Riggsbee
Alex Hashemian
Jacob Houser
Shawn Tyler

April 2021

CRADA final report for CRADA number NFE-20-08041

Approved for public release. Distribution is unlimited.

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

ORNL/ TM-2021/1960
CRADA/NFE-20-08041

US DEPARTMENT OF ENERGY
Office of Nuclear Energy
Gateway for Accelerated Innovation in Nuclear (GAIN) Program

TESTING OF INSTRUMENTATION AND CONTROL SENSORS AND CABLES FOR SMALL MODULAR REACTORS: FINAL CRADA REPORT

Nesrin Cetiner
Robert Duckworth
David Felde
Edwin Riggsbee
Alex Hashemian
Jacob Houser
Shawn Tyler

April 2021

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AMS	Analysis and Measurement Services Corporation
DOE	US Department of Energy
FDR	frequency domain reflectometry
GAIN	Gateway for Accelerated Innovation in Nuclear
HELB	high-energy line break
I&C	instrumentation and control
IEEE	Institute of Electrical and Electronics Engineers
MS	main steam
NPM	NuScale Power Module
NPP	nuclear power plant
ORNL	Oak Ridge National Laboratory
P&L	Perkins and Leppert
PEEK	polyether ether ketone
PSIA	pounds per square inch absolute
PWR	pressurized water reactor
R&D	research and development
RCS	reactor coolant system
RTD	resistance temperature detector
SMR	small modular reactor
SR	silicone rubber
T/H	thermal hydraulic
TW	thermowell
UTB	underneath the bioshield

ABSTRACT

As advanced reactor concepts like small modular reactors (SMRs) progress towards design maturity and commercial deployment, it is important to assess their instrumentation and control (I&C) system sensors and cables to assure their safe, reliable, and efficient operation throughout their service lifetimes. The I&C system of any nuclear power plant (NPP) is the central nervous system of the plant and is made up of field devices such as sensors which are connected via cables to analog and/or digital systems. These systems are responsible for control and/or protection of the plant. The performance of I&C sensors and cables is dependent on several factors, including plant operating conditions. In particular, the plant operation can affect the static (accuracy) and dynamic (response) performance of the sensor, whereas the surrounding ambient environment can impact the remaining useful life of the cables, connectors, and other associated components within I&C sensor circuits.

Although there is extensive operating experience and information on the performance of I&C sensors and cables in conventional large-scale light-water reactors [1], advanced reactor designs such as SMRs present unique operating regimes and harsh environmental conditions that may challenge the nuclear I&C sensors and cables currently available. As a result, a collaboration was initiated between the Oak Ridge National Laboratory (ORNL) and Analysis and Measurement Services Corporation (AMS) under the Gateway for Accelerated Innovation in Nuclear (GAIN) Program. This collaborative effort involved experiments performed on I&C sensors and cables under SMR conditions. ORNL facilities and resources were used to characterize their expected performance in SMR applications.

Based on previous work performed by AMS in collaboration with SMR developers [2], it was determined that there is a need to characterize the dynamic performance of nuclear-grade resistance temperature detectors (RTDs) under the primary system conditions expected in a natural circulation light-water SMR. To safely obtain the high temperatures and variable low flow rates that characterize a natural circulation SMR such as the NuScale Power Module (NPM) and the Holtec SMR-160, AMS needed access to a thermal/hydraulic facility capable of achieving these conditions. The ORNL Thermal Hydraulic (T/H) facilities were successfully adapted to emulate SMR-like reactor coolant system (RCS) flow rates and temperatures. The ORNL T/H flow loop was subsequently used to facilitate the response time tests of five nuclear-grade temperature sensors at temperatures of 70, 150, 250, 340, and 400°F at flow velocities ranging from 0.04 to 1.5 ft/s. The data generated from the comprehensive testing were used to characterize the dynamic response of the sensors as if they were installed in an operating SMR such as the NPM or SMR-160.

In addition, there was interest from SMR developers to better understand the dynamic performance of an RTD subjected to a high-energy line break (HELB) event. Limited data exist on the response characteristics of nuclear-grade RTDs to transient steam phenomena such as a HELB event [3]. As a result, AMS coordinated with the ORNL Advanced Reactor Engineering and Development Section to perform tests at the ORNL steam plant to measure the response time of RTDs suddenly exposed to high-temperature steam. The results from this work established an approximate range of response times for RTDs exposed to transient HELB conditions, as well as the nominal response times of RTDs used for SMR main steam (MS) temperature measurements.

Cable insulation materials are important for ensuring that the signals from sensors are reliably fed to the plant control and/or protection system. Insulation materials are designed to protect the cable conductors from moisture intrusion and environmental stressors such as humidity, and they also provide isolation to prevent the conductor from contacting other conductors, metal, or materials that can cause problems like signal spiking, electrical shorts, high circuit impedance, or erratic performance. As such, it is important to identify cable insulation materials that can withstand the effects of the surroundings for an extended period of time, ideally for the entire life of the SMR. Relative to a large-scale light-water reactor, the

containment conditions of an SMR like the NPM are much harsher (i.e., elevated temperatures, low pressures) to cable insulation materials. In particular, heat transfer in this environment will be reduced, resulting in increased joule heating of energized I&C cables. Although the impact of this environment can be reduced through derating, very little work has been performed prior to this effort to evaluate cables at high temperatures and near-vacuum conditions like those expected in an SMR containment vessel during normal operation.

To address this information gap, testing was performed at the ORNL Advanced Cable, Cryogenic, & Superconducting Technology Development Facility. The ORNL cable laboratory facilitated the evaluation of high-current cables (i.e., ampacity rating between 70 to 80 amperes) that were exposed to conditions expected in the containment of an SMR. Cables insulated with silicone rubber (SR), Kapton, polyether ether ketone (PEEK), and mineral-insulated (MI) cables were exposed to these conditions for a short period of time, and nondestructive electrical test measurements were made in situ. At the conclusion of these tests, offline mechanical, chemical, and thermal tests were performed at the AMS Materials Testing Laboratory to characterize the material changes of the cable insulations. The in-situ electrical measurements and insulation material test results will be leveraged by AMS to inform nuclear industry stakeholders on cable performance, derating, and survivability under SMR conditions.

The results of the sensor response time testing and cable performance characterization in SMR-like operating environments will be shared with sensor and cable manufacturers and SMR I&C design engineers, in addition to other advanced and/or microreactor developers. AMS will use the results to provide guidance on specifications for safety-related RTDs in SMR applications, including RCS temperature and MS temperature services. It should be noted that the types of RTDs eventually selected and procured may be subject to additional testing or qualification prior to installation in an SMR. Similarly, the cable performance data obtained during this project can be used to focus the design and development process for I&C cables used in SMRs and other advanced reactor installations.

1. STATEMENT OF OBJECTIVES

The technical objectives for this Cooperative Research and Development Agreement (CRADA) involved use of the Oak Ridge National Laboratory (ORNL) Thermal Hydraulic (T/H) Facility and Steam Plant for response characterization of resistance temperature detectors (RTDs) and the Advanced Cable, Cryogenic, & Superconducting Technology Development Facility for assessment of I&C cables operating in high temperature vacuum conditions. Analysis and Measurement Services Corporation (AMS) utilized the T/H facility to characterize RTD response time at the high temperatures and low flow rates associated with natural circulation small modular reactors (SMR)s such as the NuScale Power Module (NPM) and the Holtec SMR-160. The steam plant was used to facilitate response time tests of RTD exposed to high-temperature steam transients. For assessment of I&C cables, candidate cables were instrumented and monitored at the Advanced Cable facility to evaluate cable performance as a function of vacuum, operating temperature, and load current.

For the test sequence at the ORNL T/H Facility, response time measurements were made on several thermowell-mounted RTDs at flow rates ranging from 0.04 to 1.5 ft/sec at temperatures ranging from 70 to 400°F. For a given temperature, RTD response times were measured at each flow rate, and this process was repeated for several temperatures up to 400°F. The test results were used to produce a response time vs. flow rate curve in order to assess the sensitivity of RTD response time to changes in flow at low flow rates and as a function of temperature. The response time vs. flow rate curves were then used to establish correlations of RTD response time as a function of heat transfer coefficient. These correlations can be used to estimate nominal RTD response time in process media such as water and steam at various temperatures and flow rates.

For the cable performance tests, three different sets of conditions were used to evaluate cables that could be used in SMRs. Tests at ambient temperature and pressure were used to establish a baseline for each cable. Follow-up testing at ambient- and high-temperature vacuum were then used to assess the derating requirements and survivability of each cable sample compared to normal operating conditions. The tests were carried out for short, 30-minute duration under intermittent loading (from 10 to 100% of rated current) to establish derating factors, and they were performed for long, 1-week duration under continuous loading to track cable survivability at the elevated conditions. The overall cable derating and survivability test plan is outlined as shown in Table 1. Upon completion of the tests, mechanical, electrical, and chemical properties were measured to determine the extent of degradation with respect to each cable type and environmental condition.

Table 1. GAIN cable testing matrix.

Duration	Rated Current @ Ambient	Rated Current @ Vacuum (1 Torr)	Rated Current @ Vacuum / High Temperature (1 Torr, 250°C)
30 min	10%	10%	10%
	30%	30%	30%
	50%	50%	50%
	70%	70%	70%
	85%	85%	85%
	100%	100%	100%
1 week	N/A	50%	50%

2. BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

ORNL is the home of the Thermal Hydraulics (T/H) Facility and the Advanced Cable, Cryogenic, & Superconducting Technology Development Facility. Both the T/H Facility and the Advanced Cable Facility provide opportunities for users, including public research institutions and private companies, to build partnerships with ORNL researchers that accelerate the development of solutions and technologies to address key needs in the United States and throughout the international community.

This project specifically addresses the US Department of Energy (DOE) mission to "…advance nuclear power as a resource capable of making major contributions in meeting our nation's energy supply, environmental, and energy security needs by focusing on the development of advanced nuclear technologies." The development of reliable sensor and cable technologies for advanced reactors will support the timely and cost-efficient management of I&C assets in current and future nuclear power plants to preserve and advance the investment in nuclear energy within the United States.

3. TECHNICAL OUTCOMES

3.1 RTD RESPONSE TIME CHARACTERIZATION

As part of an ongoing DOE research and development (R&D) project on the I&C needs of SMRs, AMS is characterizing the dynamic performance of typical nuclear-grade RTDs to verify that these sensors can satisfy technical specifications for response time at the conditions expected during operation of a natural circulation SMR. As with any nuclear power plant, the safe and efficient operation of an SMR depends on the timely and accurate measurement of primary system parameters such as temperature, pressure, level, flow, and neutron flux. It is expected that thermowell-mounted RTDs will be used for safety-related measurements of primary coolant and main steam (MS) temperatures in SMRs and bare RTDs will be used for safety-related temperature measurements of the space outside the NPM containment vessel above the liquid level of the reactor pool and underneath the bioshield (UTB). All of these safety-related measurements provide input to reactor trip and engineered safety features, which must respond to changes in temperature within a specified limit as defined in plant technical specifications.

The response time of an RTD is a function of its physical properties, as well as flow rate and temperature, among other variables. In general, RTD response time increases as flow rate decreases, and for natural circulation SMRs, primary system flow will be very low relative to that in existing large-scale nuclear power plants. Therefore, AMS has collected data on response time vs. flow for several nuclear-grade RTDs installed on a T/H test loop within the AMS laboratory at 70 and 150°F. These data were then used to develop heat transfer correlations to estimate RTD response time at higher temperatures that are expected in SMRs. While this information is useful to SMR vendors, additional testing was needed at higher temperatures to validate the correlations. As such, AMS coordinated with ORNL to gain access to a facility capable of achieving these conditions to perform the work reported here.

ORNL provided the T/H Facility in support of this work, and AMS provided the sensors to be tested, which included four nuclear-grade Weed Instrument Co. Model N9004 RTDs with matching thermowells (TWs), and another RTD and TW that was custom manufactured by Conax Nuclear. In support of this work, the ORNL thermosyphon loop was modified by the addition of a 20 kW heater, a heat exchanger to cool the pump seal, a low-range turbine flow meter, and a test section to allow for installation of two thermowell-mounted RTDs (Figure 1 and Figure 2). The test loop included a Series R4000 Met-Pro Dean Pump that provided the desired flow conditions and an AlfaNova 27-40H heat exchanger that rejects the excess heat to a chilled water system. All modifications were completed by September 2020, and testing began in October 2020.

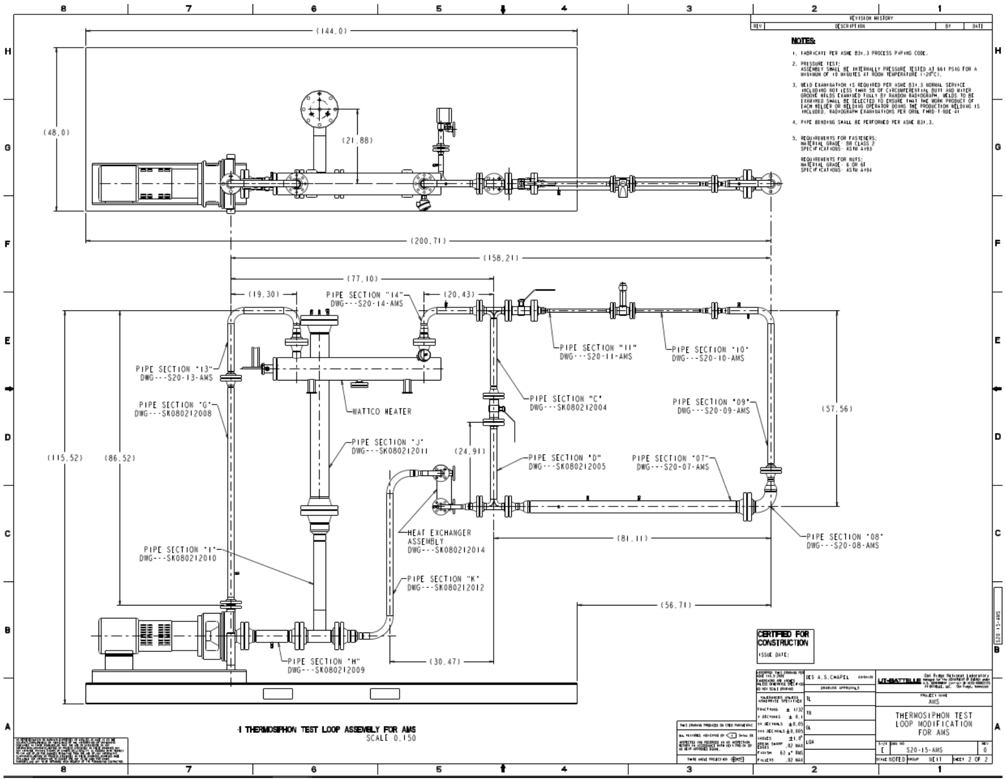

Figure 1. Test loop design.

Figure 2. Photo of the test loop.

3.1.1 Introduction to Response Time vs. Flow Characterization

The type of RTDs tested in this work is used in many pressurized water reactors (PWRs) around the world to measure the RCS temperature for control and safety. Typically, these RTDs are exposed to flow rates greater than 10 feet per second (ft/s) and temperatures up to 610°F. In the NuScale NPM and Holtec SMR-160, these RTDs will operate at about the same temperatures of a large-scale PWR but at much lower flow rates (i.e., less than 1 ft/s). As such, the sensitivity of response time to these low flow rates is an important consideration for reactor control and safety analysis.

Analysis of detailed response time vs. flow measurements was performed in the AMS laboratory at flow rates ranging from 0.25 up to 10 ft/s at a temperature of 70°F and also at 150°F. These measurements led to development of a correlation of RTD response time vs. heat transfer coefficient. However, the usefulness of this correlation was uncertain, as the maximum safe temperature of the AMS T/H test loop was 180°F, and the minimum operating temperature of the NPM and SMR-160 are projected to be significantly higher. The results of the AMS tests had already demonstrated sensitivity of the RTD response times to coolant temperature, so it was important to fully evaluate and validate the response time correlations at higher temperatures and lower flow rates that more closely approximate the NPM and SMR-160 process conditions. Therefore, AMS coordinated with ORNL experts to perform these tests at ORNL's T/H facility over a two-week period in October 2020.

3.1.2 Theoretical Background of Response Time Correlation

For calculation of the film heat transfer coefficient (h) and its relationship to RTD response time (τ), the following relationships presented by H. Hashemian, [1] were used:

$$\tau = C_1 + C_2 / h \tag{1}$$

$$Nu = hD/K. \tag{2}$$

Therefore, *h* is derived as:

$$h = K\,Nu / D. \tag{3}$$

The magnitude of the heat transfer coefficient (*h*) is directly proportional to the thermal conductivity (*K*) of the process fluid and the Nusselt (*Nu*) number. The Nusselt number is typically expressed in terms of empirical correlations for heat transfer between the RTD of diameter (*D*) and the perpendicular flow past the cylindrical RTD using the Reynolds Number (Re) and the Prandtl Number (Pr) as described by either Rohsenow and Choi or Perkins and Leppert.[1] The Rohsenow and Choi correlation is:

$$Nu = 0.26\, Re^{0.6}\, Pr^{0.3} \quad for \quad 1{,}000 < Re < 50{,}000\ , \tag{4}$$

and the Perkins and Leppert correlation is

$$Nu = 0.26\, Re^{0.5}\, Pr^{1/3} \quad for \quad 40 < Re < 10^5\ . \tag{5}$$

The key variables (Re, Pr) of these correlations were obtained based on the flow, temperature, fluid properties, and RTD diameter of the experimental data, as follows:

$$Re = Du\rho/\mu, \text{ and} \tag{6}$$

$$Pr = C\mu/K. \tag{7}$$

These parameter variables are defined as follows:

h	=	film heat transfer coefficient
D	=	sensor diameter
K	=	thermal conductivity of process fluid
u	=	average velocity of process fluid
ρ	=	density of process fluid
μ	=	viscosity of process fluid
C	=	specific heat capacity of process fluid

3.1.3 Data Collection and Data Evaluation

Five nuclear-grade RTDs and three TWs from two different manufacturers were tested at the ORNL T/H Facility at temperatures of 70, 150, 250, 340, and 400°F at flow velocities ranging from 0.04 to 1.5 ft/s. Some of these test conditions have been previously evaluated at the AMS flow loop as part of a separate research and development activity and were used to cross-check the results [4]. The overall division of test conditions for the RTD response time tests at the AMS laboratory and ORNL test facility are presented in Table 2.

Table 2. Summary of conditions for RTD response time tests at AMS and ORNL.

Flow	70°F	150°F	250°F	340°F	400°F
0.04	ORNL	ORNL	ORNL	ORNL	ORNL
0.10	ORNL	ORNL	ORNL	ORNL	ORNL
0.20	AMS/ORNL	AMS/ORNL	ORNL	ORNL	ORNL
0.50	AMS/ORNL	AMS/ORNL	ORNL	ORNL	ORNL
0.70	AMS/ORNL	AMS/ORNL	ORNL	ORNL	ORNL
1.00	AMS/ORNL	AMS/ORNL	ORNL	ORNL	ORNL
1.50	AMS/ORNL	AMS/ORNL	ORNL	ORNL	ORNL

The data from the comprehensive response time testing at ORNL were used to generate the consolidated results shown in Figure 3. This figure presents the averaged response time results from each Weed RTD tested as installed in a Weed TW at the ORNL T/H facility for each flow velocity at each temperature. It is apparent from this figure that there is a range of response times for each flow velocity. Distilling the results at each flow velocity by temperature yields the response time vs. flow velocity plots shown in Figure 4. Note that these plots represent the average response time vs. flow at each temperature for the Weed RTDs/TWs tested. It is evident that there is some reduction in RTD response times vs. flow at 250°F compared to 70°F, but there is not a significant difference between the response time results vs. flow at 250, 340, and 400°F. Comparable results were obtained for the Conax RTD that was installed in a Conax TW. The Conax RTD exhibited similar response time sensitivity at low flow.

The response time results were then used to establish correlations of typical RTD response times as a function of heat transfer coefficient (h) and as a function of thermal resistance (1/h). Statistical evaluation of the results from the ORNL tests confirmed that the Perkins and Leppert (P&L) correlation provided a better estimation of response times at the lower flow rates and higher temperatures that characterize natural circulation SMRs such as the NPM and the SMR-160. Therefore, all calculations of h presented in this report are derived from the P&L correlation. The overall consolidated results for the Weed Model N9004 RTDs/TWs are plotted against h and 1/h, as shown in Figure 5 and Figure 6, respectively. All of the individual correlations plots and values are similar to the composite shown here.

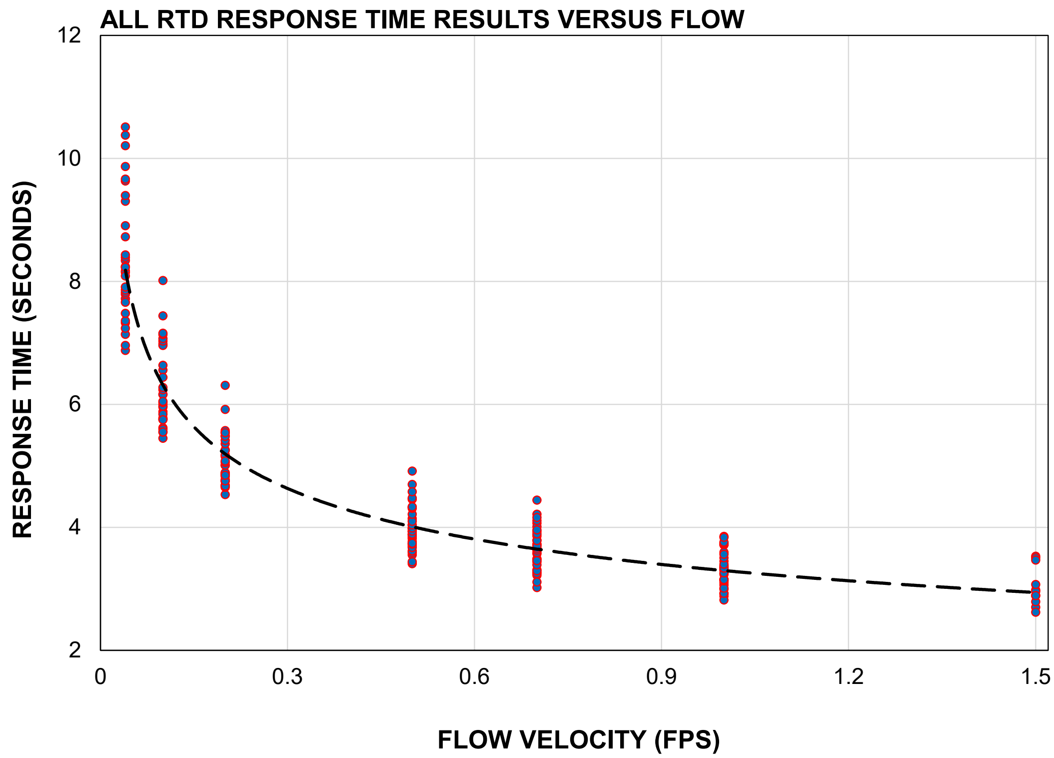

Figure 3. All test results vs. flow.

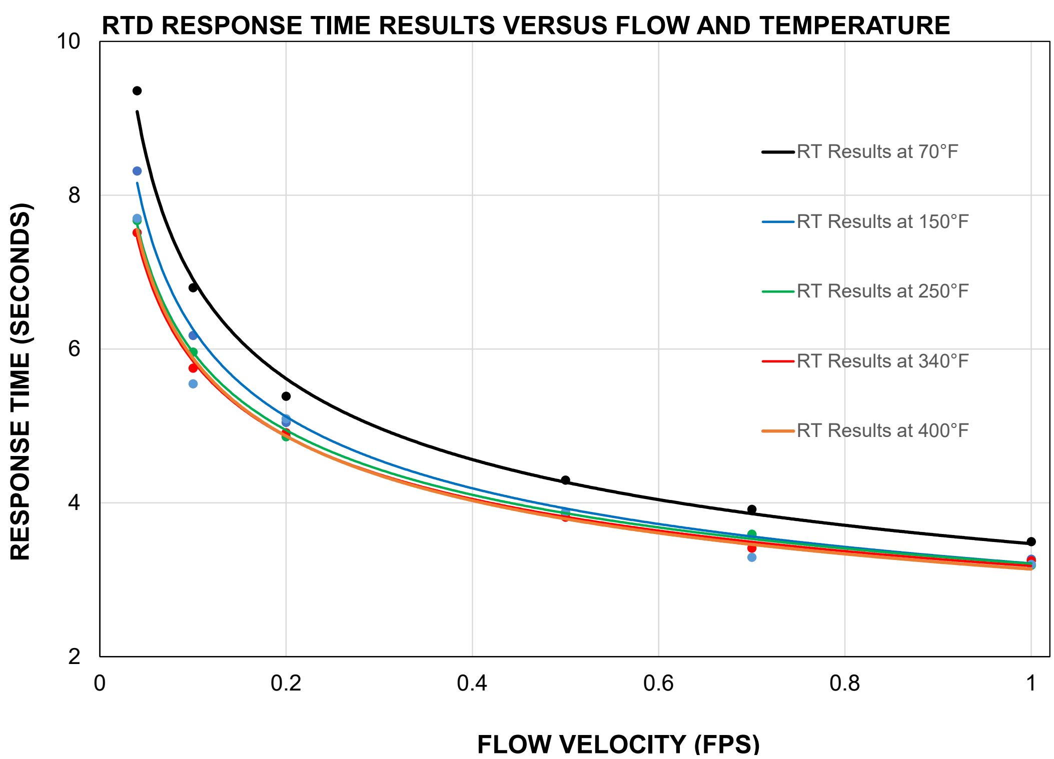

Figure 4. Test results segregated by temperature.

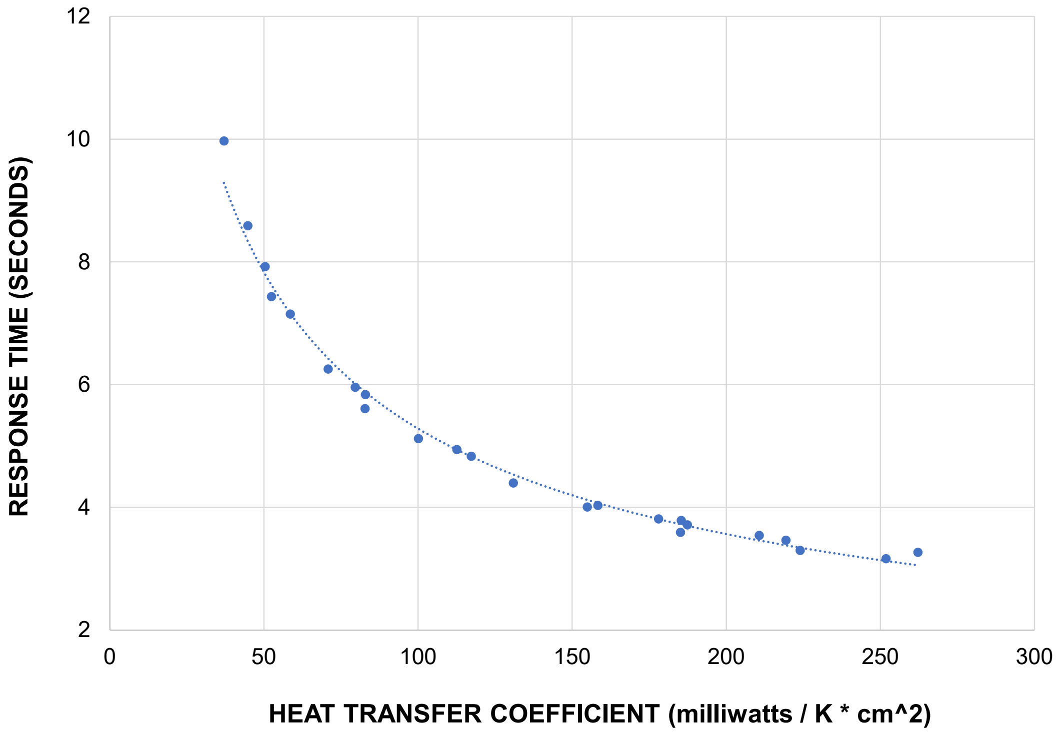

Figure 5. Response time correlation vs. h.

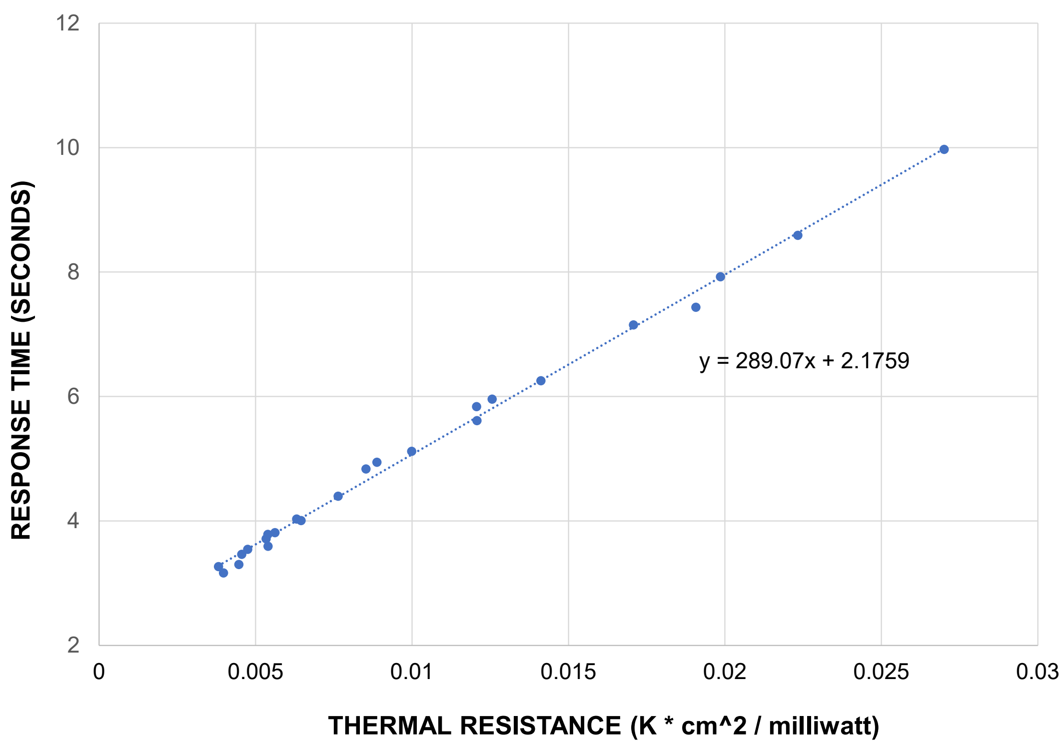

Figure 6. Response time correlation vs. 1/h.

These correlation values are significant because they can be used to estimate what the response time of these RTDs would be if they were installed in a natural circulation SMR such as the NPM or SMR-160. All that is needed for the estimate is a calculation of the *thermal resistance*, which is obtained from fluid and flow parameters such as the thermal conductivity, the Prandtl number, density, viscosity, flow velocity, and the Reynolds number. AMS developed a calculator which is used in conjunction with the National Institute of Standards and Technology (NIST) reference thermal properties database to obtain these values for various operating conditions within the NPM SMR. The average values of the correlation constants obtained from the tests at ORNL were used in conjunction with these thermal resistance calculations to estimate the typical response times of these RTDs if they were installed in the NPM (Figure 7). Estimates are provided for the NPM at 100% power (full flow), the NPM at less than 5% power (low flow), the NPM MS service, and for the scenario in which these RTDs are installed in an operating PWR. The estimate for MS is important for the NPM SMR in particular, because MS temperature is a safety-related measurement, and there is limited experience with RTD response time testing in superheated steam environments [3].

For existing PWRs, Weed N9004 RTD response times at full power operation typically range from about 2 to 4 seconds with reactor coolant flow velocities of 25 to 50 ft/s at coolant temperatures of 540 to 610°F. Response times greater than 4 seconds can usually be attributed to either poor installation or component aging/degradation. Any Weed RTDs with response times much greater than 4 seconds are typically reinstalled or replaced to obtain a better fit and thus better response time. With the NPM, it will be very important to detect response time outliers prior to power operation, as it will be extremely difficult to replace a failed RTD after the NPM is in operation. Therefore, actual in-service response times must be confirmed by in-situ testing, and any outliers must be detected and corrected prior to NPM operation. The response time correlations developed herein will provide useful metrics for detection of outliers prior to NPM operation.

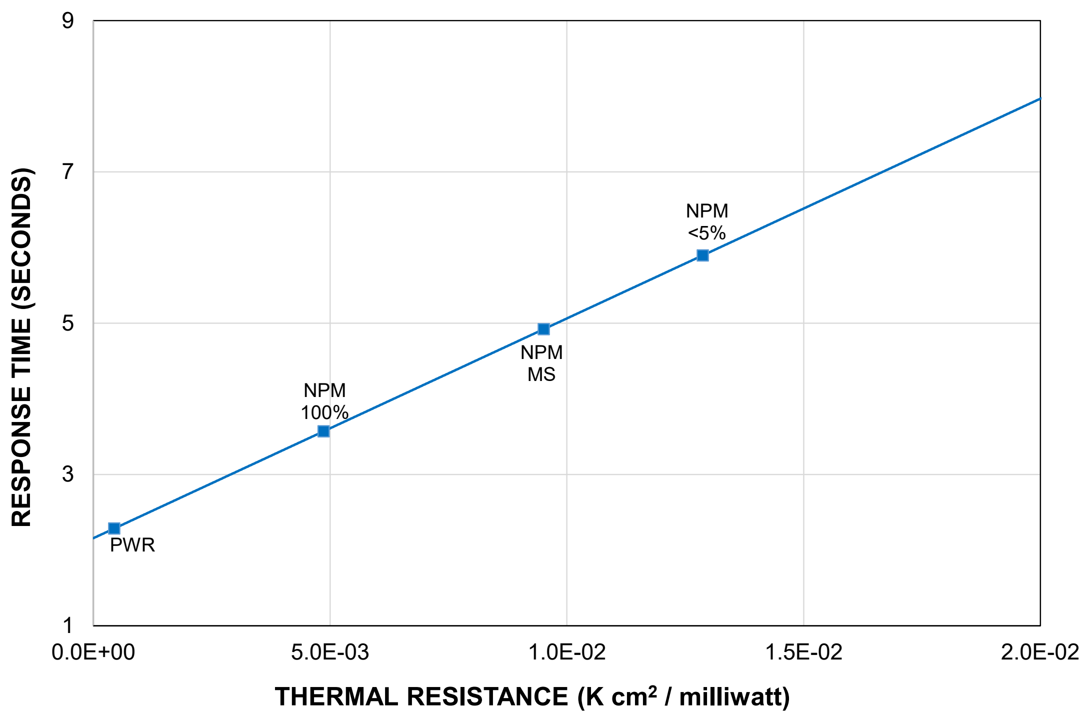

Figure 7. Response time estimates for typical PWR and NuScale NPM.

3.2 RTD RESPONSE TO STEAM TRANSIENTS

In addition to the NuScale RCS temperature measurement, it is important to measure the temperature of the space outside the NuScale containment vessel above the liquid level of the reactor pool and UTB, as illustrated in Figure 8. Measuring the UTB temperature may be accomplished using bare (i.e., without a TW) RTDs. The UTB temperature measurement is classified as safety-related, as it serves to detect a high energy line break (HELB) of the MS piping that runs from the reactor vessel, through the containment vessel, and to the turbine generators located in the main service building. A break in the superheated steam line must be detected quickly to mitigate equipment damage due to a HELB event by tripping the reactor and activating engineered safety features, including containment isolation and decay heat removal actuation.

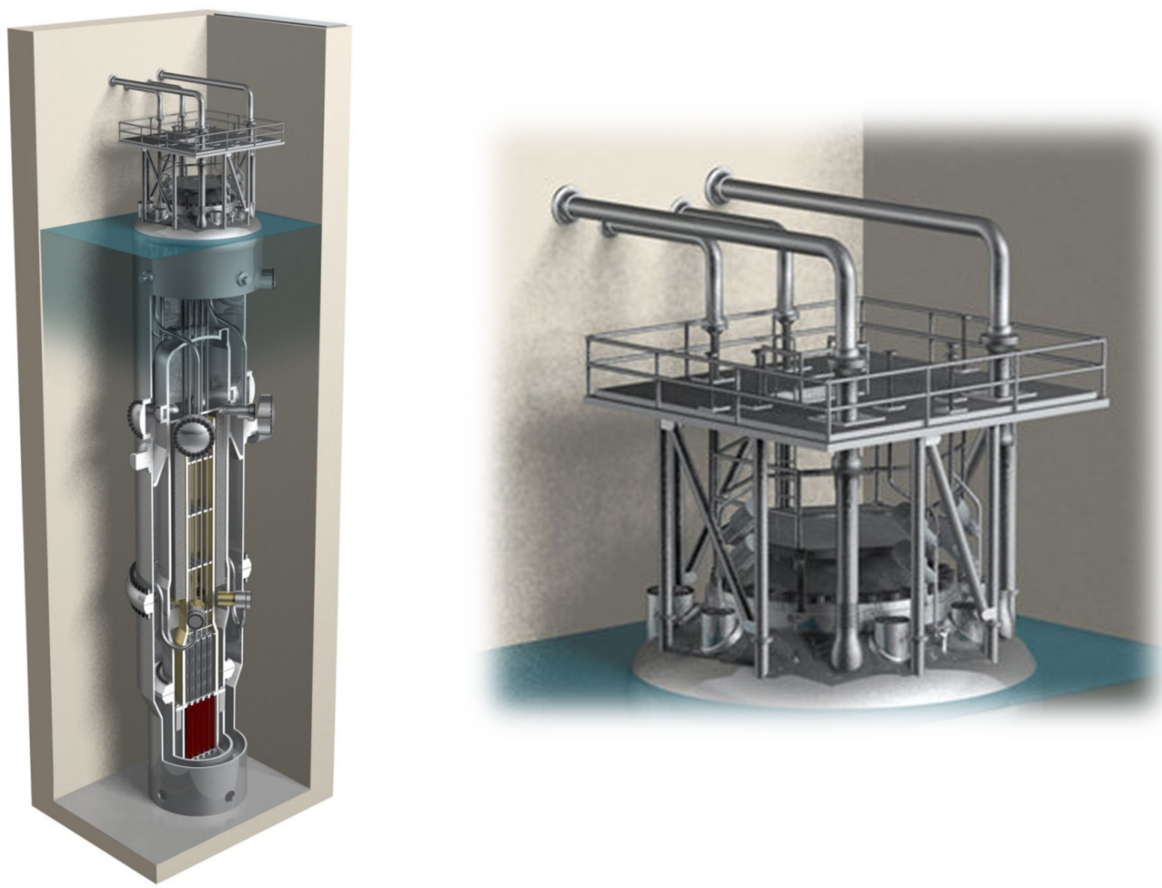

Figure 8. Illustration of NuScale Reactor, Main Steam Lines, and UTB [5]

3.2.1 Introduction to Steam Transient Tests

Because the dynamic performance of an RTD depends in part on the surrounding medium, it must be demonstrated that the RTDs selected for safety-related applications can meet the associated response time requirements outlined in the plant technical specifications. The response characteristics of RTDs are well established in the PWR RCS environment, but they are not well established for steam transients like those resulting from a HELB event. As such, it is important to establish the response characteristics of nuclear-grade RTDs operating in air that are suddenly exposed to steam to ensure that these sensors can promptly actuate safety functions and mitigate the consequences of a HELB as defined in the SMR plant technical specifications.

As a result, AMS designed and constructed an experimental test setup to simulate a steam transient and measure the response time (τ) of a bare RTD when subjected to a sudden change in temperature and surrounding process from air to steam. For these tests, the RTD output is an exponential transient, and the response time of the RTD may be defined as the time it takes for the RTD output to reach 63.2% of its final value following the change in temperature.

A diagram of the setup is provided in Figure 9. In this setup, the cylindrical tank is initially isolated from the steam source by a valve, and when the valve is opened, it exposes the RTD to a sudden change in temperature, as shown in Figure 10. Several RTDs from AMS's sensor inventory were tested using this configuration. Based on the results of the testing at AMS, it was determined that additional steam transient testing was needed to evaluate the effect of higher steam temperatures on the RTD response times. Therefore, AMS coordinated with the ORNL Energy Systems Development Group under Advanced Reactor Engineering and Development Section to perform steam transient tests at the ORNL steam plant to assess the sensitivity of RTD response time results to higher temperature steam and to evaluate any sensitivity of the results to the initial ambient air temperature and pressure of the sampling cylinder. A general assessment of response times for different types of RTDs exposed to steam transients was an additional objective. Various types of RTDs were tested to demonstrate that RTDs from different manufacturers may have unique response time characteristics.

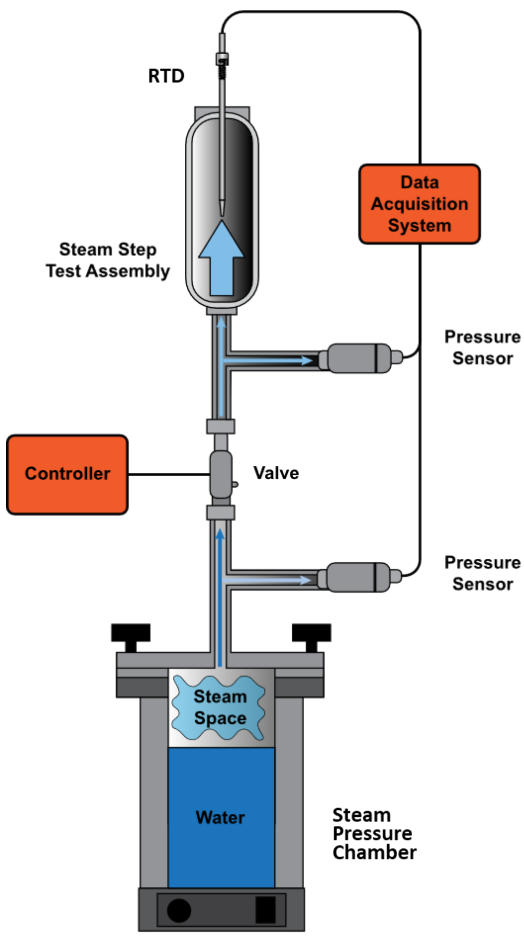

Figure 9. Diagram of AMS steam test setup.

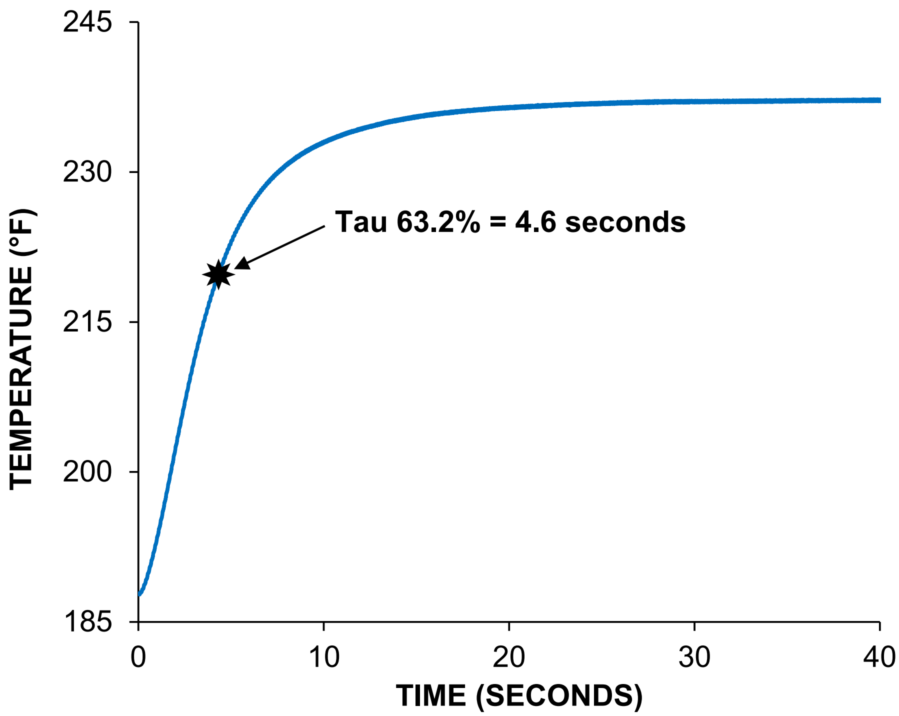

Figure 10. Example of steam test transient at AMS.

3.2.2 Testing at ORNL Steam Plant

The final phase of steam transient testing was performed at the ORNL steam plant in February 2021. The premise of the tests was to connect the AMS steam transient test assembly to the ORNL steam plant's main header, as shown in Figure 11 and Figure 12. The test consisted of opening an isolation valve that separates the sampling cylinder from the ORNL steam supply and measuring the RTD signal output in response to the steam transient. The components of the test system were selected based on the steam temperature and pressure of approximately 380°F at 180 PSIG. All components were subjected to a safety evaluation prior to being used for these tests. Appropriate test and safety procedures were also developed, reviewed, and approved prior to the performance of the tests.

Several different types of RTDs—including four Weed N9004E, a Weed N9017, two custom RTDs manufactured by Conax Nuclear (Mirion Technologies), and an Omega commercial-grade RTD—were included in the test plan for the ORNL steam plant. The Weed N9004E RTDs are nuclear qualified sensors and commonly used for reactor coolant temperature measurements in existing PWRs. Three of the N9004E RTDs were tested bare, and a fourth N9004E was installed in a TW for the tests at the ORNL steam plant. The Weed N9017 is also a nuclear qualified RTD that is offered by Ultra Electronics for ambient temperature measurement and for steam leak detection in nuclear power facilities, either in containment or balance of plant applications. The Weed N9017 RTD is a candidate for use in the NPM UTB application.

Conax Nuclear provided two models of custom-built Conax dual element RTDs for evaluation by AMS. One of the RTDs (Conax Model N20021) was tested bare, and a second RTD (Conax Model N20022) was installed in a matching TW. Conax Nuclear is interested in offering RTDs that could be used for SMR safety-related applications such as RCS and UTB temperature measurements. An RTD manufactured by Omega was also selected for the steam transient tests. It is a standard commercial-grade RTD with a ¼ in. sheath that has appropriate specifications for use in high-temperature steam.

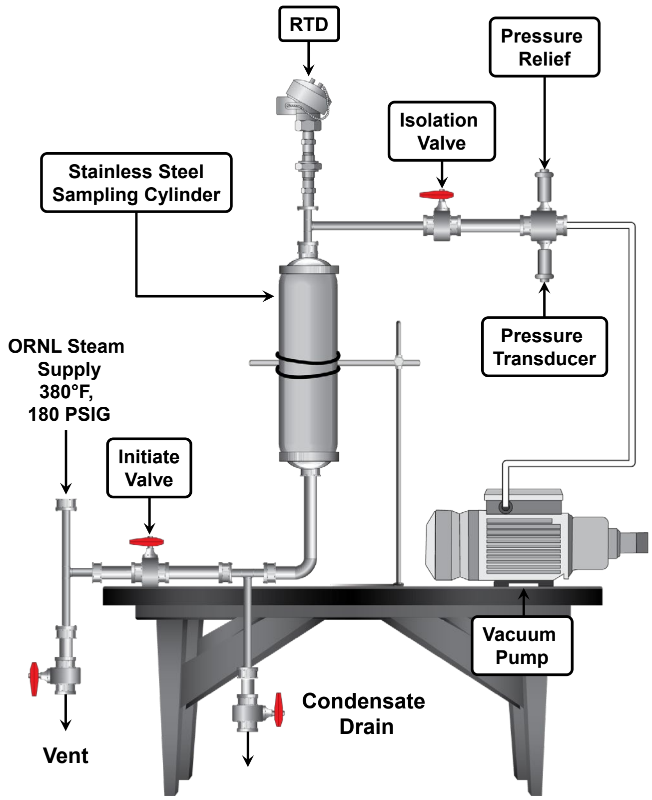

Figure 11. Diagram of steam test setup at ORNL.

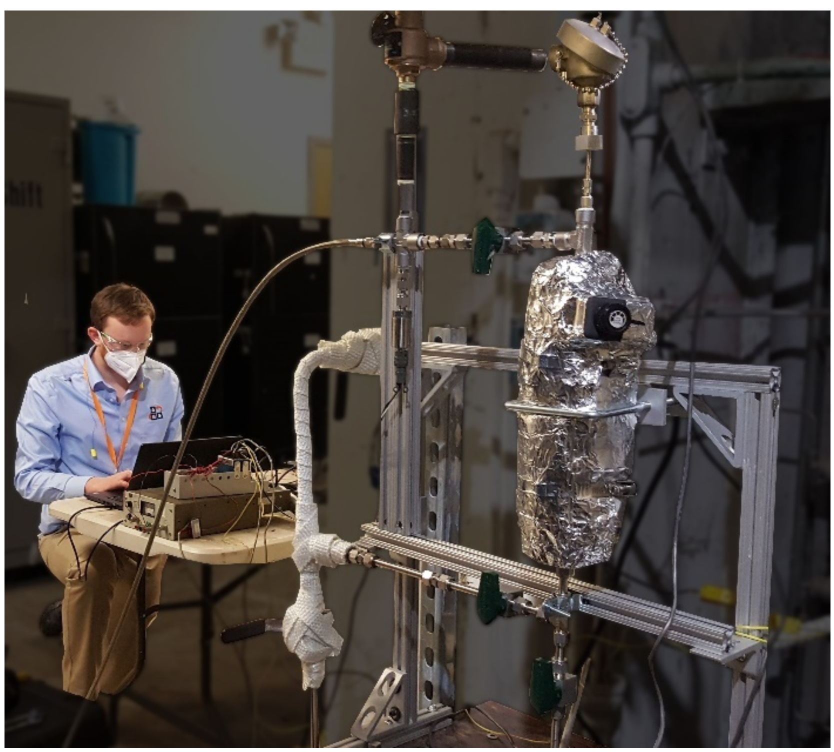

Figure 12. Photo of the steam test setup at ORNL.

A series of three steam transient tests was performed with a Weed N9004E dual element RTD installed in the sampling cylinder at an initial temperature of 120°F and 12 pounds per square inch absolute (PSIA), which emulates the NuScale UTB conditions during normal operation. This was followed by testing with an initial temperature of 190°F and about 1 PSIA, and then it was repeated at 190°F and 14.7 PSIA. Response time results from these three tests are provided in Table 3. No significant differences in results based on initial condition (temperature and pressure) were observed.

Table 3. Steam transient response time results at different initial conditions.

Test	Pressure (PSIA)		Temperature (°F)		Response time (Sec)	
	Initial	Final	Initial	Final	Element 1	Element 2
1	12.0	195	120	370	2.0	2.2
2	1.0	195	190	380	2.2	2.4
3	14.7	195	190	370	2.1	2.3

A subsequent series of tests of the six bare RTDs (no TW) were performed at an initial cylinder temperature of approximately 120 to 190°F, all at 14.7 PSIA. This was followed by tests of the Conax N20022 RTD installed in a TW and a Weed N9004E RTD installed in a TW. All response time results ranged from 1.1 to 8.0 seconds, as shown in Table 4. The response times of the three bare Weed N9004E RTDs were generally consistent, ranging from 1.9 to 2.5 seconds. In comparison, the Weed N9017 RTD, which is a nuclear-qualified sensor for steam leak detection, had a response time of 3.9 seconds for the first element and 4.1 seconds for the second element. Steam transient test results from one of the Weed N9004E RTDs and the Weed N9017 RTD are compared as shown in Figure 13. Both elements of the bare Conax RTD (N20021) were tested and found to have a response time of 1.1 seconds, which is very fast compared to the relatively slow response of the Omega RTD at 5.5 seconds. The difference in response of the Conax RTD and Omega RTD is shown in Figure 14.

Like the bare Conax N20021, the Conax N20022 in a TW was found to be very fast, with a response time of 2.7 seconds for both elements. The Weed N9004E in a TW had a response time of 3.4 seconds for the first element and 3.9 seconds for the second element. This is somewhat slower than the nominal response of a Weed N9004E RTD/TW operating in the RCS of a PWR.

Table 4. Comparison of steam transient results from ORNL tests.

Item #	RTD Model	Temperature (°F)		Response time (seconds)	
		Initial	Final	Element 1	Element 2
1	Weed N9004E	190	370	2.0	2.2
2	Weed N9004E	160	370	1.9	2.2
3	Weed N9004E	190	370	2.3	2.5
4	Weed N9017	190	370	3.9	4.1
5	Conax N20021	180	370	1.1	1.1
6	Omega PR-10H-4-100	170	365	5.5	N/A
7	Conax N20022 / TW	180	370	2.7	2.7
8	Weed N9004E / TW	180	370	3.4	3.9

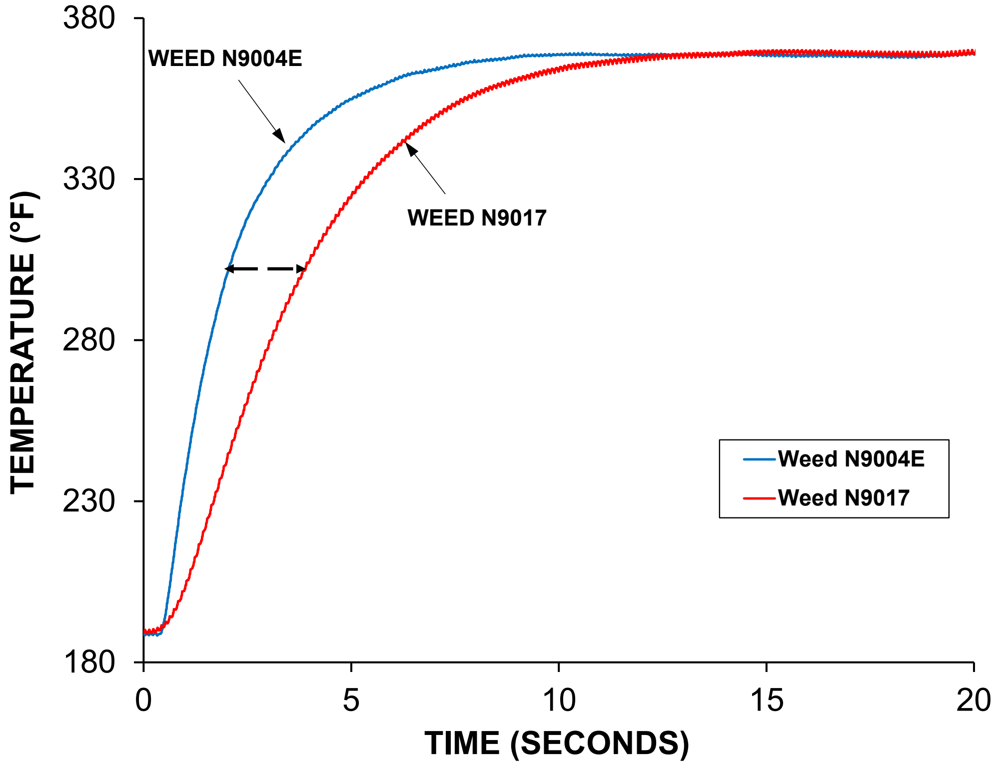

Figure 13. Response of a Weed N9004E and Weed N9017 RTDs to steam transient.

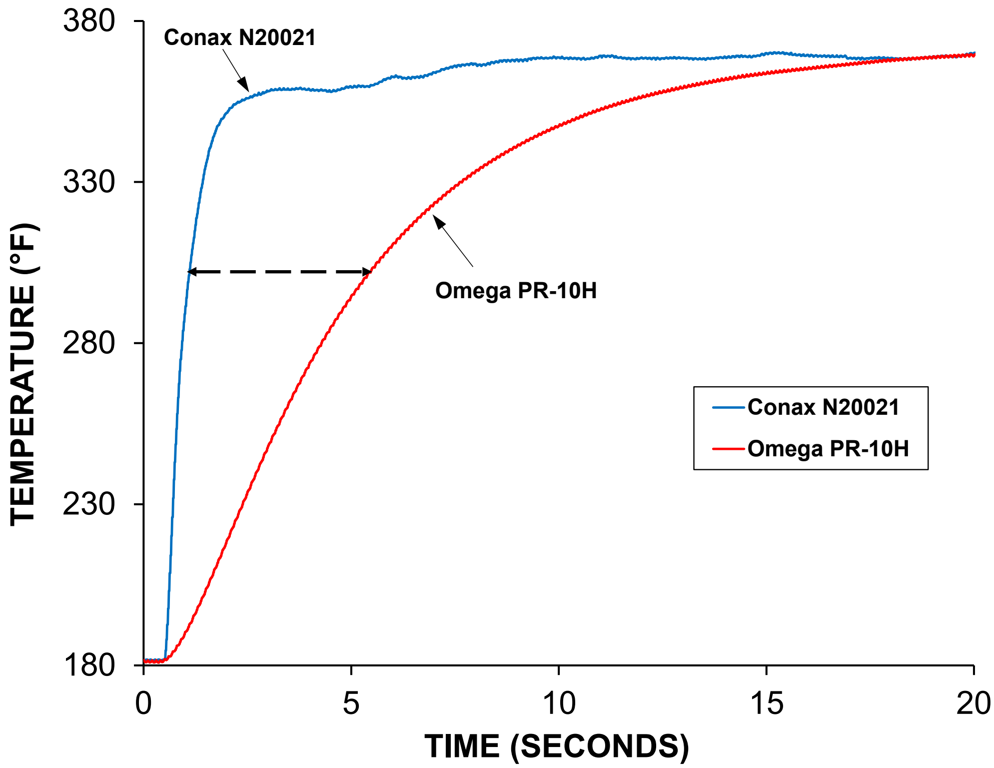

Figure 14. Comparison of response of a Conax and Omega RTDs.

3.2.3 Sensitivity of RTD Response Time to Steam Temperature

The relationship of RTD response to steam temperature can be inferred from the heat transfer characteristics of steam vs. temperature. As described in Section 3.1.2, the key contributors to the heat transfer coefficient are the fluid velocity, thermal conductivity, density, viscosity, and Prandtl number. Unlike water, the density and thermal conductivity of saturated steam are very sensitive to steam temperature, as shown in Figure 15. The data plotted in Figure 15 is from the NIST Thermal Properties Database. The sensitivity of these properties to steam temperature results in a heat transfer film coefficient with a wide range of values vs. temperature, as shown in Figure 16. In this figure, the heat transfer coefficient of the steam was calculated with a velocity of 100 m/sec and with saturated water at a velocity of 1 m/sec. As shown in the figure, the heat transfer film coefficient of high velocity steam is significantly less than that of low velocity saturated water at temperatures below 580°F.

For confirmation of these heat transfer characteristics, several tests were performed at AMS and at the ORNL steam plant on a bare Weed N9004 RTD and a separate Weed N9004 RTD installed in a TW. The tests at AMS were performed under two sets of conditions: with steam temperature and pressure of 239°F at 24 PSIA (AMS-1) and 261°F at 35.6 (AMS-2) PSIA. The tests of the same sensors at ORNL were performed with steam temperature of ~380°F at 195 PSIA. The values of the estimated thermal properties of the steam and corresponding response time test results at these conditions are presented in Table 5. The values of steam density and thermal conductivity shown in the table were obtained from the NIST Thermal Properties Database.

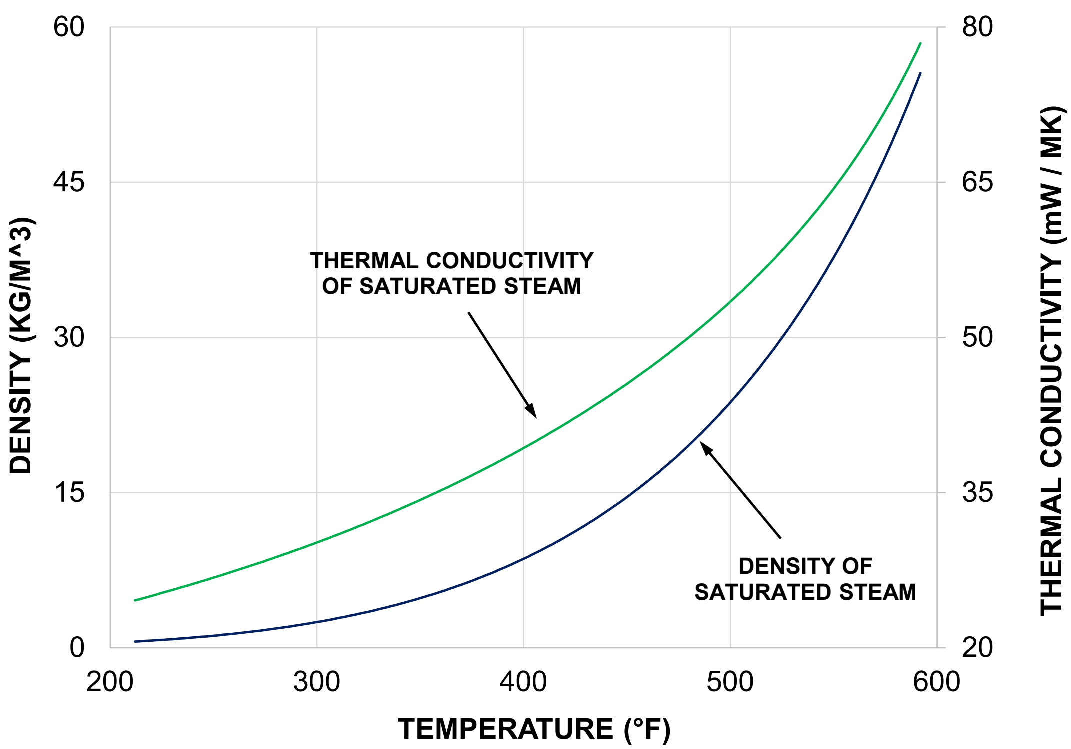

Figure 15. Density and thermal conductivity of saturated steam plotted vs. temperature.

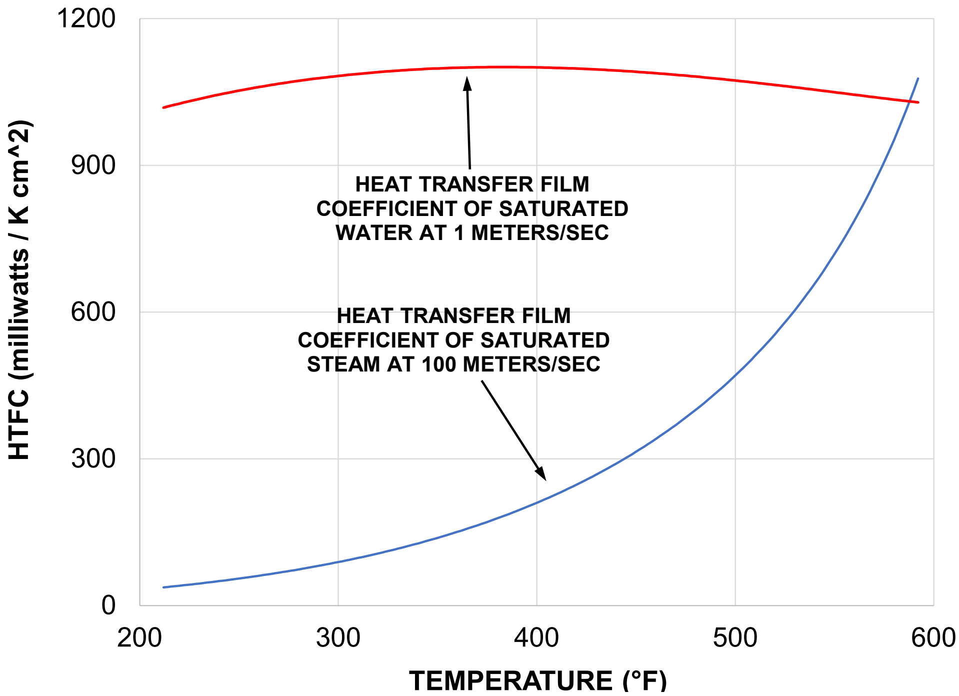

Figure 16. Comparison of heat transfer film coefficient of saturated water and steam.

Table 5. Comparison of results from different test conditions

Description	AMS-1	AMS-2	ORNL
Pressure (PSIA)	24.0	35.6	195
Temperature (°F)	239	261	380
Density (kg/m^3)	0.944	1.366	6.828
Conductivity (W/m-K)	0.0261	0.0275	0.0371
N9004 bare response (Sec)	3.6	3.3	2.1
N9004 in TW response (Sec)	6.7	6.0	3.9

These response time results are plotted vs. calculated thermal resistance (1/h) as shown in Figure 17 and Figure 18. The heat transfer film coefficient (h) was calculated using Eq (3) and Eq. (5) from Section 3.1.2, with the following modification:

$$Nu = 0.6\, Re^{0.5} Pr^{1/3}. \quad (8)$$

This information will be useful for establishing an approximate range of response times of bare RTDs exposed to HELB conditions and also to estimate the expected response times of RTDs installed in TWs used for SMR MS temperature measurements. However, based on the sensitivity of the heat transfer film coefficient due to temperature, velocity, and moisture content of the steam, a range of response times can occur, depending on the conditions of the HELB. Also, if an RTD is not directly impacted by the high-velocity steam from a HELB, then the sensor response time and the time for the RTD output to pass through a setpoint for safety actuation could be significantly slower than the results shown here. Therefore, careful consideration must be given to HELB accident models that rely on temperature sensor response time to actuate safety functions.

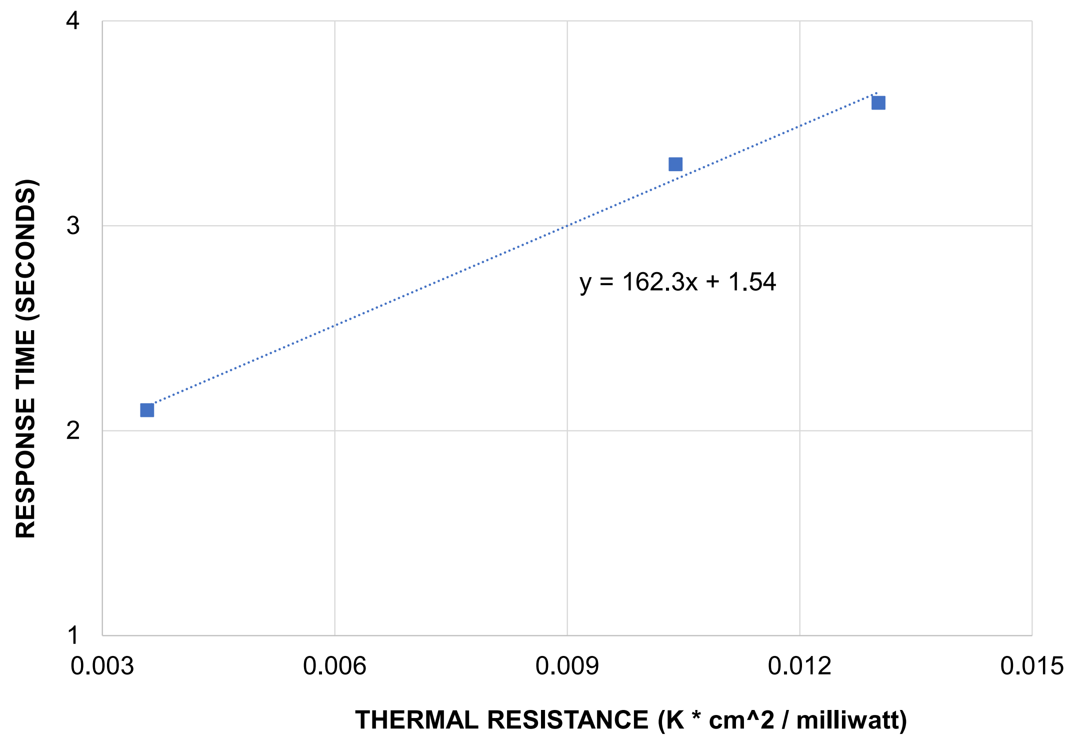

Figure 17. Bare RTD response time results plotted vs. thermal resistance of steam step tests.

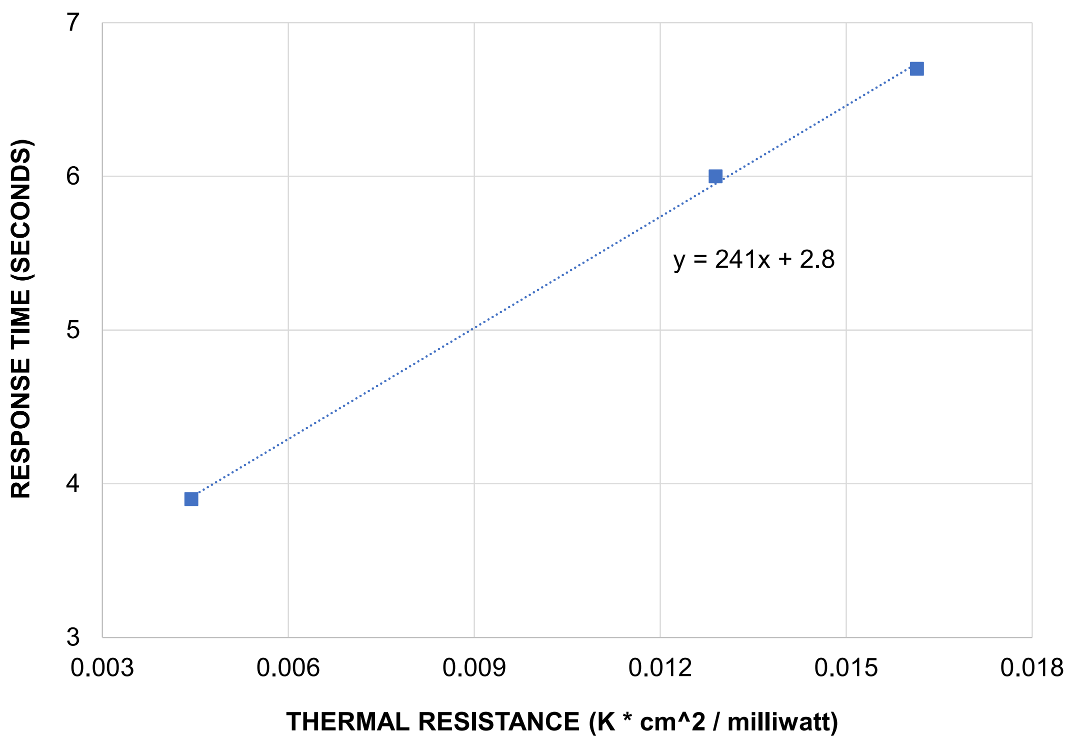

Figure 18. RTD/TW response time plotted vs. thermal resistance of steam step tests.

3.3 I&C CABLE AGING AND DERATING

Over time, exposure to harsh environmental conditions in a nuclear power plant can result in degradation and failure of I&C cables. This is especially true for the I&C cables in SMRs, which will be subjected to elevated temperatures, high radiation, and a vacuum atmosphere within the containment vessel during normal plant operation. These conditions lead to excessive ohmic heating within the cables, which further accelerates damage to the cable insulation material that can result in premature failure. Frequent cable replacement due to premature degradation is not practical or economical for SMR plant owners. To combat these environmental stressors, the ampacity of the cable must be derated. However, there is limited experience to date with cable derating in vacuum, and there is no experience with cable derating in vacuum at high temperature and radiation [6]. As a result, AMS conducted a study in coordination with the ORNL Advanced Cable, Cryogenic, & Superconducting Technology Development Facility for assessment of I&C cables operating in high-temperature vacuum pressure to determine how various insulation materials perform at conditions that emulate those anticipated in the containment of an SMR.

3.3.1 Introduction to Cable Aging and Derating

Elevated temperatures, high radiation levels, and low atmospheric pressures (i.e., vacuum) contribute to poor cable insulation performance, accelerated material degradation, and thus premature failure of cables. To assess the survivability of common nuclear I&C cable insulation materials and the need for derating of high current carrying cables under SMR containment conditions, AMS engineers designed and fabricated a heated vacuum chamber, shown schematically in Figure 19. This test apparatus allowed for multiple cables to be exposed to elevated temperature (250°C) while operating in a vacuum. The cables were physically isolated from each other to prevent thermal conduction between cables, and each had a thermocouple mounted to the cable jacket to monitor the surface temperature during testing. These cables cover a range of manufacturers, and they are constructed with common types of high-temperature insulation materials, including Kapton, silicone rubber (SR), polyether ether ketone (PEEK), and magnesium oxide (MgO). Information on each of the cables included in this testing is provided in Table 6.

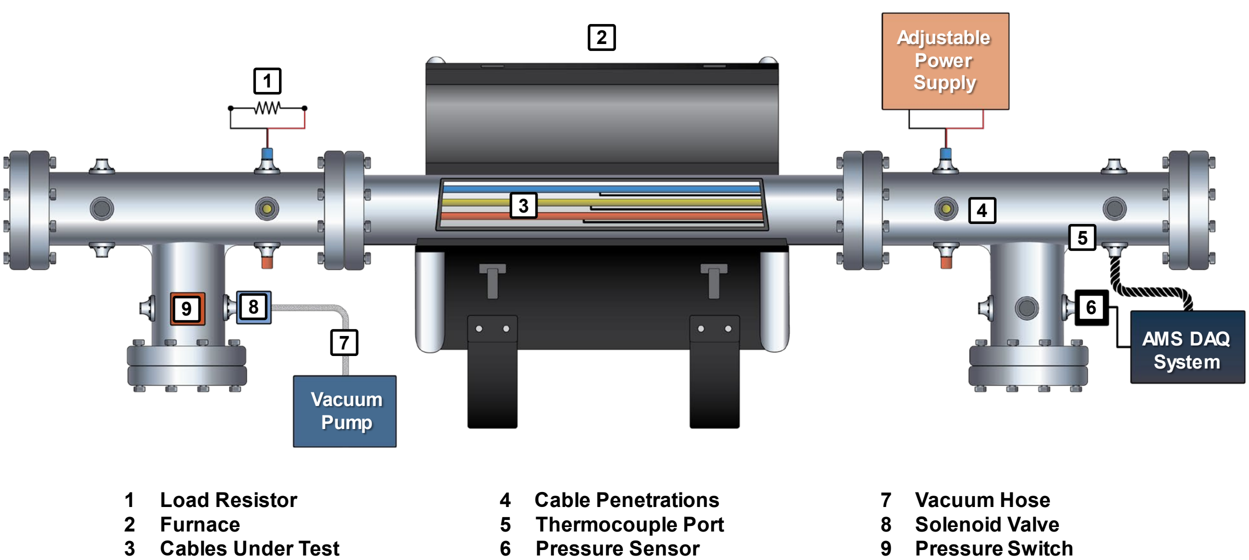

Figure 19. Diagram of AMS high-temperature vacuum chamber.

Table 6. Details of cables used for thermal aging study.

Insulation material	Number of conductors	Conductor material	Wire gauge (AWG)	Maximum rated temperature (°C)
SR-A	9	Tinned Cu	16	250
SR-B	16	Ag-Plated Cu	16	250
PEEK	3	Ni-Cr / Al	14	260
Kapton	1	Ag-Plated Cu	18	250
MgO	4	Ni 201	18	>500

To assess the need for derating of cable ampacity for operation in high-temperature vacuum, AMS performed joule heating tests in which the electrical current that passed through the cable was steadily increased, and the associated temperature rise was measured via a surface-mounted thermocouple on the outer jacket of the cable. Initial joule heating measurements demonstrated that the high-temperature vacuum environment expected in the NuScale containment vessel has a significant effect on ohmic heating. Figure 20 shows the results of the AMS laboratory tests for PEEK insulation.

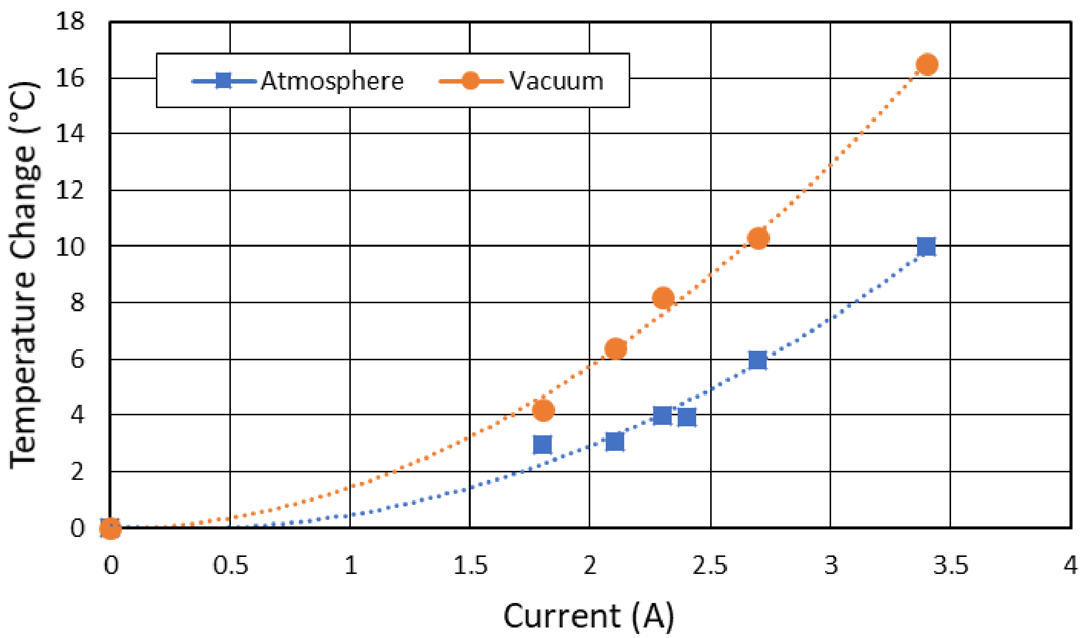

Figure 20. PEEK insulation joule heating in high temperature atmosphere and vacuum.

Although the testing at AMS provided good introductory information, the AMS custom-built chamber could only accommodate a few small gauge cables that are not representative of the high-gauge power cables required for control rod drive mechanisms and pressurizer heaters. To generate the most useful data for cable derating and to accomplish the primary goals of this work, AMS needed access to the specialized vacuum test chambers and high-current power supplies available at ORNL. The power supplies and vacuum system at the ORNL Advanced Cable Facility complement the expertise needed to assess the performance of these cable materials operating in a high-temperature vacuum with respect to temperature, current, and heat dissipation.

3.3.2 Preparation for High Temperature/Vacuum Testing of I&C Power Cables

Four candidate cables with the specifications presented in Table 7 were instrumented and mounted into the ORNL vacuum test chamber individually so that the cable performance as a function of vacuum, load current, and temperature profile could be evaluated. The ampacity of all test cables was 80 A. The environmental conditions of the I&C cables were controlled through a vacuum chamber with a nominal inner diameter of 3 inches and a length of 48 inches. The chamber was inserted into a multizone heating system with the ability to vary the heating profile along its length at temperatures at or above 250°C (Figure 21). Pressure within the vacuum space was regulated through a flow controller and mechanical roughing pump to a pressure near 1 Torr. The load current for each cable was provided from an 80 VDC 220A power supply via external connections on the vacuum chamber.

Table 7. Details of cables used for high-temperature/vacuum testing.

Insulation material	Number of conductors	Conductor material	Wire gauge (AWG)	Maximum rated temperature (°C)
SR	4	Stranded Cu	6	250
PEEK	2	Solid Cu	6	260
Kapton	2	Solid Cu	6	250
MgO	2	Solid Cu	6	>500

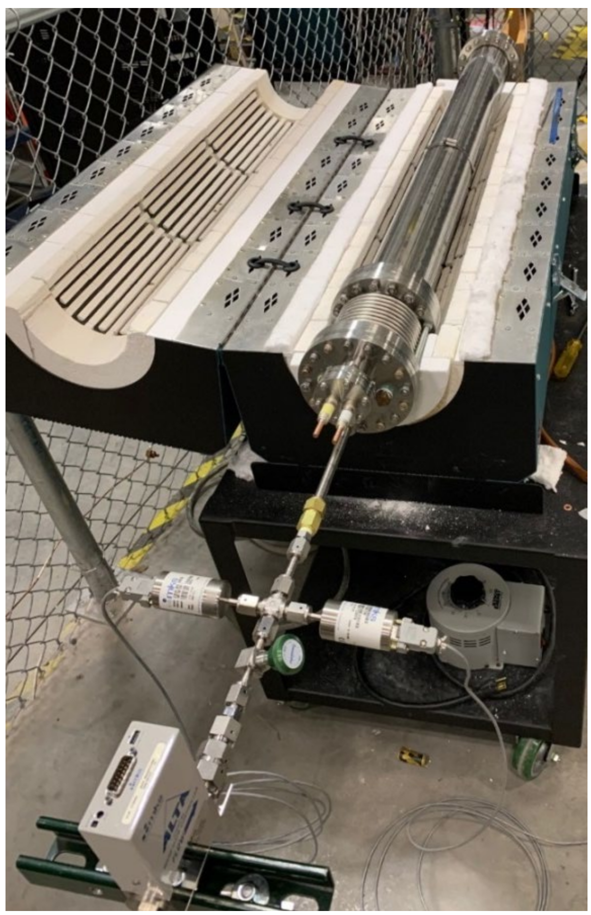

Figure 21. Vacuum test chamber at ORNL.

An individual sample of each cable type was subjected to short-term tests at all three environmental conditions. Tests at ambient temperature and pressure condition were used to establish a baseline for each cable, followed by vacuum pressure at ambient temperature, and finally vacuum at a temperature of 250°C. These tests were performed to assess the derating requirement and survivability of each sample compared to normal operating conditions. The goal was to track the temperature of the cable insulation as a function of the fraction of the rated current (10 to 100%) applied for 30 minutes at each condition to determine the level to which each cable should be de-rated with respect to its specified operating current in order to maintain safe operation. After the short-term testing was completed, additional tests were performed where 50% of rated current was applied for a duration of 7 days (168 hours) to the Peek and Kapton cable samples. Upon completion of all tests, mechanical, electrical, and chemical properties were measured to determine the extent of degradation for each cable type.

3.3.3 Results of Short-Term Testing (Derating)

Short-term testing was completed in February 2021, with some of the desired testing limited by the COVID-19 pandemic. Despite those challenges, these tests and results provide a good starting point for the assessment of cable performance in high-temperature vacuum. Results for the ambient temperature and pressure, ambient temperature vacuum, and high-temperature vacuum tests are shown in Figures 22, 23, 24, and 25 for SR, Kapton, mineral-insulated (MI), and PEEK cable samples, respectively. These results confirm the need for significant derating of current-carrying cables under high temperature vacuum conditions.

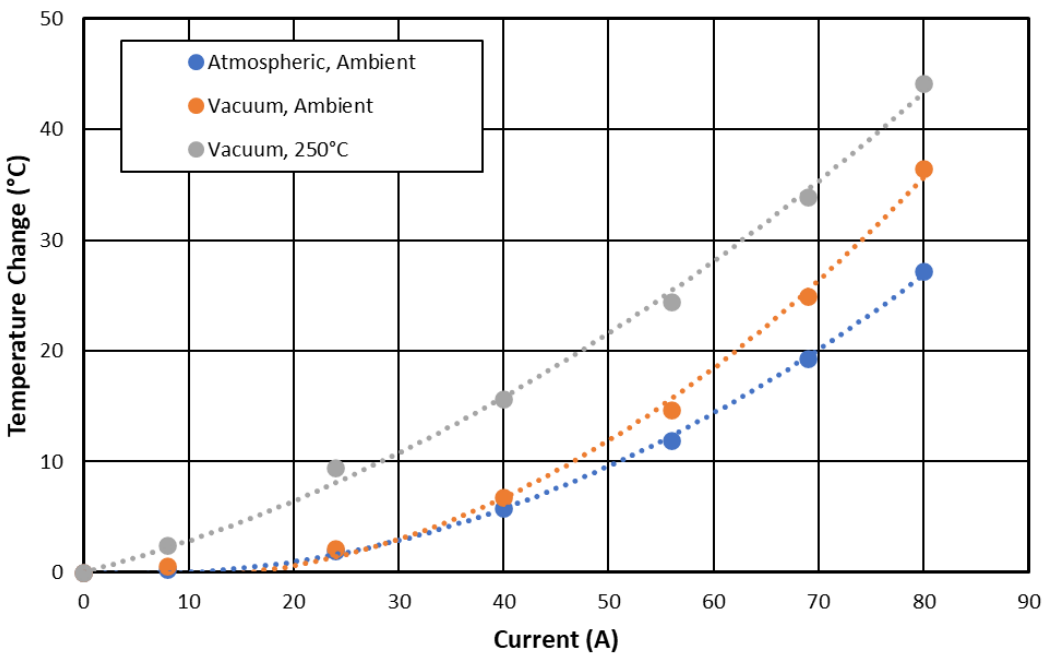

Figure 22. SR insulation joule heating in atmospheric, vacuum, and high-temperature vacuum.

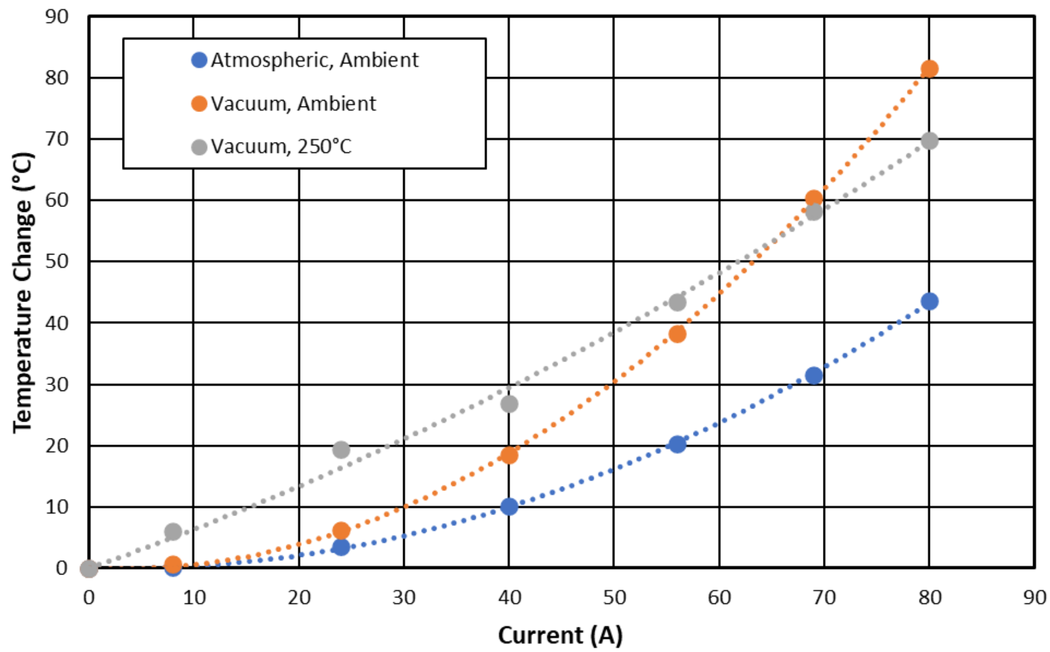

Figure 23. Kapton insulation joule heating in atmospheric, vacuum, and high-temperature vacuum.

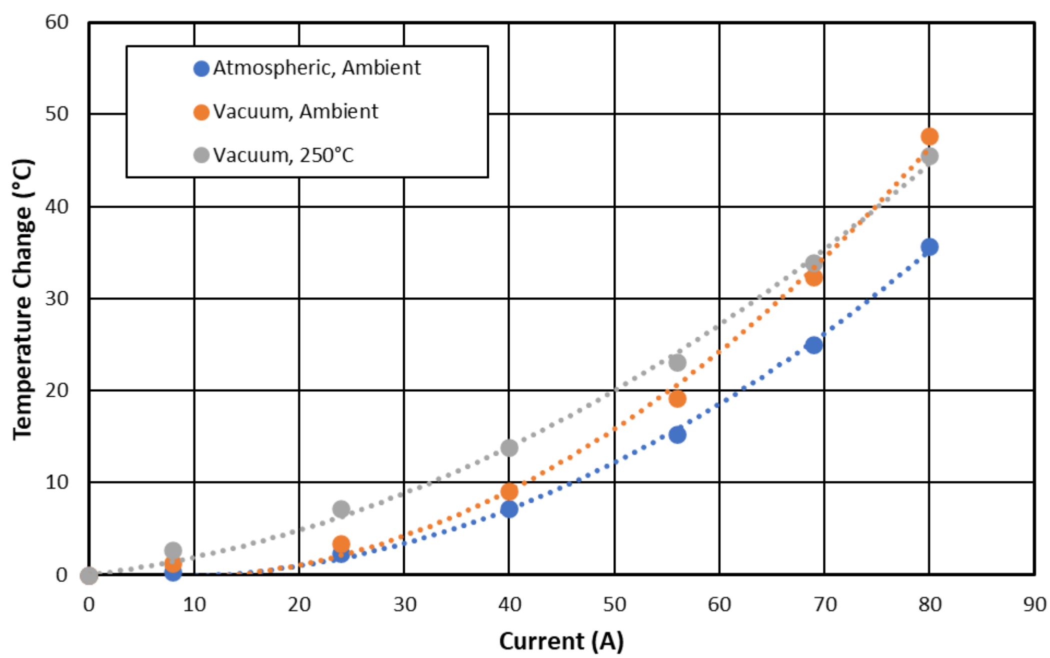

Figure 24. MI joule heating in atmospheric, vacuum, and high-temperature vacuum.

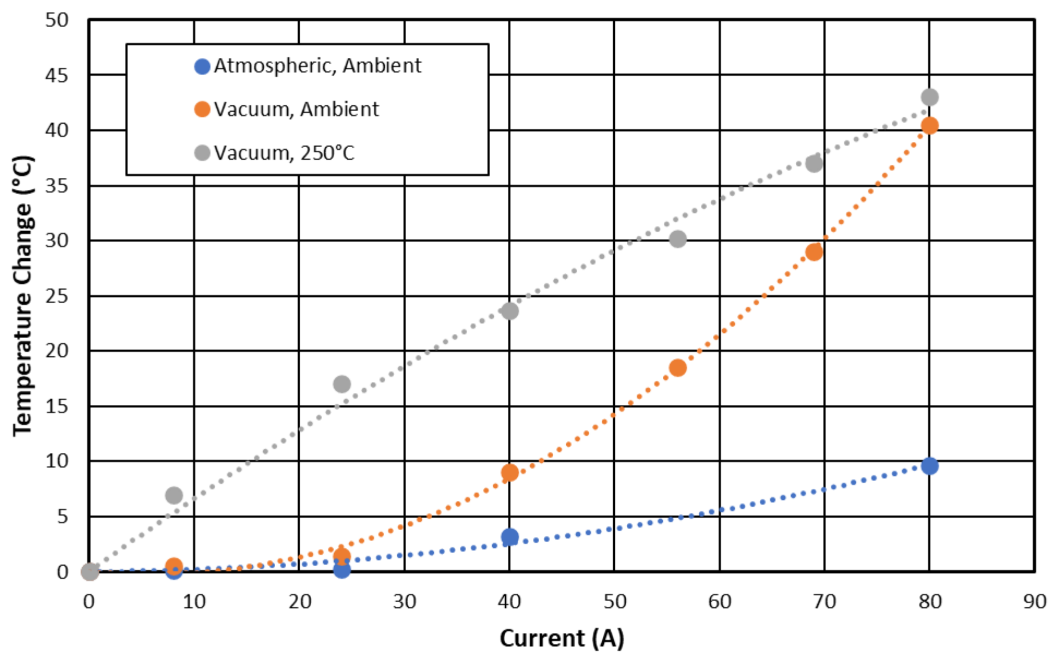

Figure 25. PEEK insulation joule heating in atmospheric, vacuum, and high-temperature vacuum.

Even though all the cables tested have ampacities of 80 amps, the temperature rise at the maximum rated current is still substantial under ambient conditions, ranging from about 10°C for the SR to 44°C for the Kapton sample. When the same test was performed under ambient temperature in a vacuum environment, the associated cable surface temperature increases were even more severe, ranging from 48°C for the MI cable to 82°C for the Kapton cable sample. Although temperature increases such as these are not problematic for most applications, when a cable is operated in surroundings approaching the rated temperature, it will require derating. Since the SR and Kapton insulation materials tested here are only rated up to 250°C, a derating coefficient cannot be determined for an operating environment of 250°C and above. Assuming a higher temperature rating of 275°C allows for a derating estimate to be obtained. Examining the joule heating curve for the SR cable (Figure 22), the current which corresponds to a 25°C increase in cable insulation temperature is around 56 Amps, or 70% of the rated current. This would indicate that for a SR cable of this construction with a hypothetical temperature rating of 275°C, the derating coefficient for a 250°C vacuum environment should not exceed 0.7. A similar analysis of the results for the Kapton and PEEK cable sample indicates that they would reach a 25°C temperature increase at around 35 amps and 42 amps, respectively, indicating derating coefficients of less than 0.44 and 0.53, respectively.

3.3.4 Results of Cable Evaluation

Each of the cable samples that were exposed to the short-term and long-term test regime were then evaluated using the following methods:

- Electrical evaluation: insulation resistance and frequency domain reflectometry (FDR)
- Visual inspection: microscopy
- Material Testing: Fourier Transform Infrared Spectroscopy (FTIR) and Thermogravimetric Analysis (TGA)
- Mass spectrometry

Over time as polymeric materials degrade, they exhibit visual signs that indicate chemical or molecular changes in the material. These changes impact the properties that govern the mechanical integrity and electrical performance of the polymer. To fully evaluate the degradation experienced by polymeric cable insulation, material testing including FTIR and TGA were used to quantify molecular changes in the material. FTIR is a vibrational spectroscopy technique that utilizes infrared absorption peaks to identify certain molecular compositions, while TGA provides several useful metrics which include the oxidation induction time (OIT) and oxidation induction temperature (OITP). A loss of mass evaluation was also performed using the TGA results.

TGA was performed here on a simultaneous thermal analyzer (STA) that increases the temperature of the specimen at a set rate to provide information on the stability of the polymers. Additional testing was performed using mass spectrometry that analyzes the gaseous byproduct of the TGA testing. This helps identify the concentration of certain atomic masses based on how those molecules or atoms behave in a magnetic field at applied currents.

Silicone Rubber

For SR, the electrical testing of the cable samples before and after all short duration tests revealed no noticeable degradation of the insulation material. Further, there were no major visual signs of degradation on the outer jacket or the inner insulation around the conductors after testing for 3 hours at currents ranging from 0 amps to 80 amps (resulting in outer jacket temperatures ranging from 250°C up to ~295°C). FTIR revealed some changes in the outer jacket insulation with no major changes to the Si-O-Si backbone of the polymer, but some in the side groups involving the CH_3, as shown in Figure 26. For the insulation that was in contact and directly exposed to the energized conductor, there were also some minor changes in the shape of the signature peaks as shown in Figure 27. For the energized conductor, the FTIR of the insulation shows an increase in the breadth of the Si-O-Si peak on the right-hand side with a decrease in the small peak on the left. This could indicate some small pendant group related changes; however further evaluation would be necessary to identify the nature of this change.

Overall, there was a slight reduction in the OITP after the short duration testing indicative of a reduction in thermal stability. These values are very small except for the energized conductor which saw a large reduction in the OITP. This is likely due to being energized and exposure to significantly higher joule heating. The difference between the baseline and the short duration for the jacket and the un-energized conductor would require further testing to establish the significance of the respective changes. OIT testing could not be performed on SR due to the inability to obtain OIT data at temperatures below the OITP. The OITP results are provided in Table 8.

Additional evaluation of the degradation mechanisms was performed using mass spectrometry to identify if any significant changes were present in the byproduct of the material during TGA up to temperatures of 500°C. Based on the results, outside of an initial evacuation of atmospheric products, nothing of any appreciable quantity was off gassed during the experimentation (Figure 28).

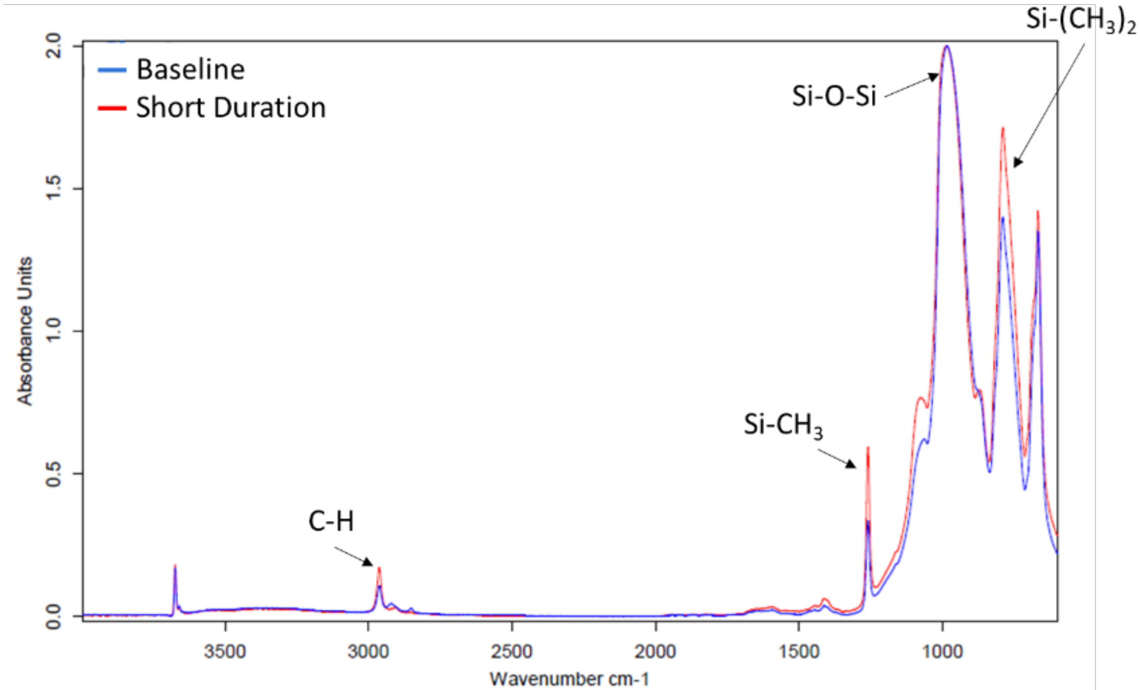

Figure 26. FTIR Data of SR Baseline and Short Duration Cable Jacket.

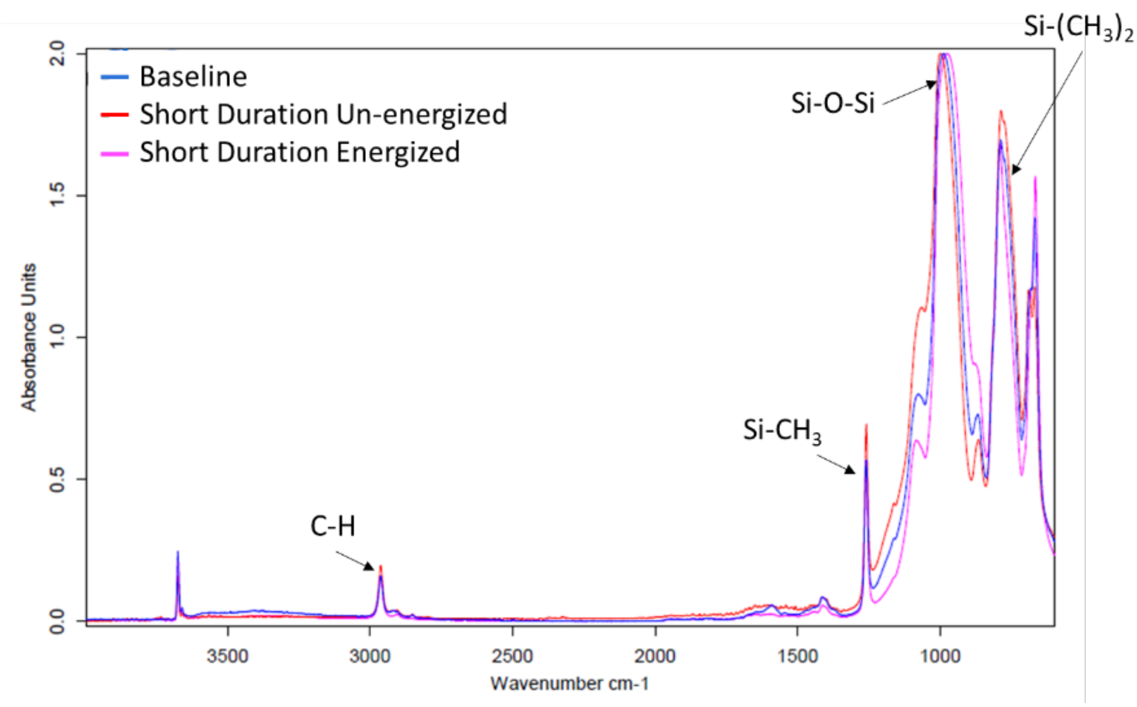

Figure 27. FTIR Data of SR Baseline and Short Duration Energized conductor insulation.

Table 8. OITP of SR.

Sample	OITP (˚C)
Baseline Jacket	378.8
Jacket Test	373.9
Baseline Conductor	366
Conductor Un-energized	365.8
Conductor Energized	346.2

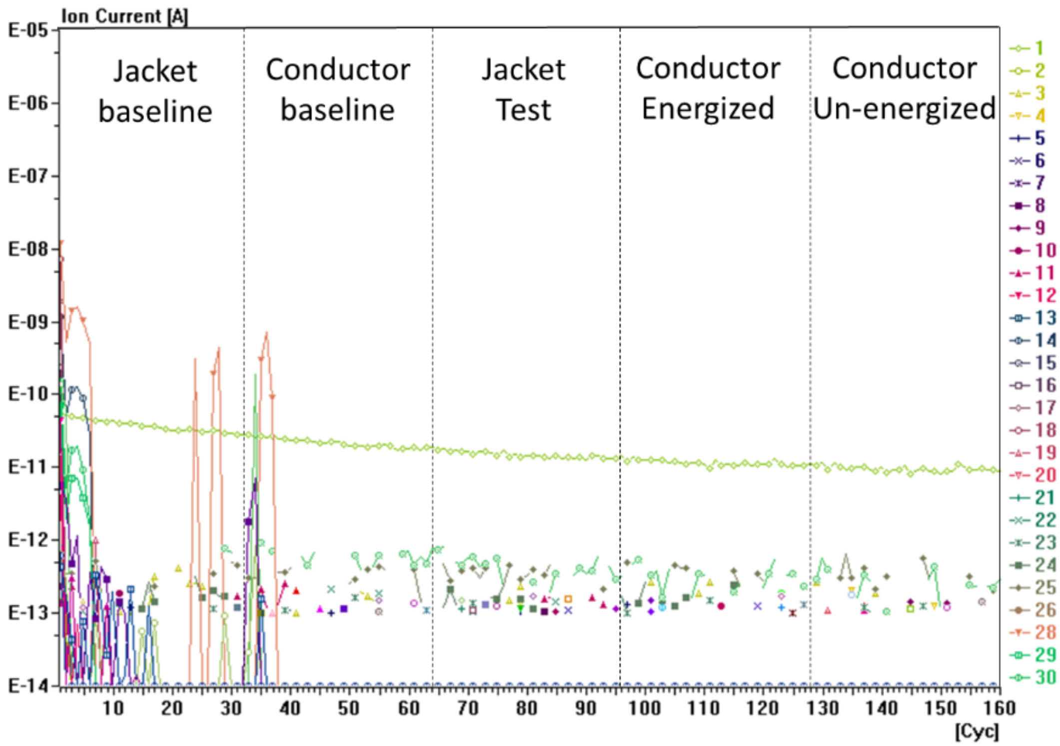

Figure 28. Mass spectrometry of SR cables.

PEEK

PEEK demonstrated some relatively significant degradation from the short duration high current applications, where the insulation was subjected to the highest temperature (up to 290°C). Despite the short duration, this elevated temperature caused significant embrittlement of the material that revealed the copper conductor beneath. This was not seen in the long duration test samples, likely due to the reduced current (50%) over the duration of that test. This visual difference was confirmed by the FTIR test, as shown in Figure 29, where the long duration and baseline material were very similar. There was a reduction in the magnitude of several peaks associated with the C-O-C bond and the aromatic rings, indicating a change in the backbone of the material and thus some amount of chain scission.

It should be noted that the insulation of this PEEK cable was very thin, likely leading to increased temperature dependent effects where more heat was directly applied to the backbone chain. Thicker polymer insulation would provide some amount of protection from this type of effect and may need to be considered when selecting cable materials for harsh environments.

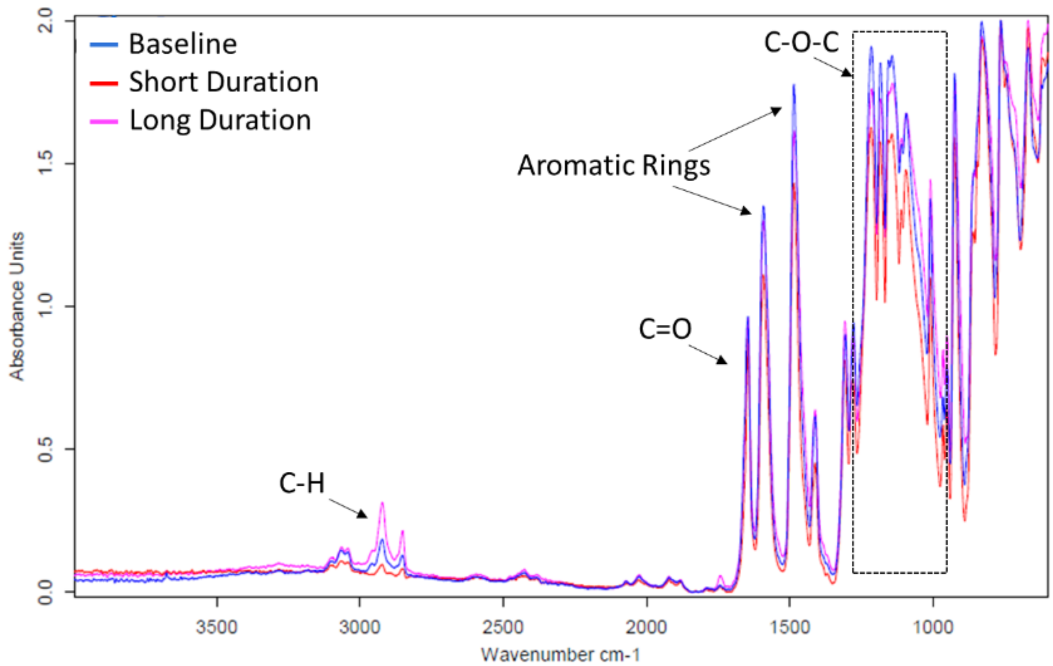

Figure 29. FTIR Data of Baseline, Short Duration, and Long Duration PEEK insulation.

For the PEEK specimens, there was only a significant change in the OITP in the short duration cable samples. This is consistent with the visual inspection where the short duration specimen was severely brittle and discolored. The reduction in the OITP for this specimen would signify a loss of thermal stability and be evidence of molecular structure changes. The OIT was relatively similar for each with a slight reduction in time of the long duration sample compared to the baseline sample. These results are summarized in Table 9.

Table 9. OITP and OIT of PEEK specimens.

Sample	OITP (˚C)	OIT (minutes)
Baseline	449.9	73.1
Short Duration	410.2	71.2
Long Duration	449.4	69.7

The mass spectrometry results for PEEK provide very little information as to what may have been off gassed where nitrogen and oxygen dominated (blue triangles and green circles) as atmospheric products flowing through the system (Figure **30**). Higher temperature experimentation would be needed to evaluate the exact products that could be expected during long duration testing.

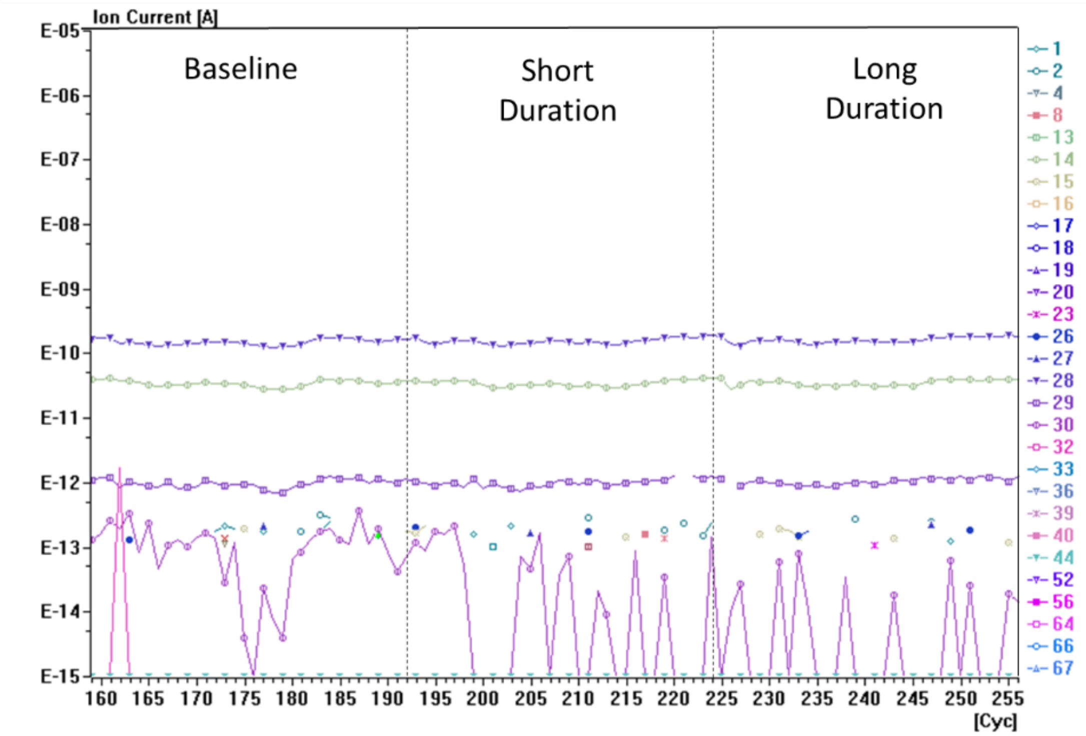

Figure 30. Mass spectrometry of PEEK.

Kapton

Kapton demonstrated very little visual change on the outer and inner insulation. Some level of embrittlement was found when cutting of material for testing, however the adhesive was still relatively well intact on both the short and long duration test samples. FTIR revealed some small changes in the outer insulation likely associated with the onset of some chain scission (Figure 31). The inner insulation material demonstrated some significant changes during the long duration testing (Figure 32). Further investigation would be necessary to identify the exact causes of these changes, however they are heavily centered on the C-O bond in the repeat unit.

OITP was performed on Kapton and very little change was seen in the OITP results indicating no major change in thermal stability. However, there was poor contact with the ceramic pan in the STA, indicated by some variability in the mass loss in the TGA. These numbers are consistent with previous results obtained by AMS on this material, however more testing is needed to validate the accuracy of those numbers. Like SR, OIT testing could not be performed on Kapton. The OITP test results are provided in Table 10.

The mass spectrometry revealed some amount of large molecules in the 40-70 atomic mass units range (Figure 33). This could be indicative of some adhesives being off gassed, but may be due to other additives. In depth analysis of the makeup of the adhesive would be needed to verify this. Further analysis at higher temperatures will need to be explored as well.

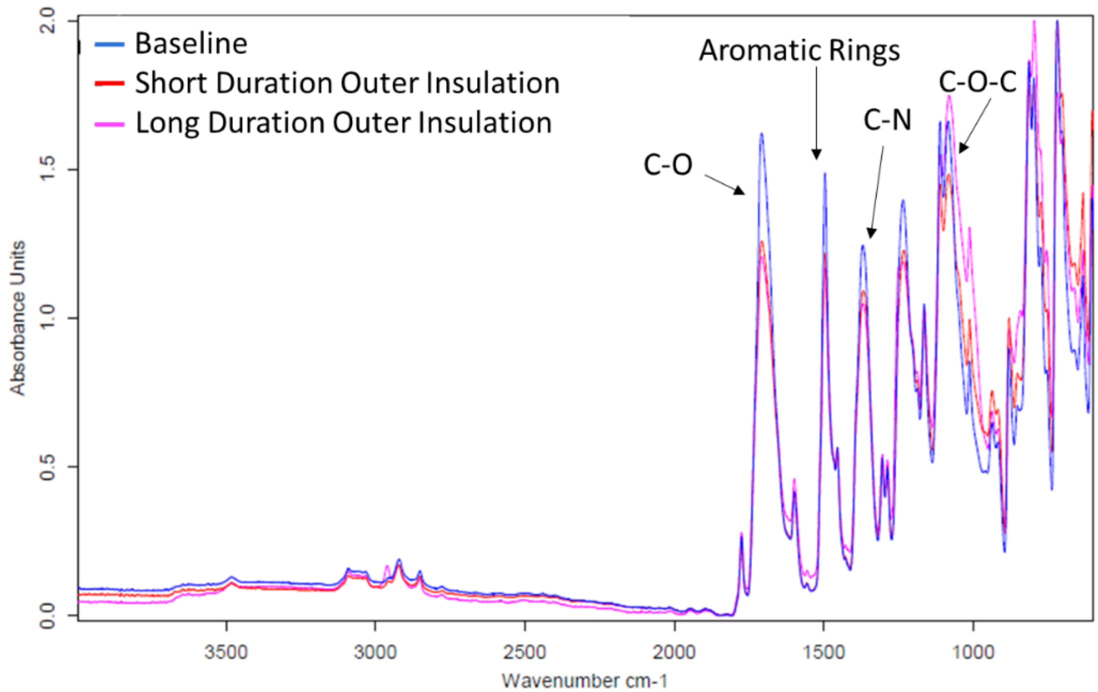

Figure 31. FTIR of Baseline, Short Duration, and Long Duration outer Kapton Insulation.

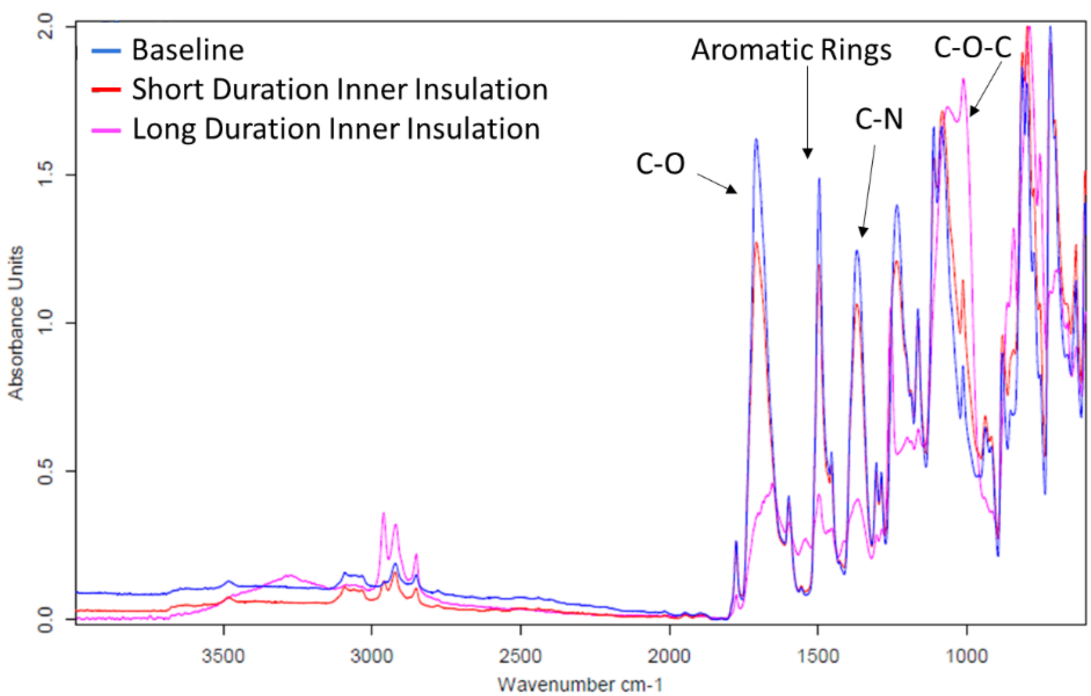

Figure 32. FTIR of Baseline, Short Duration, and Long Duration inner Kapton Insulation.

Table 10. Kapton OITP Testing Results.

Sample	OITP (˚C)
Baseline	462.1
Short Duration Inner	461.5
Short Duration Outer	459.6
Long Duration Inner	465.2
Long Duration Outer	462.4

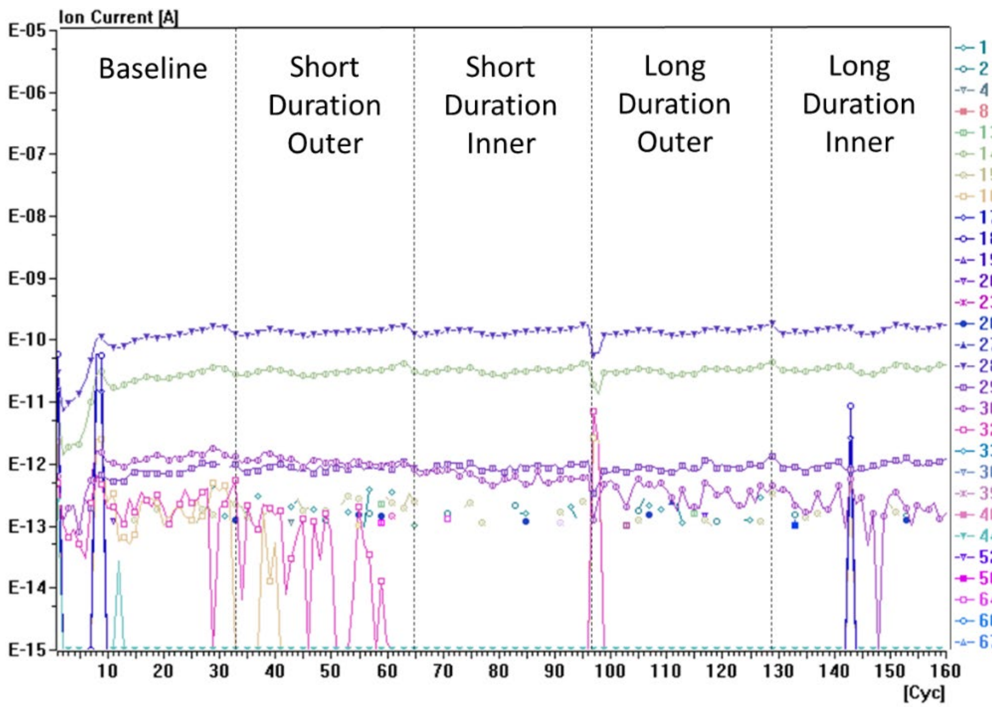

Figure 33. Mass spectrometry of PEEK.

3.3.5 Conclusions and Future Work

Cable derating is important for SMR developers seeking to utilize cables in applications close to their rated operating temperature and/or ampacity. Cables subjected to their maximum rated current in a vacuum environment reached higher surface temperatures than those operating at atmospheric conditions. The significant increase in surface temperature for both ambient vacuum and high temperature vacuum support the need for substantial derating of the cable ampacity.

The Si, Kapton, and MI cables showed very little degradation over the course of this testing. However, there was evidence of significant degradation including insulation embrittlement and cracking in the PEEK cable specimens after short-term exposure to high current and high temperatures. Due to time constraints, long term testing was limited in scope and duration. AMS recommends further evaluation of cable performance in high temperature vacuum for longer durations under full current load to fully evaluate the survivability and aging of these insulation materials. This additional work should include investigation of cable performance in high humidity and other adverse conditions in order to fully characterize various cable materials for SMR needs and other applications.

4. SUBJECT INVENTIONS (AS DEFINED IN THE CRADA)

None.

5. COMMERCIALIZATION POSSIBILITIES

The results of these activities have yielded information that will help guide the selection of RTDs suitable for safety-related temperature measurements for the NuScale NPM and Holtec SMR-160. Further evaluation and commercial testing may be required for the sensors selected for actual installation in SMRs to qualify sensor performance prior to installation.

The cable performance data obtained during this project can be used to identify any significant cable material issues as a result of operation in the NuScale NPM high-temperature, vacuum operating environment. Any cable material modifications that are needed to support operation in the NPM must be tested and evaluated to confirm acceptable performance under NPM-like operating conditions and this will provide possibilities for commercialization of testing and materials evaluation services.

6. PLANS FOR FUTURE COLLABORATION

The work performed by AMS and ORNL experts at their facilities establishes the scope of partnership needed to characterize performance of sensors and cables in the unique operating conditions of SMRs such as NuScale and Holtec. Additional collaboration between AMS and ORNL will include assessment of cables to determine the consequence of the environmental operating boundaries such as temperature, pressure, radiation, and accident scenarios that are decidedly different from current Institute of Electrical and Electronics Engineers (IEEE) 323 and 383 standards for current nuclear power plants.

7. CONCLUSIONS

The evaluation of the dynamic performance of nuclear-grade RTDs under SMR-like conditions was successfully concluded under the GAIN initiative. The RTDs tested are similar to those that will be used to measure safety-related reactor coolant, MS, and UTB temperatures in the NuScale NPM. AMS collected data from these RTDs at various temperatures and flow velocities to develop and validate correlations that have been used to estimate RTD response times at startup and normal operating conditions in the NPM and to establish approximate range of response of bare RTDs exposed to HELB conditions. The correlations developed and validated by AMS will be used to provide guidance to SMR I&C engineers and sensor suppliers on the expected dynamic performance of safety-related RTDs which are subjected to periodic response time testing to verify that plant technical specifications are met. As shown in the test results, RTD response times for SMR RCS applications are more sensitive to flow than temperature, and they are particularly sensitive to very low flows. However, the response times of RTDs used for steam applications are very sensitive to the temperature of the steam. Based on the sensitivity of the heat transfer film coefficient due to temperature, velocity, and moisture content of the steam, a range of response times can occur, depending on the conditions of the HELB.

Cable performance testing and derating for a high-temperature vacuum operating environment were also successfully completed. The resulting in-service data and subsequent materials evaluation will be used to fully assess the derating and survivability requirements for these materials. To date, preliminary results have been shared with NuScale I&C engineers and with RTD manufacturers.

8. REFERENCES

[1] Hashemian, H. M. “Sensor Performance And Reliability”. ISA - The Instrumentation, Systems, And Automation Society, 2005.
[2] Hashemian, A., Arnholt, B., “NuScale Power Module Instrumentation”, Nuclear Plant Journal, July-August 2018.
[3] Riggsbee, E., Hashemian, A., Tyler, S., Shumaker, B., “Temperature Sensor Response Time Testing in Transient Steam Environments of Small Modular Reactors”, Presented at the 2020 ANS Virtual Winter Meeting (November 16-19, 2020).
[4] “Instrumentation and Control Design for Small Modular Reactors” DOE SBIR Phase 2B Award No. DE-SC0011859.
[5] Larson, A., “Is There a Market for Small Modular Reactors?” https://www.powermag.com/market-small-modular-reactors/ (June 1, 2016).
[6] Houser, J., Hashemian, A., Tyler, S., “Derating of Instrument and Control System Cables for Small Modular Reactors”, Presented at the 38th IEEE Electrical Insulation Conference (EIC), 2020.

ACKNOWLEDGEMENTS

The activities in this report were enabled by the support provided by Adam James and Jason McLemore of Oak Ridge National Laboratory and Dr. Will Ferrell, Codi Ferree, and Patrick Ward of AMS.