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Out-of-Pile Test of LVDT-Based Creep Test Rig at PWR Prototypical Conditions

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Changing the World's Energy Future

Malwina A. Wilding
Kurt L. Davis
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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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ABSTRACT

New and improved materials are being considered to support the existing nuclear reactors and future next-generation reactors. The materials can significantly degrade and limit their properties in harsh reactor environments. To accurately understand the material's degradation, real-time data is required under prototypic-irradiation conditions. Additionally, understanding the creep behavior of materials under harsh environments is essential for an evaluation of safety concerns. To provide these capabilities, the Idaho National Laboratory's (INL's) High Temperature Test Laboratory (HTTL) has developed several instrumented test rigs to obtain real-time data from specimens in well-controlled pressurized water reactor (PWR) coolant conditions in the Materials and Test Reactors (MTRs). This technical report focuses on INL's efforts to evaluate and enhance the former prototype creep test rig that relied on linear variable differential transformers in laboratory settings. Specifically, the test rig is capable of detecting changes in the length of tensile specimen, which is useful for measuring thermal expansion and creep loading.

CONTENTS

FIGURES

TABLES

ACRONYMS

ASI	Advanced Sensors and Instrumentation
ATR	Advanced Test Reactor
DAQ	data acquisition
DOE	(US) Department of Energy
DOE-NE	Department of Energy, Office of Nuclear Energy
HBWR	Halden Boiling Water Reactor
HRP	Halden Reactor Project
HTTL	High Temperature Test Laboratory
IFE	Institute for Energy Technology
INL	Idaho National Laboratory
LVDT	Linear variable differential transformer
MTR	Materials and Test Reactor
NEET	Nuclear Energy Enabling Technologies
NI	National Instruments
PIE	Post-irradiation examination
PWR	Pressurized Water Reactor
SS	stainless steel
TC	thermocouple

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1. INTRODUCTION

Successful implementation of advanced nuclear reactors significantly relies on the performance of nuclear fuels and structural materials under extreme irradiation environments. It is a grand challenge to develop advanced materials that can withstand high temperatures, high neutron flux and fluences, cyclic variations of thermal stress, and be resistant to oxidation, corrosion, and radiation creep for over 60 years. Irradiation damage begins with the creation of primary knock-off atoms displaced by the incident high-energy particles. The interaction of these high-energy particles with a crystal lattice give rise to defects, such as interstitials, vacancies, impurities, etc. The aggregation of these point defects can cause the formation of defect clusters, such as dislocation loops, voids, etc. The irradiation-induced defects can lead to the changes of macroscopic properties like radiation-induced hardening, embrittlement, creep, and void swelling. Therefore, irradiation can significantly degrade and limit the properties of materials overtime which directly affects the longevity and safety of current and future nuclear power plants [1].

Irradiation creep is the additional strain that comes from the effects of irradiation and stress in the materials even at low operating temperatures, where thermal creep does not occur. The strain occurring in the absence of irradiation is generally called thermal creep, which begins at relatively high operating temperatures. The performance of fuel, cladding, and structural components is easily affected by dimensional instabilities caused by irradiation creep. Traditionally, the dimensional changes are determined by repeatedly irradiating a specimen to a certain displacement dose level for a defined period of time and then removing it from the reactor for post-irradiation examination (PIE). The time and labor to remove, examine, and return irradiated samples for each measurement makes this process very expensive and time consuming. However, tests with an in-pile measurement during irradiation are able to offer more control over experimental variables, more detailed results associated with the phenomena of interest, and improved accuracy relative to non-instrumented tests. Such benefits provide motivation for ongoing efforts to measure creep behavior during in-pile irradiation. Real-time creep measurement during irradiation enables the assessment of two sets of simultaneous phenomena. The first is the applied stress and displacement damage acting simultaneously under dynamic irradiation conditions, thereby changing the magnitude and spatial distribution of defect accumulation and causing the deformation behavior to substantially differ from that seen in PIE. The second is the thermal condition of the real-time test, which cannot be reproduced during PIE without once again affecting the material microstructure [2].

The INL creep test rig is based on a design developed for irradiation testing at the Halden Boiling Water Reactor (HBWR) in Norway. INL fabricated and tested an out-of-pile creep test rig as part of the Nuclear Energy Enabling Technology (NEET) Advanced Sensor and Instrumentation (ASI) program at the High Temperature Test Laboratory (HTTL). This report summarizes the status of INL efforts to develop an in-pile creep testing capability for MTRs. This rig was designed with an externally pressurized bellows to load a tensile specimen coupled with a linear variable displacement transformer (LVDT) used to detect material creep. Such a demonstration would afford an important capability to the Department of Energy (DOE) Office of Nuclear Energy (NE) programs and their stakeholders, partially replacing the testing capabilities lost along with the termination of HBWR operations. This is particularly relevant, given the plans to install water loops in the Advanced Test Reactor (ATR) I-positions in order to mimic the lost Halden capabilities [3,4,5].

2. BACKGROUND

2.1 Creep Test Fundamentals

Creep is a slow and time-dependent strain that occurs in a material subjected to a constant stress (or load) at relatively high temperatures. A typical creep curve is shown in Figure 1.

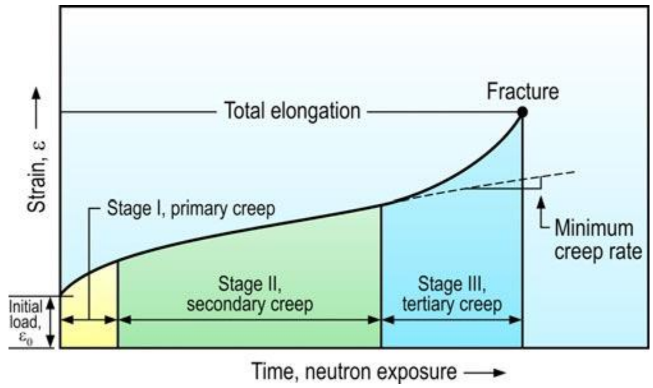


Figure 1 – Creep Curve.[6]

In a creep test, a constant load is applied to a tensile specimen generally maintained at a constant temperature, where the strain is measured over time. Primary creep (stage I) is associated with the time during which the creep rate decreases due to work hardening of the material. During this stage, initial hardening takes place, and the resistance to creep increases until secondary creep (stage II) begins. Secondary creep is associated with the time during which the creep rate is roughly constant. Stage II is referred to as steady-state creep because a balance is achieved between the work hardening and annealing processes. The slope of the curve during stage II creep is the strain rate or the creep rate of the material. Tertiary creep (stage III) occurs when there is a reduction in the cross-sectional area due to necking or an effective reduction in area due to internal void formation. The creep rate increases due to necking of the specimen and the associated increase in local stress. If stage III creep is allowed to continue, specimen fracture will eventually occur [6].

2.2 Linear Variable Differential Transformer

LVDTs are simple and reliable sensors that convert the mechanical movement of a specimen into an electrical output. A cross-section of a basic LVDT design is shown in Figure 2. As indicated, a magnetically-permeable core is attached to a specimen. The core then moves inside a tube in response to any change in specimen length or position. Three coils are wrapped around the tube: a single primary coil and two secondary coils [7].

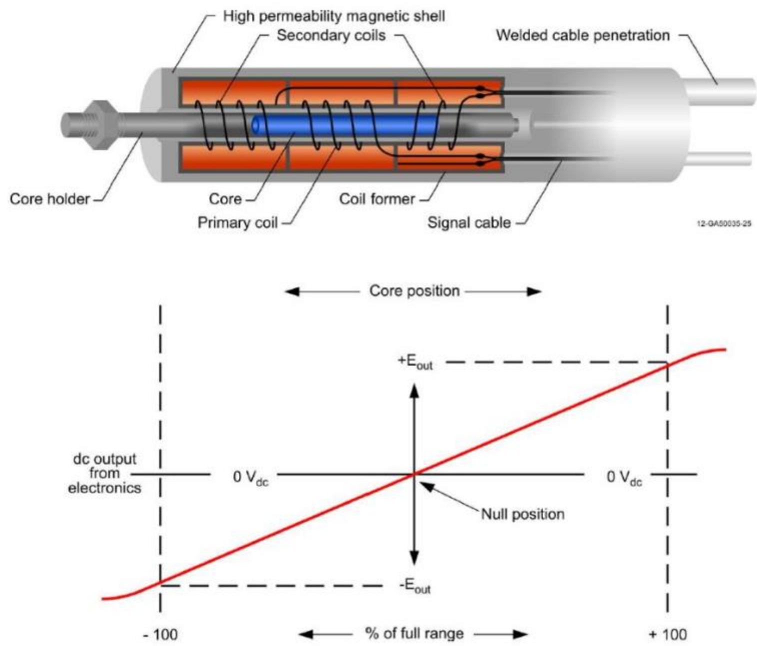


Figure 2 – LVDT design and operation. [7]

To operate the LVDT, an alternating (excitation) current is driven through the primary coil, causing a voltage to be induced in each secondary coil, which is proportional to its mutual inductance with the primary coil. As the specimen and the attached core moves, these mutual inductances change, causing voltages induced in the secondary coils to experience a corresponding change. The secondary coils are connected in reverse series; an output voltage can be conveniently derived from the difference between the two secondary voltages. Specifically, when the core is in its central position (equidistant between the two secondary coils), equal but opposite voltages are induced in the secondary coils, so the output voltage is zero. When the core is moved to its full scale mechanical position (in either the positive or negative direction) the coil nearest to the core goes full scale while the voltage in the other secondary coils goes to zero [7].

The Institute for Energy Technology (IFE) is one of the pioneers in LVDT development for in-pile testing. In an IFE LVDT Design [8], the primary coil is activated by a 400 Hz constant current generator, and the position of the core can be measured with an accuracy of ±1 µm. Since the IFE began making in-core measurements, more than 2200 LVDTs of different types have been installed in different test rigs in their HBWR. Failure rates of less than 10% after 5 years of operation are expected for their LVDTs operating in BWR or PWR conditions [7].

Currently, the INL is working with IFE directly to manufacture high-temperature LVDTs to support DOE testing needs. INL has been working to establish prioritized hardware needs, and IFE has already been supporting the delivery of sensors for various projects. Similar plans are being formulated for Fiscal Year 21 with a focus towards delivery of more sensors for experiments as well as a unique high-speed LVDT signal conditioning system [7].

3. CREEP TEST RIG

3.1 Linear Variable Differential Transformer Bellow Assemblies

The LVDT bellow assembly consists of two major components: the LVDT and the LVDT probe fixture. The LVDT was supplied by IFE/HRP, and the probe fixture was manufactured by INL. The LVDT body is made of Inconel 600 with silver alloy wire used in the construction of the coils. The probe fixture, as shown in Figure 3, consists of an LVDT ferritic core inside a housing, a bellow, and connecting hardware. Most of the probe fixture was made from Inconel 600 with the exception of the core (Type 5 provided by IFE/HRP) and the bellows (Inconel 718 provided by Miniflex Corporation). An unaged Inconel 718 bellow was selected for this assembly because of its superior mechanical properties (e.g. yield strength, ductility, and radiation resistance), although the bellows may be fabricated from other materials. The housing with connecting hardware allows the mechanism to connect movement of a specimen to the movement of LVDT core as the bellows contracts (or expands). The two types of LVDT fixtures, static and variable load, are shown in Figure 3. The static bellow assembly is designed to create a static load that corresponds to the external pressure of the coolant in the reactor. The variable load bellow design allows for a variable strain rate during reactor testing [9].

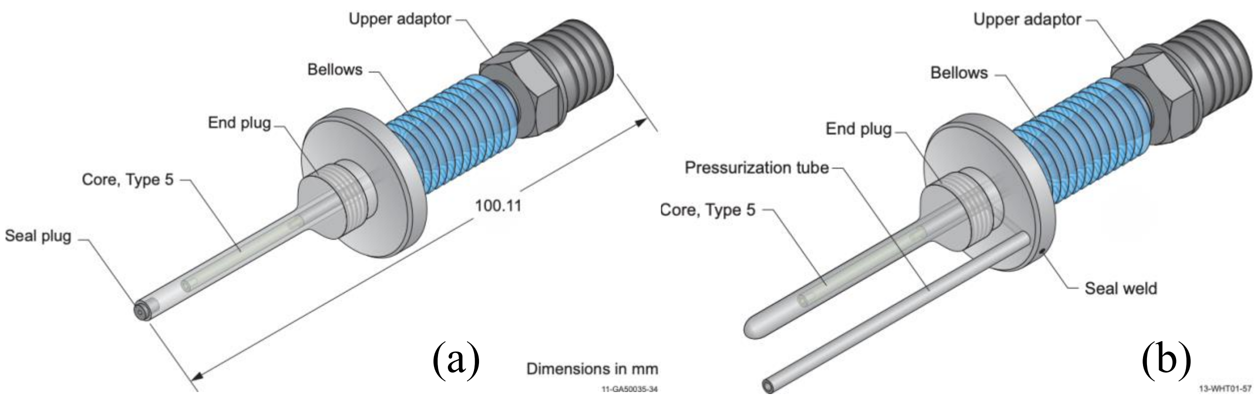


Figure 3 – LVDT probe fixture for (a) static load creep test rig, (b) variable load creep test rig.[9]

3.2 Creep Test Rig Design

The static creep test rig was initially developed to complete specimen creep testing under PWR prototypic conditions at HTTL to evaluate the performance of this design. Results from autoclave evaluations were used to finalize a test rig design for use in an ATR PWR loop [4]. The variable load creep test rig (see Figure 4) was designed and fabricated for deployment in ATR Loop 2A. This test rig was a refinement of an initial static creep test rig. Both creep test rigs are comprised of several elements, including a standard tensile specimen, LVDT to measure dimensional changes, static or variable load LVDT bellow assembly (see Figure 3), a thermocouple (TC) holder, a support structure to maintain the experiment in an in-pile environment, and a National Instruments (NI) data acquisition (DAQ) system for recording LVDT and TC signals. Lastly, the fixture is designed to constrain the LVDT bellow assembly to one end of the specimen so that the bellows contraction will place the specimen in tension. Cables extending from the LVDT and TC relay measurements of elongation and specimen temperature, respectively, monitored live during irradiation with the NI DAQ system [7].

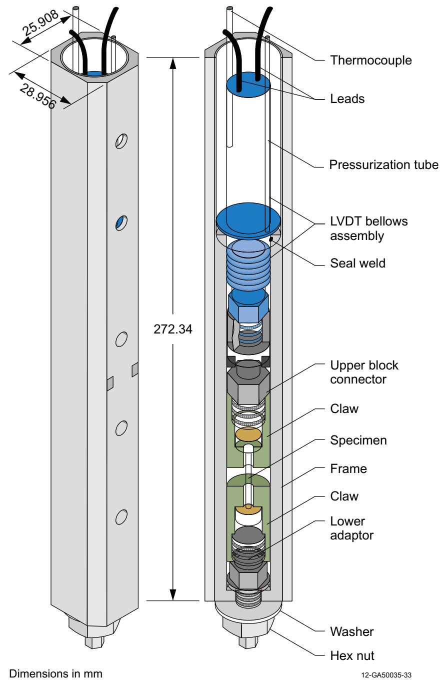


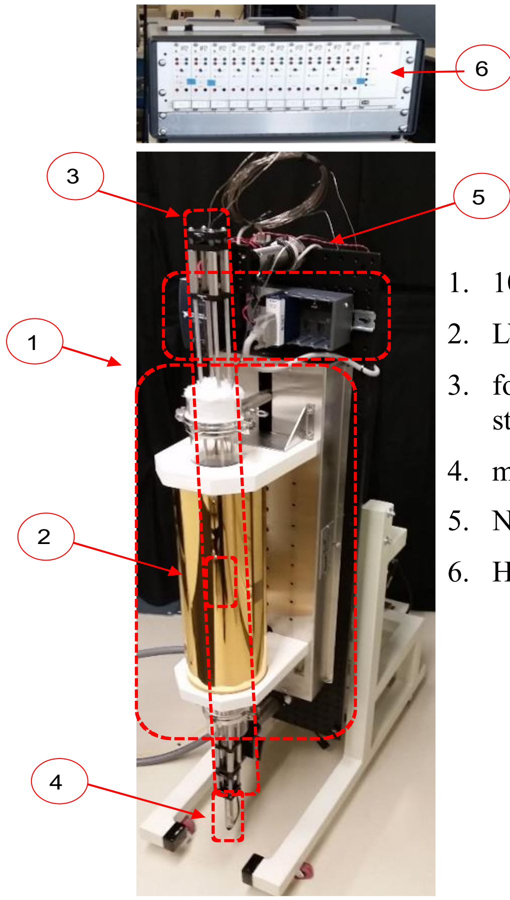
Figure 4 – Variable load Creep Test Rig design.[9]

4. CALIBRATION EQUIPMENT

4.1 Linear Variable Differential Transformer Calibration System

The LVDT calibration system was designed to apply a known relative displacement between the LVDT coil and its ferritic core. The known displacement allows other system variables (primarily temperature) to be varied in order to characterize and optimize the LVDT performance for a particular target environment. The physical system to perform these studies (see Figure 5) consists of:

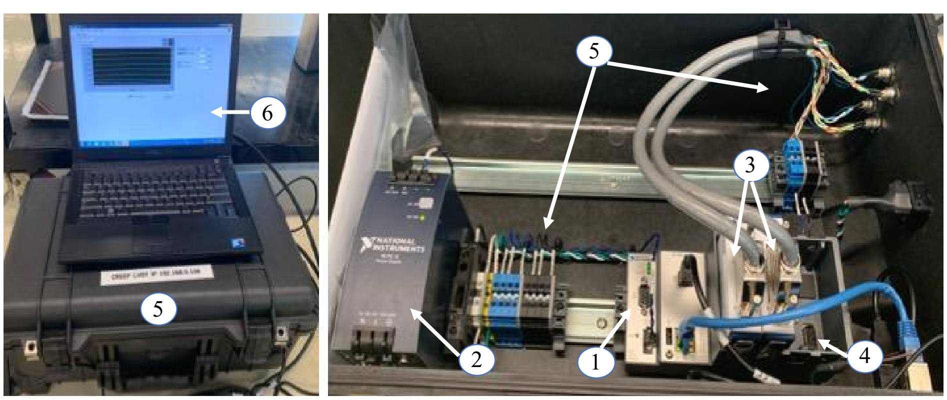
1. 1000°C tube furnace
2. LVDT and its ferritic core
3. four rod cage structure
4. micrometer to drive precise system displacement
5. NI DAQ system to measure LVDT output voltage and TC data simultaneously via LabView programming
6. Halden DAQ system.



1. 1000°C tube furnace
2. LVDT
3. four rod cage support structure
4. micrometer
5. NI DAQ system
6. Halden DAQ system

Figure 5 – LVDT calibration system located at HTTL.

The furnace can operate at a maximum temperature of 1000°C. Its tube dimensions are 75 mm ID x 80 mm OD x 815 mm long, and the base is supported by a linear actuator (driven by a stepper motor), which rotates a bearing at the center of the furnace base. The configuration allows the system to achieve conventional horizontal orientation and vertical orientations as more rarely applicable intermediate angle orientations. The cage structure (shown as number 3 in Figure 5) was designed to retain the LVDT components in the furnace tube and achieve reliable micron level relative motion described in the calibration results section of this report.



1. cRIO 9063
2. PS-16 Power Supply
3. SET 9312 LVDT Demodulator (2)
4. Open spot for the NI 9210 TC Module
5. Supporting hardware for compact NI DAQ
6. LabVIEW programming

Figure 6 – NI DAQ system.

The National Instrument's DAQ system (Figure 6 & number 5 in Figure 5) was employed to not only automate the data recording process but also to find an alternate DAQ system to Halden's system that can be purchased here in the U.S. This system allows for real-time communication with the actuated micrometer's driver, multiple LVDTs, and TC signals. LabVIEW programming was developed that would allow the incremental progression of the LVDT's ferritic core between an initial position, an end position, and back to the original position for the LVDT calibration system. The NI DAQ system consists of a compact cRIO 9063, an NI PS-16 power supply, a SET 9312 LVDT Demodulator to read the LVDT output voltage, an NI 9210 TC Module to read the TC signal, and supporting hardware, depending on if it is for the HTTL calibration or specific experiment' measurements. Therefore, this DAQ system is very customizable to a specific experiment and easily converted to a compact case for running measurements anywhere from a lab setting to a reactor's experimental room.

4.2 Autoclave

The accuracy of the creep test rig (see Figure 4) was evaluated using an autoclave system at HTTL. Figure 7 shows the autoclave and supporting equipment layout for creep test rig evaluations. The autoclave was designed for operation at a maximum allowable working pressure of 22.75 MPa at 454ºC. A pressure relief valve, currently set at 19.31 MPa, prevents the overpressurization of the autoclave. The heater is controlled by a proportional-integral derivative controller, which uses a thermocouple inserted into the thermowell to detect and control temperature. An over-temperature TC, which is located between the heater and the vessel body, shuts off the heater if the vessel temperature exceeds the user-specified high temperature limit. The sub-cooled water pressure is maintained by a high-pressure pump, which will run throughout each experiment. The system pressure is controlled by a back-pressure regulator, which is manually set for the specific experiment. A vent valve is used to manually vent the air as the system fills and also to vent air that is released from the solution as the water heats up. Instrument leads from the device being tested exit the autoclave through appropriately configured Conax fittings [5].

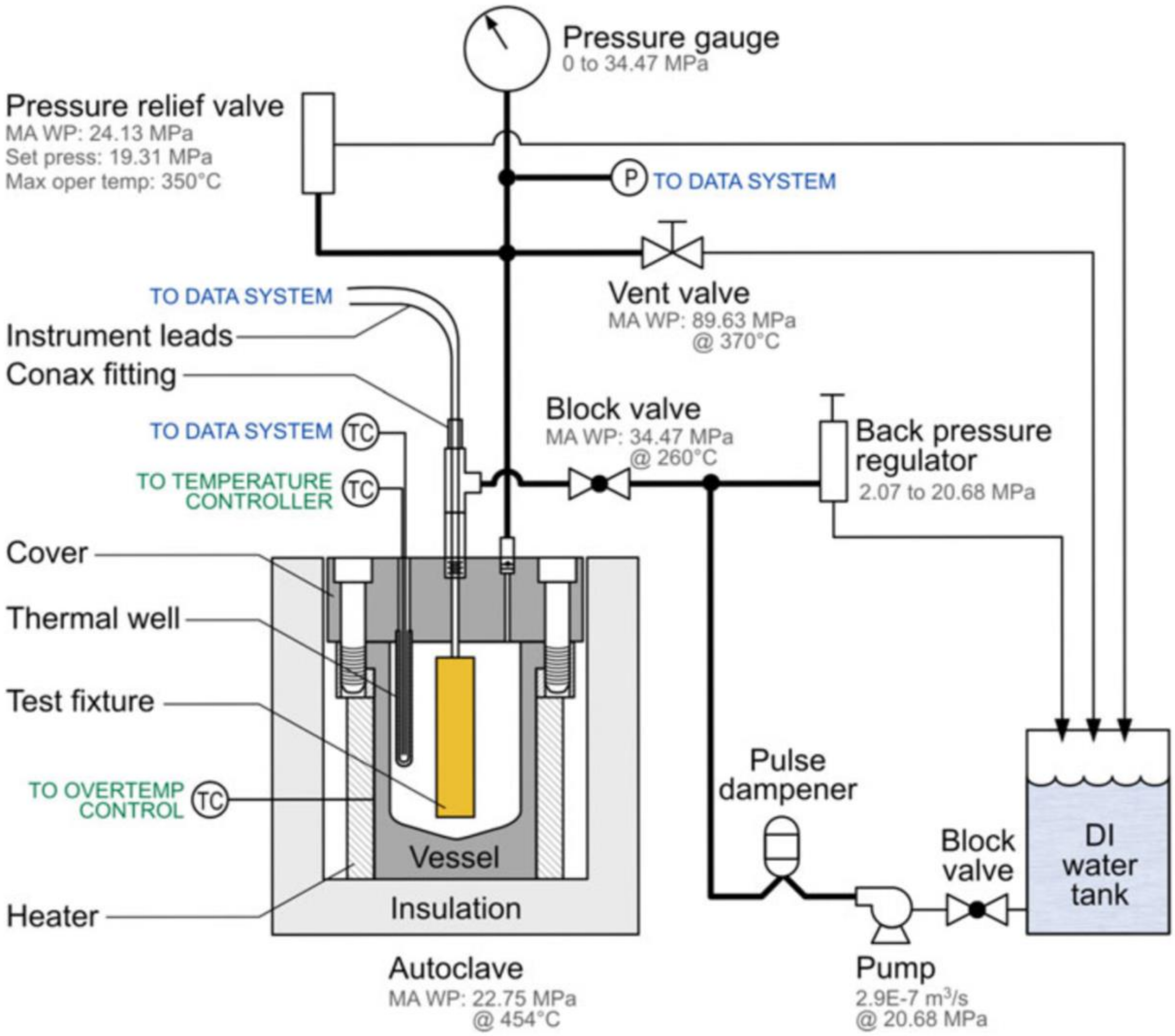


Figure 7 – Static autoclave and supporting equipment layout.[5]

5. CALIBRATION RESULTS

The LVDT bellow assemblies must be calibrated over the range of temperatures that could be expected during deployment in the PWR coolant conditions. This required calibration provides the means to relate any measured LVDT output voltage to a corresponding displacement. Because internal pressure in the variable load LVDT bellow assembly was not required, the internal pressure line was capped during calibration. Calibration was completed at room temperature and at 100°C, 200°C, and 300°C. This temperature range is expected to adequately cover operating conditions of interest during PWR conditions. Benchtop and autoclave calibrations at room temperature, 100°C, 200°C, and 300°C were completed. That way, a degree of confidence was achieved relative to the validity of all autoclave testing. Additionally, each benchtop and autoclave testing were done using both the Halden DAQ and NI DAQ, systems to verify the NI DAQ system as a reliable option. Complete details associated with this calibration efforts are discussed in the remainder of this section.

5.1 Benchtop

The benchmark evolution was done using the LVDT calibration system (see Figure 5) at room temperature, 100°C, 200°C, and 300°C. Both DAQ systems (Halden and NI) were used for comparison purposes. The LVDT and ferritic core were placed inside the inner cage, and the tube furnace was placed in a vertical orientation with the manual micrometer protruding from the bottom. This orientation allowed the weight of the inner cage, in combination with the force from the restoring springs, to maintain intimate contact between the inner cage's end plate and the micrometer despite the direction of travel. A maximum displacement of an LVDT is +/- 2.5 mm, so the data was collected in 0.25 mm intervals, as shown in Figure 8 and Figure 9. However, the anticipated maximum range of travel for this LVDT in the creep test rig is about 2.29 mm.

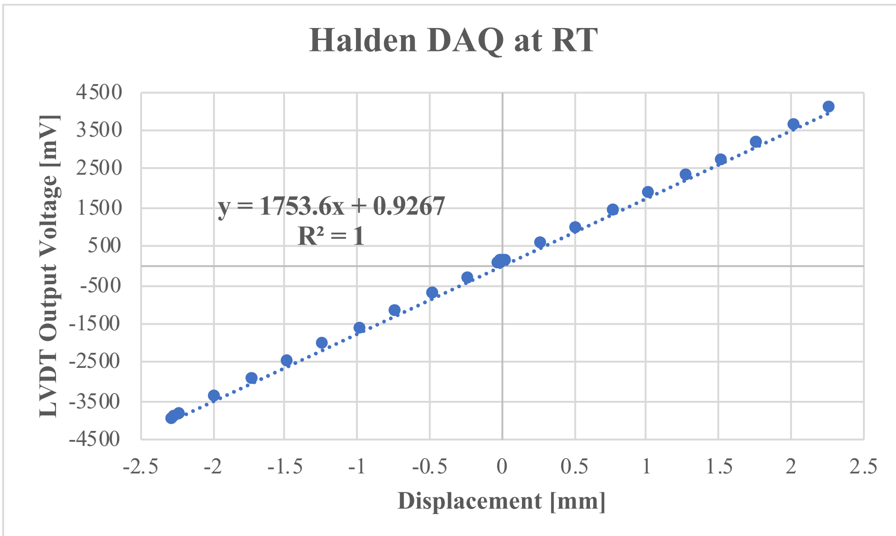


Figure 8 – LVDT calibration results using the Halden DAQ and LVDT calibration system at room temperature.

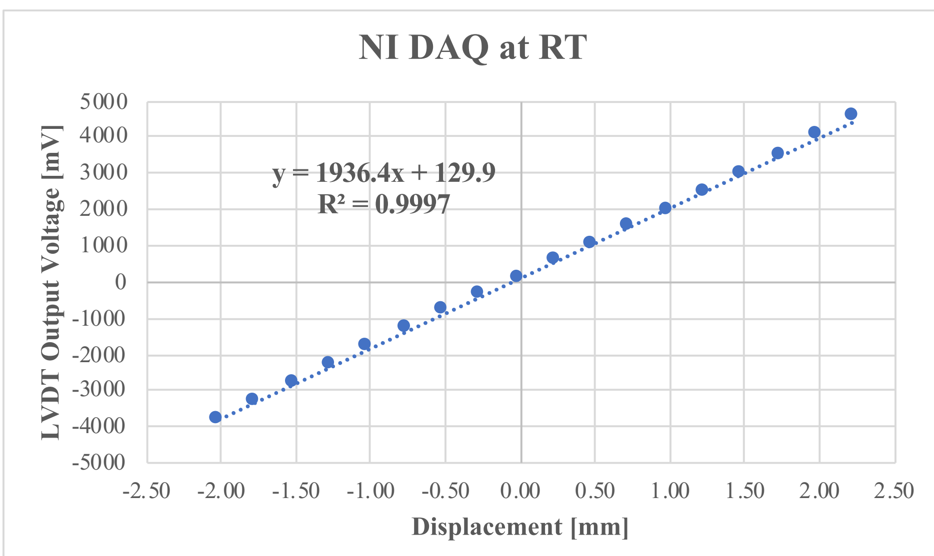


Figure 9 – LVDT calibration results using the NI DAQ system and LVDT calibration system at room temperature.

Data was averaged for each position using the NI and Halden DAQ systems. Both figures, Figure 8 and Figure 9, show the averaged data with a linear curve fit that intercepts the null position. The slope of the curve, which is equivalent to the LVDT sensitivity, indicates a sensitivity of 1.754 V/mm for Halden DAQ and 1.936 V/mm for NI DAQ. Published data suggests that, for this type of LVDT, sensitivity should range from 1.6 to 2.2 V/mm for acceptable operation [10]. Because the sensitivity was within acceptable limits, it is believed that the LVDT is functioning correctly for both DAQ systems.

Table 1 – LVDT calibration sensitivity using Halden and NI DAQ systems.

Temperature [ºC]	Sensitivity [mV/mm]	
	Halden DAQ	NI DAQ
20	1753.6	1936.4
100	1756	1951.1
200	1752.6	1955.8
300	1753.3	2046

A change in temperature can change the sensitivity of the LVDT, as shown in Table 1. Thermal expansion may have an effect on the operation of the test rig at elevated temperatures. Mechanical wear will impact test rig accuracy, as well as the magnetic fields induced by the furnace coil on the LVDT's primary and secondary coils. The same number of data points were collected at 100°C, 200°C, and 300°C as were collected for the room temperature evaluation discussed above. Evaluation of this data at 100°C resulted in a sensitivity value of 1.756 V/mm for Halden DAQ and 1.951 V/mm for NI DAQ systems. These sensitivities are very close to the sensitivity of the LVDT at room temperature (see Table 1) and suggested that temperature effects to the LVDT were negligible from room temperature to 200°C (Table 1). Looking at the 300°C results, it seems that the NI DAQ has a much higher change in sensitivity compared to the Halden DAQ. The Halden DAQ system shows superior performance with minimal effects from temperature; therefore, further testing at elevated temperatures is required to verify the NI DAQ system.

5.2 Autoclave

Autoclave testing was considerably more complex than benchtop testing because of difficulties in measuring displacement inside the autoclave. Those difficulties were addressed through the design and fabrication of a specialized fixture with positive mechanical stops to accurately define a displacement. The components and assembled fixture are shown in Figure 10 [9].

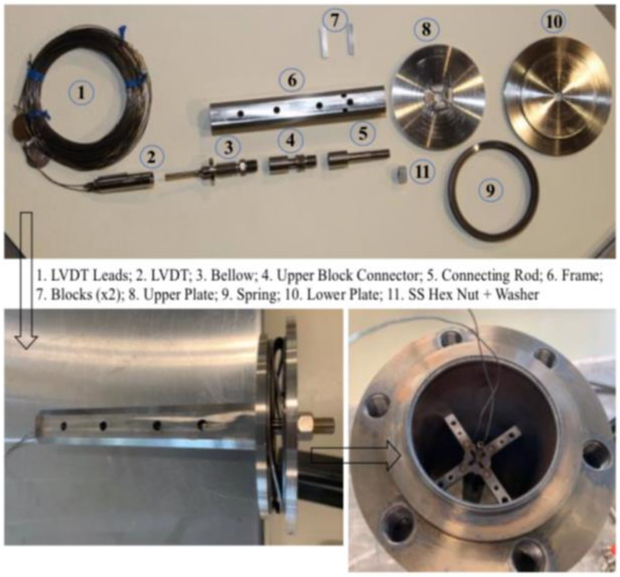


Figure 10 – Autoclave testing using calibration fixture.

The calibration fixture is assembled by first threading the LVDT probe assembly into the LVDT. The travel adapter is then threaded onto the bottom of the probe assembly, and the extender is threaded onto the bottom of the travel adapter. Those assembled components are then lowered inside the frame to a point where the flange on the LVDT probe assembly rests on a shoulder internal to the frame. The frame shoulder is positioned so that the top of the travel limiting recess (number 4 in Figure 10) is just slightly above the travel block slots in the frame. After the travel blocks are inserted in the travel block slots, the spring and spring plates are stacked on the bottom of the frame and secured with the retaining and lock nut [9].

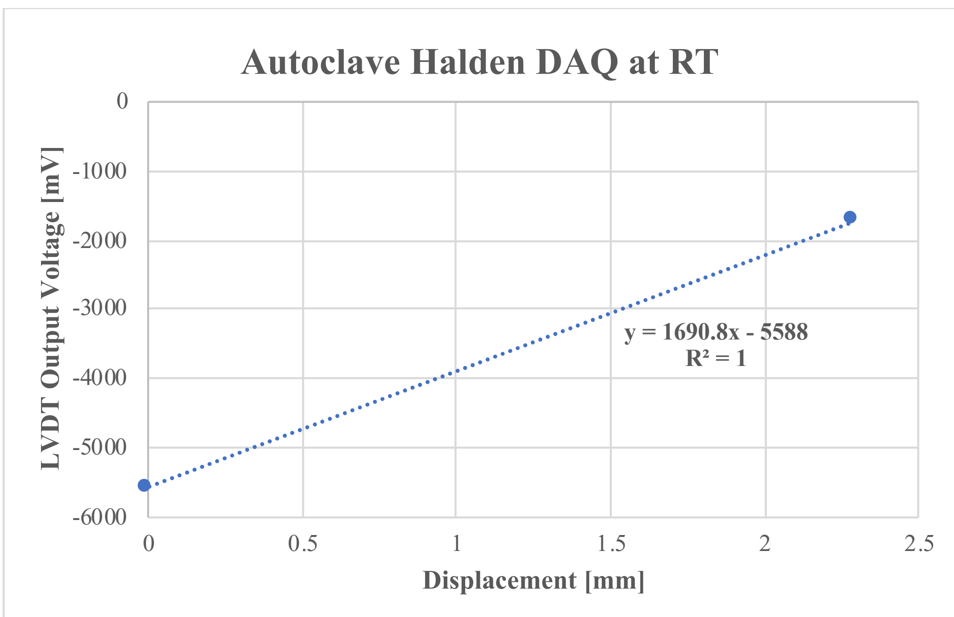


Figure 11 – Autoclave calibration testing using Halden DAQ at room temperature.

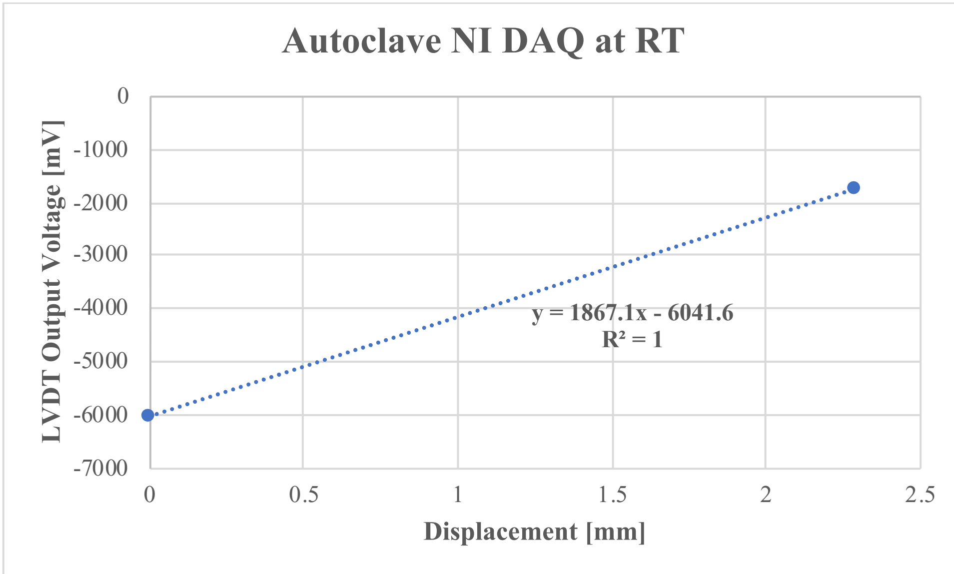


Figure 12 – Autoclave calibration testing using the NI DAQ system at room temperature.

The autoclave calibration fixture was assembled with the retaining nut tightened just enough to stretch the bellows very slightly and pull the top of the travel limiting in the upper block connector into the contact with the travel blocks. That provides the initial position of the LVDT for the autoclave testing, and, as the pressure increases, the bellow compresses, changing the LVDT output voltage. At some autoclave pressure, the bellow will stop compressing due to the limiting travel blocks stopping the upper connector movement that defines the final LVDT output voltage. The maximum movement of the bellow is 2.29 mm, which will relate to the final LVDT output voltage. Also, the maximum workable pressure range for the autoclave is 2,500 psia in a deionized water environment. Results from calibration tests at room temperature and at 100°C, 200°C, 300°C are summarized in Table 2 for autoclave calibration testing. The sensitivity between the benchtop and autoclave calibration testing differ from each other due to using two different ferritic cores with the same LVDT. Autoclave testing further confirmed that LVDT signal changes with increasing temperature for both DAQ systems (NI and Halden).

Table 2 – Autoclave LVDT calibration sensitivities using Halden and NI DAQ systems.

Temperature [ºC]	Sensitivity [mV/mm]	
	Halden DAQ	NI DAQ
20	1690.8	1867.1
100	1696.9	1885.5
200	1709.2	1907.3
300	1752.4	2045

6. CREEP TEST RIG VERIFICATION

Test objectives include the following steps:

- Test rig verification to make sure it can withstand elevated temperatures and pressures
- Verification of signal processing equipment
- Gain insights for finalizing the design for deployment into MTRs.

To address the first two objectives, a Type 304 stainless-steel (SS) specimen, with a gauge diameter of 2 mm and a gauge length of 27.99 mm, was loaded into the creep test rig inside the autoclave (see Figure 13). Instrument indications for temperature and the LVDT output voltage were noted using both DAQ systems, NI and Halden, while the autoclave temperature and pressure remained at normal conditions. The autoclave temperature and pressure were then gradually increased and ultimately stabilized at 300°C and 2,500 psi. The corresponding instrument indications for temperature and the LVDT output voltage were again noted using both systems, NI and Halden DAQ. When the system stabilized, the NI DAQ system was used to record the LVDT output voltage and TC signal for 1 hour with 15 second intervals at 2,500 psi and 300ºC (see Figure 14). Additionally, once the test was completed the SS 304 specimen measurements based on the recorded LVDT output using both, NI and Halden DAQ systems, were compared with caliper measurements. The results indicated that the final gauge length was 28.92 mm (3.32% change in length) using the caliper, 28.95 mm (3.45% change in length) using the Halden DAQ, and 29.00 mm (3.80% change in length) using the NI DAQ. Accordingly, the disparities between the NI DAQ and caliper measurements with respect to final lengths were found to be the biggest between all; however, they are still very small differences of only ~0.5%. Hence, both of the LVDT DAQ systems were in close agreement with caliper data given the measurement techniques that were used.

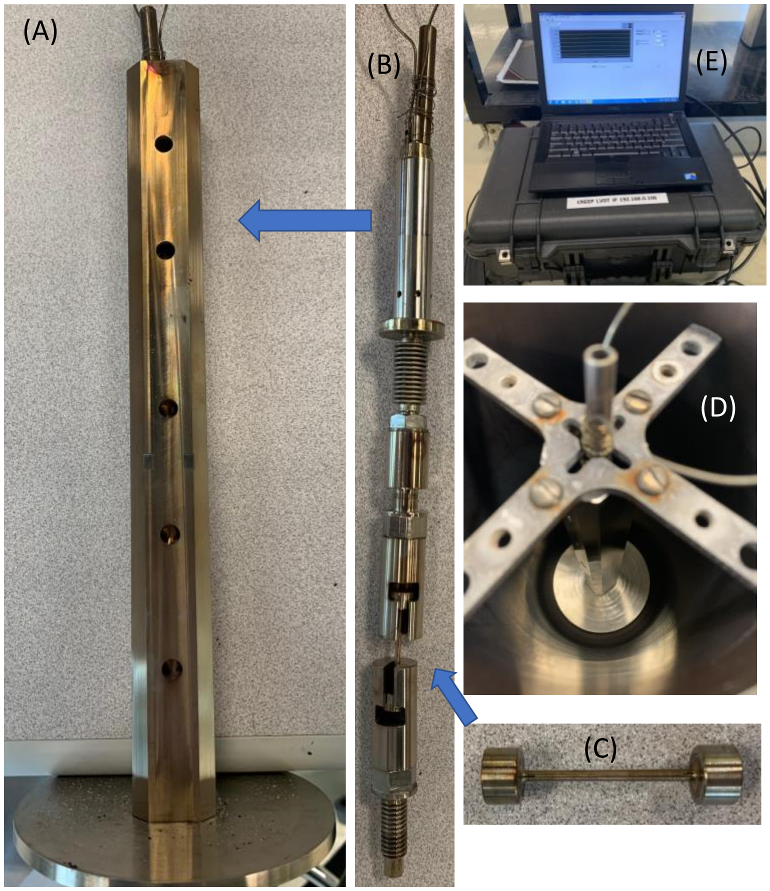


Figure 13 – Verification testing of Creep Test Rig with SS 304 sample: (A) Creep Test Rig ready for testing, (B) components of the Creep Test Rig, (C) standard SS 304 specimen, (D) Creep Test Rig positioned in the static autoclave, and (E) NI DAQ system.

This verification testing provided indications that the creep test rig functioned as designed and that the creep test rig can withstand the PWR coolant conditions. In addition, the NI signal processing equipment operated properly, where the LVDT signal stayed the same even with a slightly decreasing temperature (see Figure 14). Note that the LVDT output signal is sinusoidal as you can see using the NI DAQ, this might be due to the external noises coming from running the autoclave (i.e. high-pressure pump and/or pulse dampener). Further autoclave NI DAQ system testing is required to fully understand this sinusoidal response.

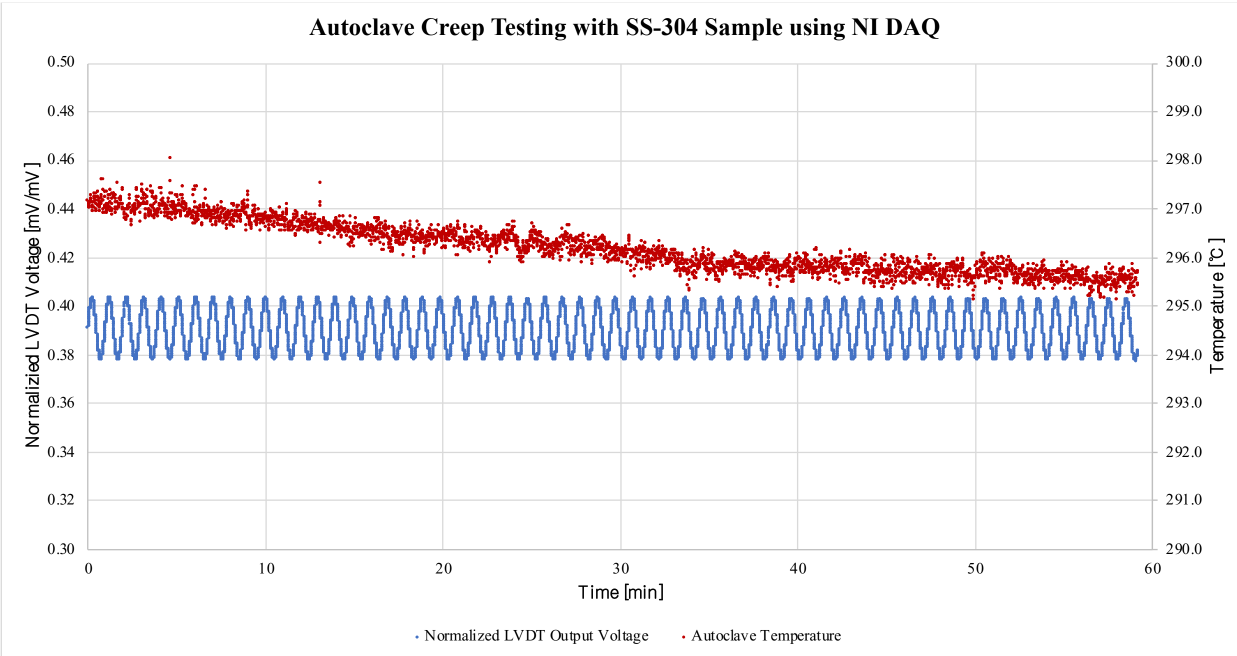


Figure 14 – NI DAQ verification testing for Creep Test Rig with 304 SS sample.

7. SUMMARY

As part of the NEET ASI, an instrumented creep testing capability was developed by the HTTL team to allow specimens to be tested during irradiation in PWR coolant conditions. Results from the laboratory evaluations were used to finalize recommendations for an enhanced design that will be inserted into the flowing autoclave. Although, the INL-developed creep testing capability will ultimately be used for a wide range of materials, initial efforts focused on Type 304 stainless steel verification testing. In summary, testing of the in-situ creep test rig confirmed the availability for deployment and will partially replace the testing capabilities lost along with the termination of HBWR operations.

8. Acknowledgement

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