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EVALUATION OF LVDTS FOR USE IN ATR IRRADIATION EXPERIMENTS

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ABSTRACT

New materials are being considered for fuel, cladding, and structures in next generation and existing nuclear reactors. Such materials can experience significant dimensional changes during high temperature irradiation. Currently, these changes are determined by repeatedly irradiating a specimen for a defined period of time in the Advanced Test Reactor (ATR) and then removing it from the reactor for evaluation. The time and labor to remove, examine, and return irradiated samples for each measurement makes this approach very expensive. In addition, such techniques provide limited data and may disturb the phenomena of interest.

To address these issues, the Idaho National Laboratory (INL) recently initiated efforts to evaluate candidate linear variable differential transducers (LVDTs) for use during high temperature irradiation experiments in typical ATR test locations. Two nuclear grade LVDTs were considered – a smaller diameter design qualified for temperatures up to 350 °C and a larger design with capabilities to 500 °C. Calibration and long duration performance evaluations were completed for temperatures up to 500 ºC with a focus on changes or degradation in sensitivity and electrical resistance. This paper presents results from these evaluations, which will ultimately lead to recommendations for an improved design for use in the ATR.

Key Words: in-pile displacement sensors, high temperature irradiation instrumentation

1 INTRODUCTION

In accordance with the Energy Policy Act of 2005, the Department of Energy (DOE) designated the Advanced Test Reactor (ATR) as a National Scientific User Facility (NSUF) to advance USA leadership in nuclear science and technology. By attracting new users from universities, laboratories, and industry, the ATR will support basic and applied nuclear research and development and help address the nation's energy security needs. A fundamental component of the ATR NSUF program is to develop in-pile instrumentation capable of providing real-time measurements of key parameters during irradiation experiments.

An understanding of dimensional changes is important because new materials are being considered for fuel, cladding, and structures in next generation and existing nuclear reactors. Such materials can experience significant changes during high temperature irradiation. Currently, dimensional changes are determined by repeatedly irradiating a specimen for a defined period of time in the Advanced Test Reactor (ATR) and then removing it from the reactor for evaluation. The time and labor to remove, examine, and return irradiated samples for each measurement makes this approach very expensive. In addition, such techniques provide limited data (i.e., only characterizing the end state) and may disturb the phenomena of interest.

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To address these issues, the INL recently initiated efforts to evaluate candidate linear variable differential transducers (LVDTs) for use during high temperature irradiation experiments in typical ATR test locations. Two nuclear grade LVDTs are under consideration – a smaller diameter design qualified for temperatures up to 350 °C and a larger design with capabilities to 500 °C. Current evaluation efforts include collecting calibration data as a function of temperature, long duration testing of LVDT response while held at high temperature, and the assessment of changes in performance that may be introduced as a result of high temperature operation. The performance assessment focuses on the potential for any changes or degradation in sensitivity and/or electrical resistance. This paper presents results from these evaluations, which will ultimately lead to recommendations for an improved design for use in the ATR. Evaluation of the impact of irradiation on performance will be addressed in subsequent studies.

It should be noted that related efforts are also underway at INL to provide high-temperature sensors suitable for ATR in-pile measurement of temperature (via thermocouples and silicon carbide monitors), thermal conductivity (via two-wire and hot-wire techniques), and general material deformation (via ultrasonic transducers).[1]

2 EVALUATION SCOPE AND SETUP

The use of LVDTs to measure linear displacement is a relatively mature technology. LVDTs have become common because they are accurate, very reliable, simple in terms of design and operation, and relatively inexpensive. However, the options for candidate LVDTs for use in the ATR are quite limited when selecting among available sensors with operating histories in a nuclear reactor environment. The choices are further reduced when ATR-specific customer requirements as listed in Table I are considered.

Table I. Desired LVDT characteristics for use in ATR.

Parameter	ATR Specification
Minimum LVDT displacement, mm	> +/- 2.5
Resolution, mm	10^{-2}
Sensitivity, mV/mm	> 50
Maximum operating temperature, °C	500
Normal operating pressure, MPa	0.101 - 15.5
Peak thermal flux, E < 0.625 MeV, neutrons/cm^2-s	1×10^{14}
Integrated thermal fluence, E < 0.625 MeV, neutrons/cm^2[a]	8×10^{21}
Peak fast flux, E > 20 MeV, neutrons/cm^2-s[a]	3×10^{14}
Integrated fast fluence, E > 20 MeV, neutrons/cm^2[a]	2×10^{22}
Integrated gamma exposure, γ/cm^2[a]	9×10^{22}
Maximum LVDT diameter, mm	< 25.4
Maximum LVDT length, mm	63.8
Test environment	Water (to 350 °C) and inert gas (to 500 °C)
Distance from test capsule to use of soft extension cable, m	12
Length of leads until temperature < 200 °C, m	7

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[a] Peak values based on a NE lobe source power of 18 MW. Fluence is based on 3 years of operation at 75% utilization.

In this study, two candidate LVDTs were identified as having the potential for meeting all requirements if minor modifications can be incorporated into their designs. Specifically, one supplier, hereafter identified as Vendor A, can currently provide LVDTs qualified to a maximum operating temperature of only 350 ºC while another supplier, hereafter identified as Vendor B, can currently provide only LVDTs with diameters exceeding listed ATR design limits. (Note that the Vendor A temperature limitation was established primarily because of response instabilities associated with passing through a material-specific Curie temperature at approximately 350 ºC. However, including the Vendor A LVDT was deemed appropriate because the sensor response may be otherwise acceptable up to the temperatures identified in this evaluation.)

The fact that acceptable design modifications appear to be readily available and possible to implement was the primary basis for selecting LVDTs from Vendors A and B for evaluation. For example, components used in LVDTs developed for INL's Loss of Fluid Test were found to produce stable signals up to 500 ºC.[2] Appropriate material substitution(s) may therefore resolve Vendor A temperature issues. Furthermore, Vendor A (and other LVDT suppliers) have sensors within the ATR geometric constraints. Liewise, it would appear that appropriate design changes could be implemented by Vendor B to meet identified diameter limits. Specific details associated with the scope and setup for the evaluation of these LVDTs is provided below.

2.1 Evaluation Scope

This evaluation includes collecting calibration data as a function of temperature, long duration testing of LVDT response while held at high temperature, and the assessment of changes in performance that may be introduced as a result of high temperature operation. The performance assessment focuses on the potential for any changes or degradation in sensitivity and/or electrical resistance. Primary elements of this evaluation are summarized in Table II, where responses for the listed conditions were collected for two LVDTs from each vendor.

Table II. Summary of evaluation conditions.

Evaluation Conditions[a]		
Calibration	**Long Duration**	**Degradation Assessment (of sensitivity and electrical resistance)**
@ room temperature	@ 500 ºC for 1000 h	@ each calibration temperature
@ 200 ºC		
@ 300 ºC		@ room temperature after calibration
@ 400 ºC		
@ 500 ºC		@ room temperature after long duration

It should be noted that all Table II data was collected while LVDTs were operating at stable (steady state) conditions. In addition, the selected long duration assessment period of 1000 h is consistent with current ATR operating cycles. Demonstration of reliable operation throughout such a period was deemed appropriate.

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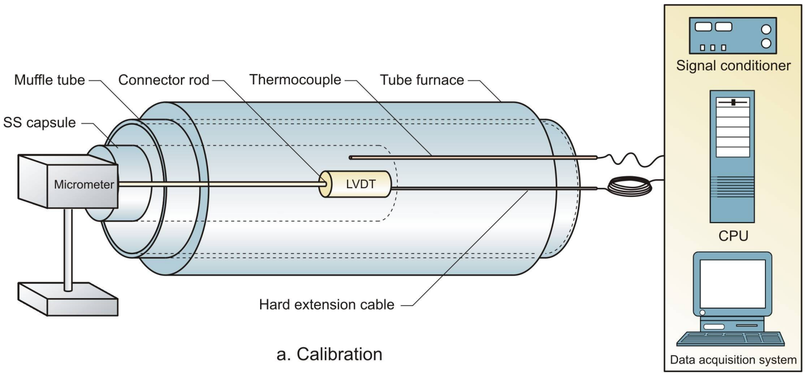
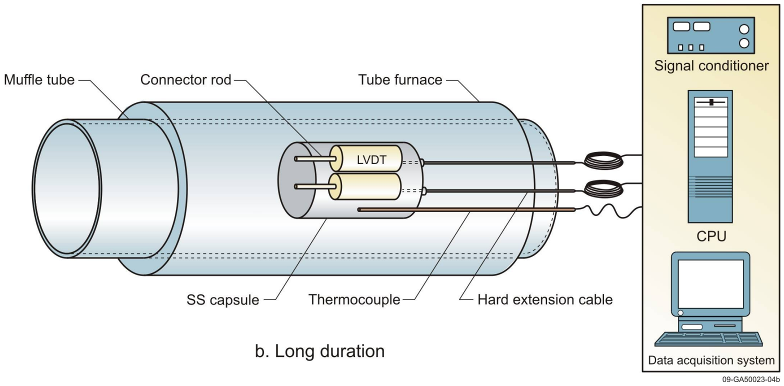
[a] Where all data collection was made during stable (steady state) conditions.

2.2 Evaluation Setup

In addition to the tested LVDTs, the evaluation setup included specialized fixtures for LVDT positioning, vendor-specific LVDT signal conditioning equipment, and a computerized data acquisition system (DAS) to be used in conjunction with a high temperature tube furnace. The general arrangements for both calibration and long duration testing are depicted in Figure 1.



a. Calibration

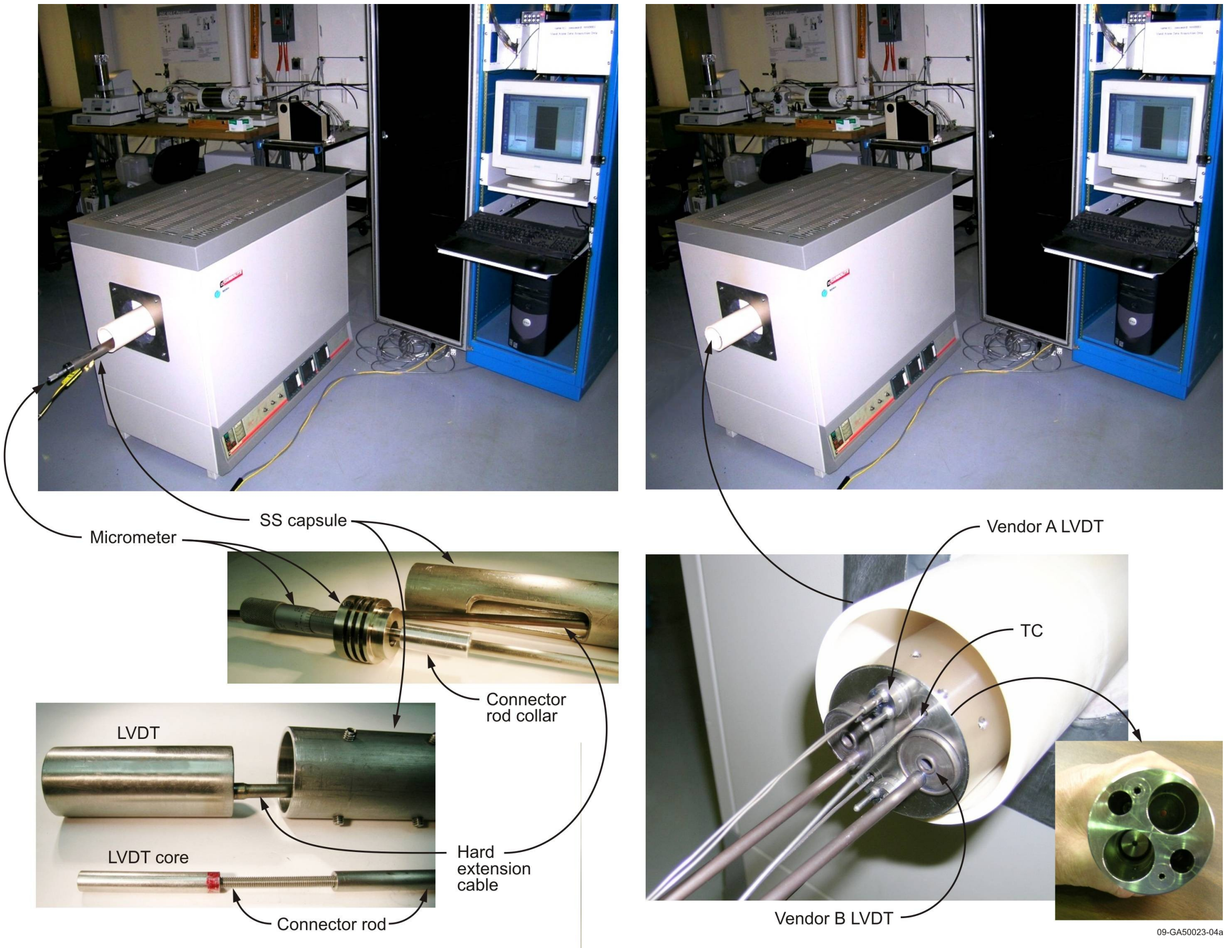


b. Long duration

Figure 1. Schematic of the LVDT evaluation setup.

Stainless steel tubing was used to fabricate the calibration fixtures. The tubing was configured to secure an LVDT body at one end and a micrometer at the opposite end. The tubing was of a length sufficient to allow positioning of the LVDT at the center of a high temperature tube furnace with the micrometer outside the furnace (and thereby unaffected by the furnace temperature). A stainless steel rod was used to connect the micrometer to the LVDT core, which was initially placed at the null position relative to the LVDT body. The micrometer then provided the mechanism for precise movement of the core (with respect to the body) for calibration purposes. Both ends of this fixture and its configuration relative to the tube furnace are shown in Figure 2a.

The long duration fixture was machined from a cylindrical stainless steel block to accept four LVDTs simultaneously. LVDT bodies were secured at one end of this fixture while connecting rods were secured at the opposite end. Connecting rods were of a length sufficient to place LVDT cores at null positions relative to the LVDT bodies. Holding the resulting assembly at a constant temperature can reveal any tendency for LVDT signal degradation or oscillation over time. This fixture and its configuration relative to the tube furnace are shown in Figure 2b.



a. Calibration

b. Long duration

Figure 2. Specialized fixtures used in LVDT evaluations.

A comprehensive set of tests was conducted prior to the formal evaluation to ensure that the LVDTs would not be affected by operating in close proximity to each other. Tests were also completed to ensure that LVDT response was not altered through use of the specialized fixtures. In addition to supporting the validity of this evaluation, these tests provide important insights needed in the design of ATR in-pile test configurations.

3 RESULTS

Two candidate nuclear grade LVDTs were evaluated for use during ATR high temperature irradiation experiments. The evaluation consisted of calibration and long duration tests. Results, which will ultimately lead to recommendations for an improved design, are summarized below. Note that in the interest of space, many of the results will specifically focus on LVDT 1 from Vendor A (LVDT A1) and LVDT 1 from Vendor B (LVDT B1). These results are considered representative and conclusions drawn through their comparison apply generically in this evaluation.

3.1 Calibration

Calibration data (i.e., output voltage vs displacement) at temperatures identified in Table II would be typical of the characterization needed to support use of LVDTs in the ATR. Consistent with established practice, linear curve fits for such data at each temperature over the design range (of +/- 2.5 mm for both candidate LVDTs) were successfully determined. Results for LVDT A1 at 500 ºC, as shown in Figure 3, are typical.

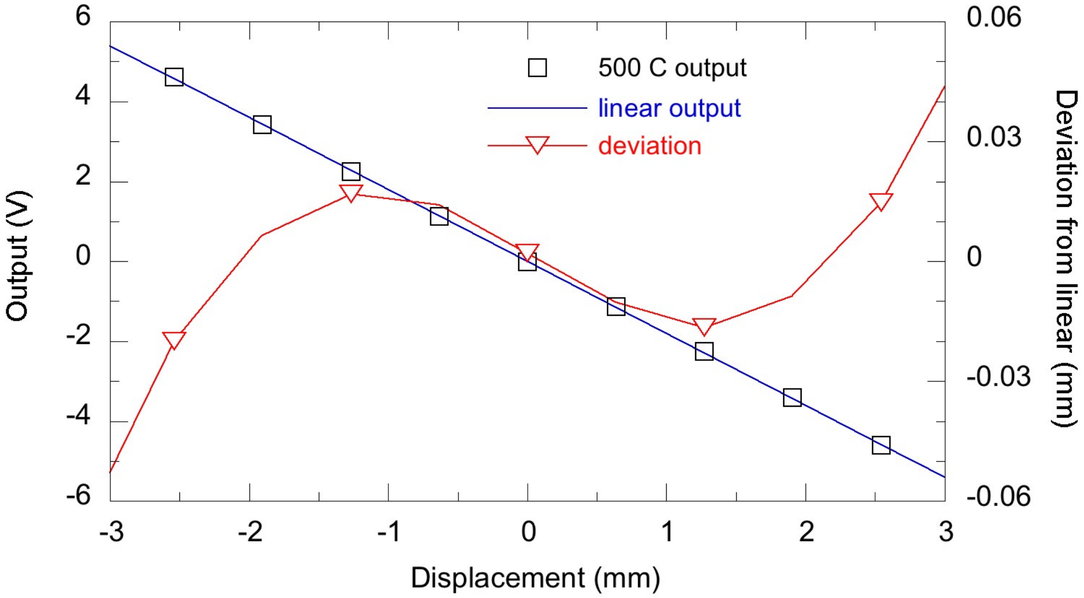


Figure 3. Calibration data for LVDT 1 from Vendor A (LVDT A1) at 500 ºC.

LVDT response data, a linear fit through that data, and the deviation of the data relative to the linear fit are all shown in the figure. It is worth noting that LVDT A1 has a maximum deviation of less than +/- 0.02 mm (or +/- 0.8%) over its design range of +/- 2.5 mm. Furthermore, its linear deviation is symmetric with respect to its null position. This is evident in that its deviation is ~0 at a displacement of 0 and the (absolute value of) deviations are approximately equal for equal but opposite displacements from null.

Corresponding results for LVDT 1 from Vendor B (LVDT B1) are shown in Figure 4. There are several notable differences apparent through comparison of Figures 3 and 4. Specifically, the maximum linear deviation of LVDT B1 (at more than 0.044 mm, or more than 1.8%, over its design range of +/- 2.5 mm) is more than twice the LVDT A1 maximum deviation. Furthermore, the linear deviation of LVDT B1 is not symmetric with respect to its null position. In fact, its deviation is ~0 at a displacement of ~1.2 mm. Deviations at +/- 2.5 mm are ~0.017 and 0.044 mm, respectively. Although there are no ATR symmetry specifications, symmetric behavior is desirable. Both LVDTs should be capable of resolution in the 0.010 mm range, which is an ATR specification. However, LVDT A1 would be expected to have a lower degree of uncertainty (as compared to LVDT B1) because its deviation from linearity is relatively small.

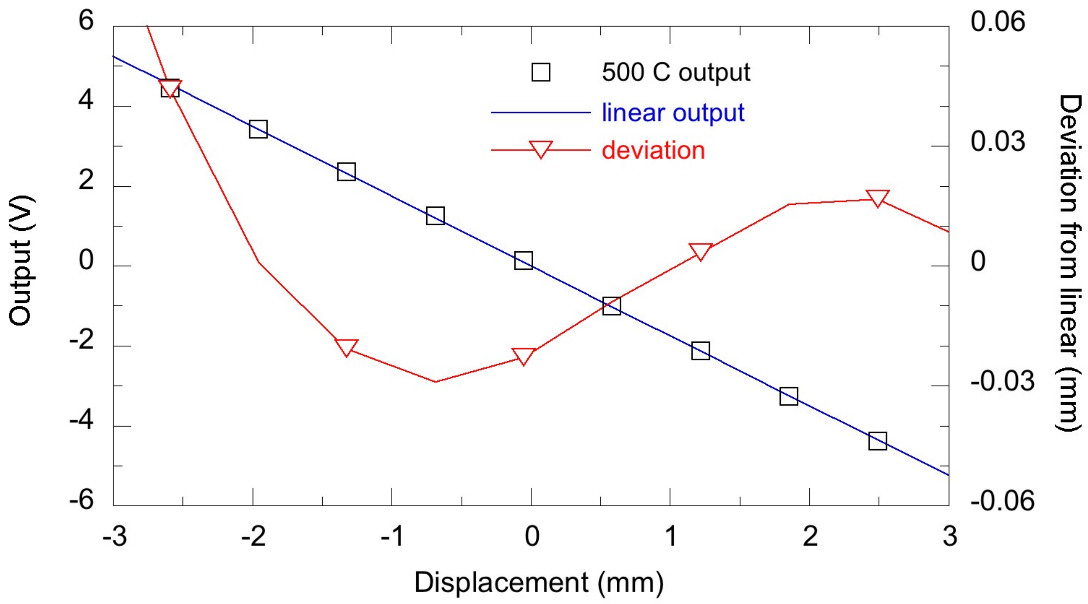


Figure 4. Calibration data for LVDT 1 from Vendor B (LVDT B1) at 500 ºC.

The sensitivity of an LVDT is expressed in terms of electrical output developed for a given displacement. This key metric is equivalent to the linear slope of a calibration curve (often given in terms of an absolute value). LVDTs A1 and B1, with sensitivities at 500 ºC of 1800 and 1750 mV/mm, respectively, easily exceed the ATR specification of 50 mV/mm. However, the effects of temperature on sensitivity are of interest given the cyclic nature of ATR operations. This temperature dependence was evaluated through the collection of calibration data at values identified in Table II. Associated results for LVDTs A1 and B1 are presented in Figure 5.

LVDT A1 sensitivity was found to increase (somewhat linearly) with temperature as shown in the figure. This increasing trend is beneficial in that sensor resolution is favorably affected. Furthermore, the sensitivity of LVDT A1 was found to return to its room temperature value following calibration at temperatures as high as 500 ºC. These results provide some evidence that Vendor A LVDTs are robust through temperature cycling up to the design specification. In contrast, LVDT B1 sensitivity increased (almost) linearly with temperature only up to ~300 ºC. Thereafter, the sensitivity decreased sharply as shown. Although LVDT B1 sensitivity at 500 ºC exceeds ATR specifications, the sharply decreasing trend is not favorable. Relative to LVDT A1, LVDT B1 pre- and post-calibration room temperature sensitivities differed noticeably. Again, this LVDT B1 result is not favorable (as compared to results for LVDT A1).

Electrical resistance is one factor that could affect LVDT sensitivities. In this study, the resistance of (both primary and secondary) loop windings was found to increase with temperature in LVDTs from both vendors, which was expected. Insulation resistance, however, generally tends to decrease with temperature. Insulation resistance measurements relative to primary and secondary windings for LVDTs A1 and B1 are shown in Figure 6 as a function of temperature. (Note that $1x10^8$ ohms was a limitation of the meter used in this study.)

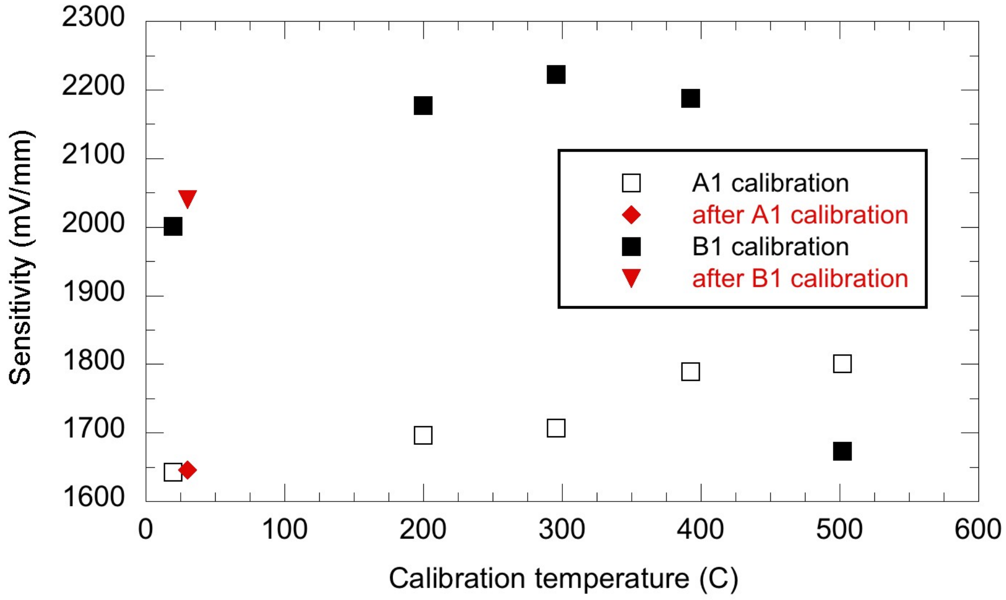


Figure 5. Comparison of LVDT sensitivities as a function of temperature.

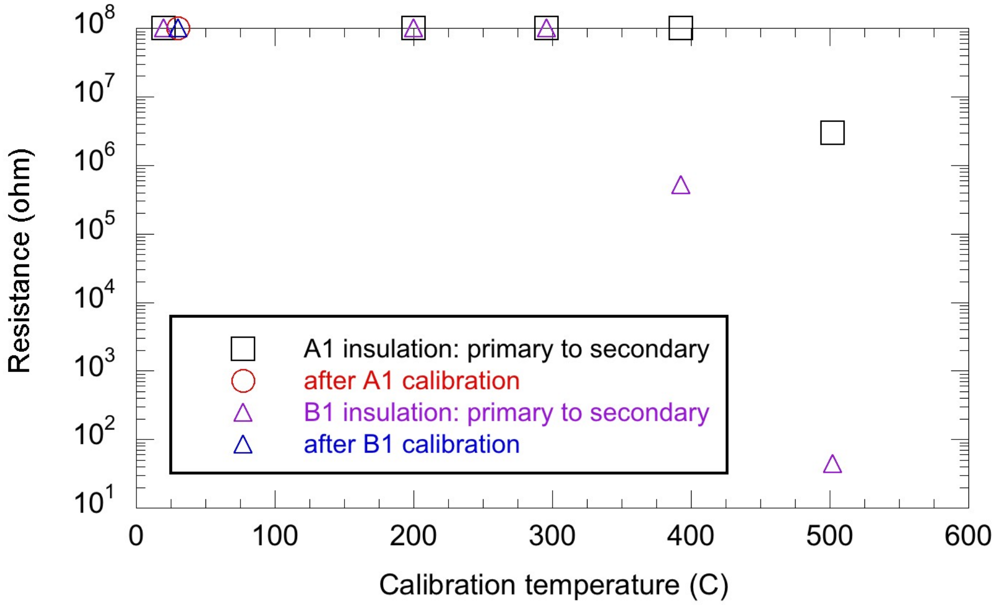


Figure 6. Comparison of LVDT insulation resistances as a function of temperature.

As indicated in Figure 6, the primary to secondary insulation resistance for LVDT B1 showed a sharp decrease after 300 ºC. This trend appears to be consistent with the decreasing trend in sensitivity shown in Figure 5. A value of ~40 ohms, as measured at 500 ºC, for LVDT B1 seems unreasonably low. In contrast, temperatures exceeded 400 ºC before any decreases in the corresponding insulation resistance for LVDT A1 were measured. Furthermore, the decrease for LVDT A1 was relatively small, yielding a value in excess of 1×10^6 ohms at 500 ºC.

3.2 Long Duration

Long duration testing of LVDTs from both vendors was deemed necessary to reveal any tendencies for signal degradation or oscillation over time. Results for all four tested LVDTs are compared in Figure 7. (Note that an unplanned power outage interrupted data collection during the time period between ~700 and ~760 h. The best information available indicates operation of the high temperature furnace was unaffected.)

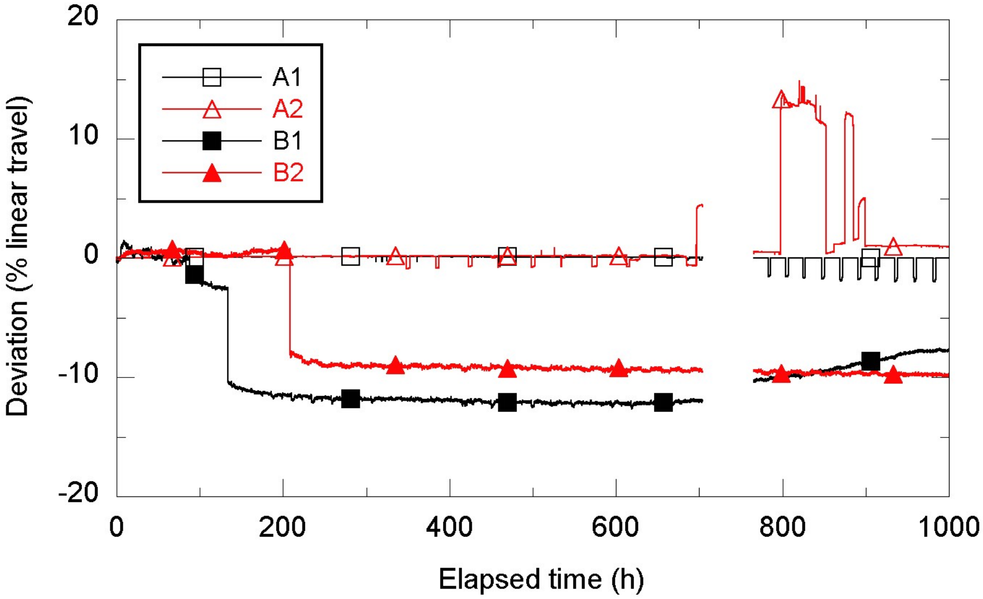


Figure 7. Comparison of LVDT response during long duration testing at 500 °C.

In this evaluation, all four LVDTs were configured in the test fixture with cores set as close to null positions as possible. Consequently, output for all four LVDTs would be expected to be remain near 0 Vdc throughout the test. For comparison purposes, calibration data for each LVDT (at 500 °C) was used to convert measured output voltage to an indicated displacement. Figure 7 presents the deviation of the indicated displacement, relative to the time 0 output, as a percentage of total linear travel (which is 5 mm for all sensors). Following this approach, a perfectly stable sensor would then register 0% deviation through time.

As indicated in the figure, Vendor A LVDTs were found to be very stable through ~330 h. Their maximum deviation during that period is equivalent to a displacement of ~0.004 mm relative to their time 0 position. (Note that ~25 h were set aside for stabilization at 500 °C before marking time 0.) However, some periodic fluctuations in the response of Vendor A LVDTs began to appear after ~330 h. Those fluctuations, primarily affecting LVDT A2, remained relatively small for more than 350 h. Just before the unplanned power outage (at ~700 h), LVDT A2 fluctuations dramatically increased in both magnitude and duration. Shortly thereafter, LVDT A1 signal fluctuations increased; with relatively frequent oscillations until the end of the 1000 h test. Although the reason (or reasons) for the behavior of Vendor A LVDTs during the later part of the long duration test are still under investigation, the vendor has indicated that they have observed similar trends as a result of insulation degradation.

Results for Vendor B LVDTs differ significantly compared to Vendor A. Specifically, Vendor B LVDTs show substantial oscillation (starting at time 0) in addition to (as yet unexplained) dramatic step changes in indicated deviations (near 130 h for LVDT B1 and near 210 h for LVDT B2). In fact, the LVDT B1 step change is equivalent to a displacement of ~0.6 mm, indicating a reduction in stability by a factor of ~150 compared to Vendor A LVDTs during the first 330 h of the test.

Further differences between the initial LVDT responses from the two vendors are illustrated in finer detail in Figure 8. As indicated, LVDT A1 remains very flat with only minor perturbations. In contrast, LVDT B1 shows considerable oscillation during the entire displayed period. The more or less periodic oscillations produced by LVDT B1 are approximately equivalent to a displacement of 0.007 to 0.010 mm; representing values that were not exceeded by Vendor A LVDTs during the first 330 h of the long duration test. In addition, perturbations in LVDT B1 outputs near 83 and 84.8 h represent unexpected output deviations that are three times larger (approaching 0.03 mm).

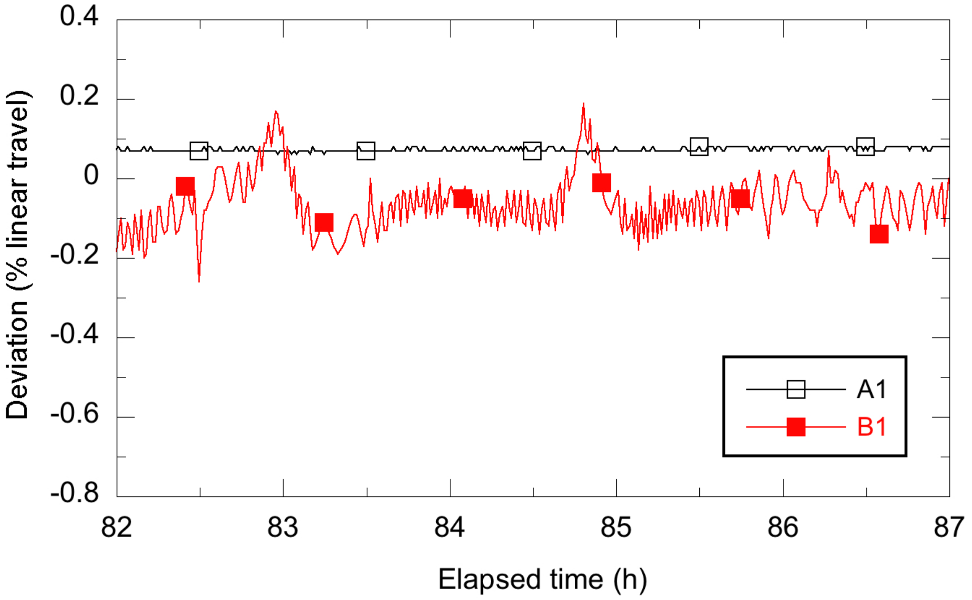


Figure 8. Comparison of the response of LVDTs A1 and B1 during the long duration test.

To date, Vendor B has not provided their evaluation or interpretation of their long duration results. However, considerable oxidation of the Vendor B LVDT cores occurred during the long duration test as indicated in Figure 9. This discovery was unexpected given that all LVDTs were calibrated at 500 °C without showing any evidence of oxidation. Furthermore, Vendor B cores were reported to be stainless steel, which should not have oxidized at the test temperature. Note the nearly pristine condition of all other pictured components subjected to the same conditions.

Although it is unclear whether oxidation had an adverse impact on Vendor B LVDT response during the long duration test, oxidation is not a desirable outcome. This oxidation and the perturbations observed during the test tend to favor the Vendor A LVDT design for use in ATR irradiation experiments. However, some additional evaluation of the Vendor A LVDT behavior is needed to resolve instabilities for long duration use at high temperatures.

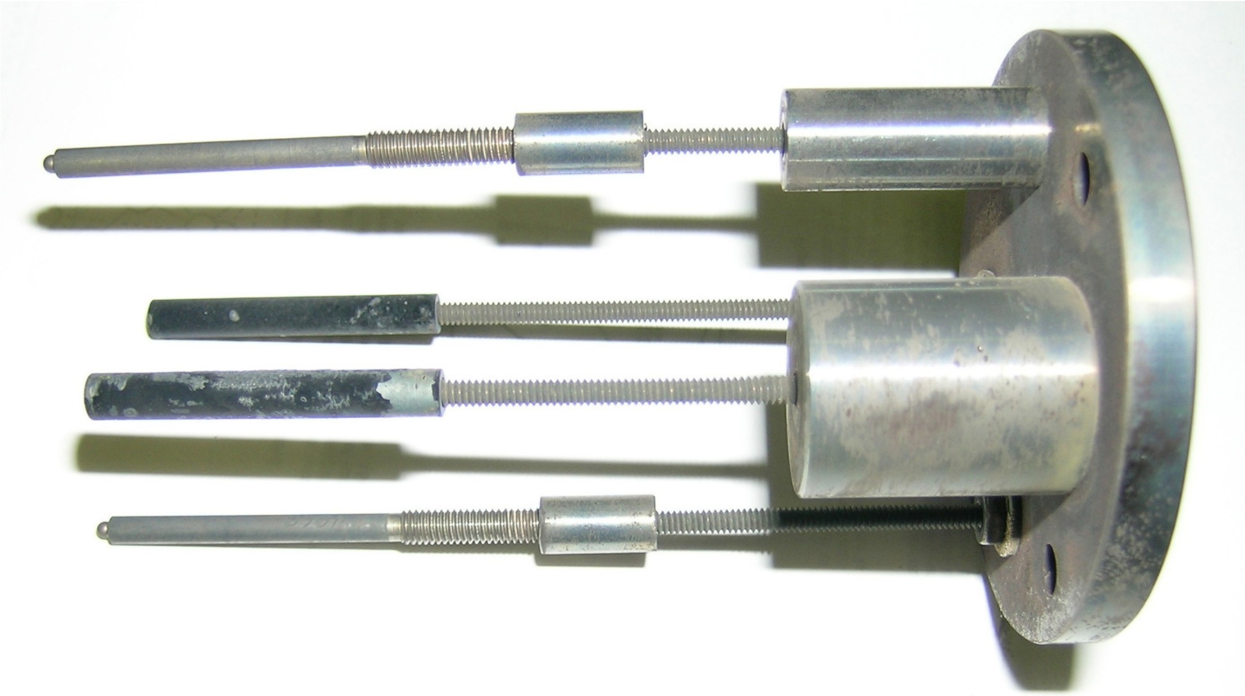


Figure 9. Comparison of LVDT cores following the long duration test at 500 ºC (where both Vendor B cores are shown centered between the Vendor A cores).

4 SUMMARY AND CONCLUSIONS

The INL recently initiated efforts to evaluate candidate LVDTs for use during high temperature irradiation experiments in typical ATR test locations. Two nuclear grade LVDTs were considered – a smaller diameter design qualified for temperatures up to 350 °C (from Vendor A) and a larger design with capabilities to 500 °C (from Vendor B). Current evaluation efforts included collecting calibration data as a function of temperature, long duration testing of LVDT response while held at high temperature, and the assessment of changes in performance that may be introduced as a result of high temperature operation.

Preliminary results from this evaluation favor the Vendor A LVDT design. Specifically, Vendor A LVDT sensitivities monotonically increase with temperature (up to the limit of 500 ºC considered here) while Vendor B LVDT sensitivities decrease beyond 300 ºC. In limited testing, Vendor A LVDTs also show better repeatability (at room temperature) after calibration at high temperature. Unlike Vendor B LVDTs, Vendor A LVDTs have high insulation resistance between primary and secondary windings, even at elevated temperatures. This may be a factor in the high temperature sensitivity advantage provided by Vendor A. Long duration testing indicates Vendor A LVDTs are very stable at 500 ºC for ~300 h. In contrast, Vendor B LVDTs show considerable noise, oscillation, and (as yet unexplainable) step changes in output during long duration testing. Finally, LVDTs from Vendor A are within geometric limits specified by the ATR while Vendor B LVDTs are not.

Some additional testing of Vendor A LVDTs is needed to resolve stability issues that were observed in the later portion of the long duration test. Based on a review by Vendor A, these issues may be related to degradation of the LVDT insulation. Furthermore, some testing appears warranted to evaluate the effects of a material-specific Curie temperature transition (near 350 °C). As appropriate, alternate materials could be substituted and testing of the refined design could be completed. Following these steps, final recommendations for a design to be used in the ATR will be developed.

5 ACKNOWLEDGMENTS

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6 REFERENCES

1. J. L. Rempe and M. K. Meyer, "Recent In-Pile Instrumentation Developments for Research and Test Reactors," submitted to the *Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies*, Knoxville, Tennessee, April 5-9, 2009.
2. J. R. Wolf, "The Linear Variable Differential Transformer and its Uses for In-Core Fuel Rod Behavior Measurements," *International Colloquium on Irradiation Tests for Reactor Safety Programmes,* June 25-28, 1979, Petten, The Netherlands.