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RECOMMENDATIONS FOR USE OF LVDTS IN ATR HIGH TEMPERATURE IRRADIATION TESTING

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ABSTRACT

New materials are being considered for fuel, cladding, and structures in next generation and existing nuclear reactors. These materials can undergo significant dimensional and physical changes during high temperature irradiations. Currently, such changes are determined by repeatedly irradiating a specimen for a specified period of time in the Advanced Test Reactor (ATR) and then removing it from the reactor for evaluation. The labor and time 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 recently completed initial efforts to evaluate candidate Linear Variable Differential Transducers (LVDTs) for in-situ deformation measurements during high temperature irradiations in typical ATR test locations. Results from that effort, which are summarized here, were used to identify the candidate nuclear grade LVDT that most closely meets ATR requirements. However, the identified LVDT is subject to the effects of a Curie point (at ~360 °C), which required further evaluation as described. In addition, an alternate design of the candidate LVDT that is free of Curie point effects was developed, but it required separate evaluation to determine its suitability for possible ATR applications. This paper presents results from these evaluations, which will ultimately lead to recommendations for a final design for use in ATR irradiation testing.

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

1 INTRODUCTION

In April 2007, the Department of Energy (DOE) designated the Advanced Test Reactor (ATR) a National Scientific User Facility (NSUF) to advance US 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. Dimensional changes that may occur during in-pile irradiation are among those parameters.

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 undergo significant changes during high temperature irradiation. Currently, dimensional changes are determined by repeatedly irradiating a specimen for a defined period of time in the 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 Idaho National Laboratory (INL) recently completed initial efforts to evaluate candidate linear variable differential transducers (LVDTs) for use in detecting dimensional changes during high temperature irradiation experiments in typical ATR test locations.[1] 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. Results from that initial evaluation, which are summarized here, clearly favor use of the smaller LVDT design. However, further evaluation was needed to investigate the potential impact of a Curie temperature effect that is characteristic of this design. In addition, an evaluation was needed to assess the response of this design with substitution of a silver alloy wire in the LVDT windings. This paper presents results from these evaluations, which will ultimately lead to recommendations for an improved design for use in the ATR. (Note that an evaluation of the impact of irradiation on performance will be addressed in subsequent studies.)

2 SUMMARY OF INITIAL LVDT EVALUATIONS

Two candidate LVDTs were identified for initial evaluation because they have the potential to meet all ATR requirements (as listed in Table I) 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 °C while another supplier, hereafter identified as Vendor B, can currently provide only LVDTs with diameters exceeding design limits. The Vendor A temperature limitation was established primarily because of response instabilities associated with passing through a material-specific Curie temperature at approximately 360 °C. However, including the Vendor A LVDT in this evaluation was deemed appropriate because the sensor response may be otherwise acceptable up to the temperatures of interest and material substitution(s) may be available to resolve Vendor A temperature issues. Likewise, including the Vendor B LVDT was also reasonable because it appears that design changes could be implemented to meet identified diameter limits.

Table I. Desired LVDT characteristics for use in ATR.

Parameter	ATR Specification
Minimum LVDT displacement (e.g., stroke), mm	± 2.5
Resolution, mm	< 1e-2
Minimum sensitivity, V/m	50
Maximum LVDT diameter, mm	25
Maximum LVDT length, mm	64
Maximum operating temperature, °C	500
Normal operating pressure, MPa	0.10 - 16
Test environment	Water to 350 °C and inert gas to 500 °C
Peak thermal flux, neutrons/cm^2-s[a]	1.8e14
Thermal fluence, neutrons/cm^2[a]	8.5e21
Peak fast flux (E > 1 MeV), neutrons/cm^2-s[a]	1.2e14
Fast fluence (E > 1 MeV), neutrons/cm^2[a]	5.7e21
Gamma flux, γ/cm^2-s[a]	1.1e15
Integrated gamma exposure, γ/cm^2[a]	5.2e22
Distance from test capsule to use of soft extension cable, m	12
Length of leads until temperature < 200 °C, m	7

[a] Peak values based on 24.3 MW center lobe power and fluence is based on 2 years of operation at 75% utilization, which are expected to bound anticipated test conditions.

The initial evaluation 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. The performance assessment focused 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 °C for 1000 h[b]	@ each calibration temperature
@ 200 °C		
@ 300 °C		@ room temperature after calibration
@ 400 °C		
@ 500 °C		@ room temperature after long duration testing

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

[b] Where test duration is consistent with ATR operating cycles.

Calibration data (i.e., output voltage versus displacement) for LVDTs A1 and B1 at 500 °C are given in Figures 1 and 2, respectively. These plots, which were typical of obtained results, also include a linear fit through the data and the data deviation relative to the linear fit. Through comparison of the plots, it is evident that LVDT A1 has advantages in terms of a lower maximum deviation (less than ±0.02 mm [or ±0.8%] over its design range of ±2.5 mm compared to 0.044 mm, or more than 1.8%). Furthermore, the linear deviation of LVDT A1 is symmetric with respect to its null position while the linear deviation of LVDT B1 is not. These results favor selection of Vendor A LVDTs for use in ATR experiments.

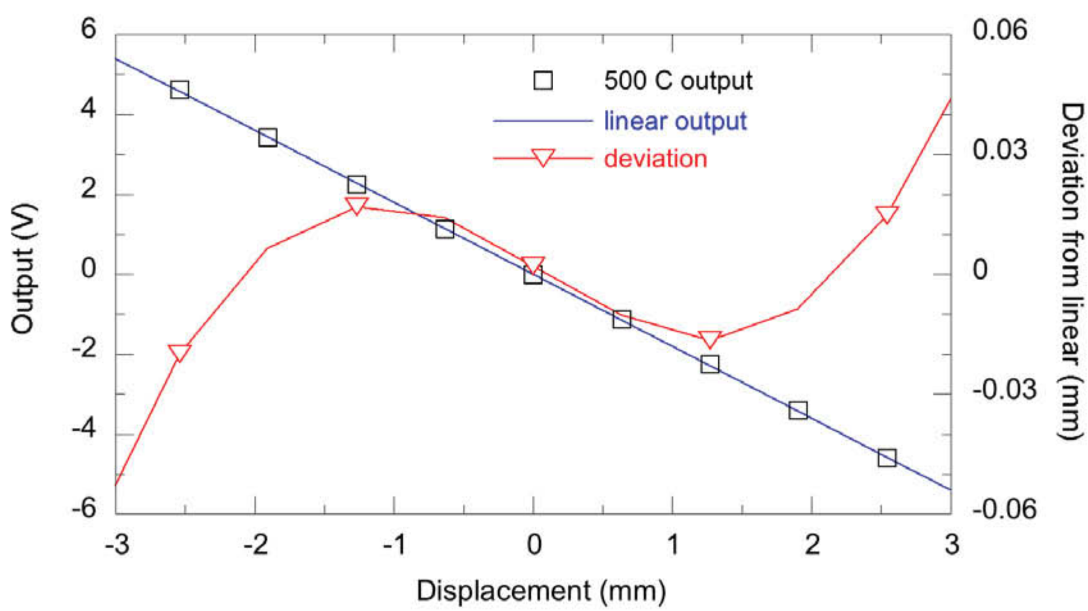

Figure 1. Calibration data for LVDT 1 from Vendor A (LVDT A1) at 500 °C.

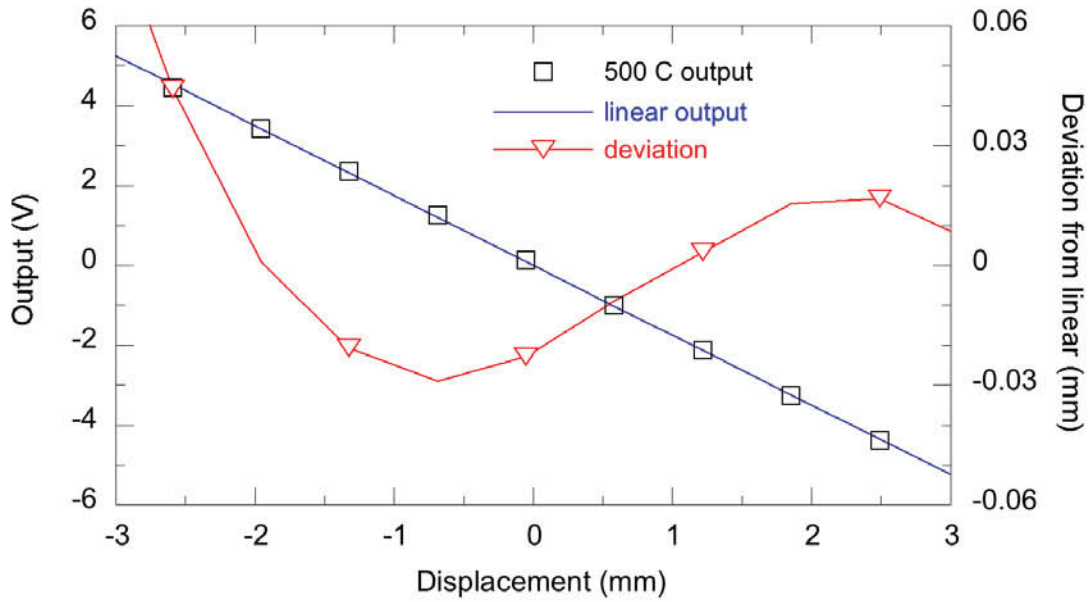

Figure 2. Calibration data for LVDT 1 from Vendor B (LVDT B1) at 500 °C.

LVDT sensitivity is expressed in terms of electrical output developed for a given displacement. This key metric is equivalent to the slope of a linear calibration curve (often given in terms of an absolute value). The effects of temperature on sensitivity are of interest given the cyclic nature of ATR operations. This temperature dependence was evaluated through collection of calibration data at values identified in Table II. Associated results for LVDTs A1 and B1 are presented in Figure 3. As indicated, LVDT A1 sensitivity was found to increase (somewhat linearly) with temperature. 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 up to 500 °C. In contrast, LVDT B1

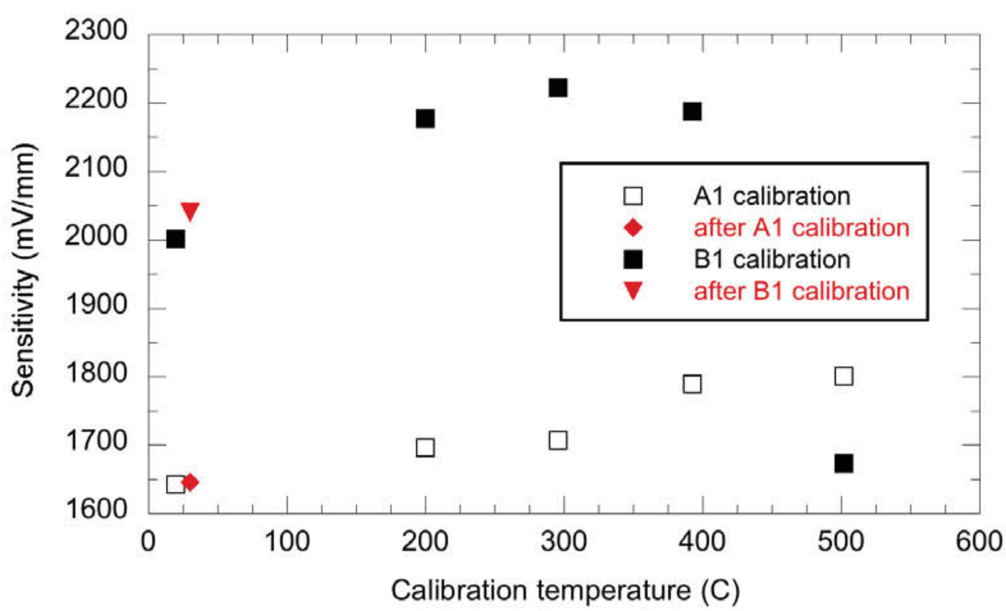

Figure 3. Comparison of LVDT sensitivities as a function of temperature.

sensitivity increased (almost) linearly with temperature only up to ~300 °C with decreasing sensitivity thereafter. Relative to LVDT A1, LVDT B1 pre- and post-calibration room temperature sensitivities also differed noticeably. Again, these results favored selection of Vendor A LVDTs.

Because insulation resistance could affect sensitivities, resistance measurements were collected as shown in Figure 4. As indicated, primary to secondary insulation resistance for LVDT B1 showed a sharp decrease after 300 °C, consistent with the decreasing trend in sensitivity shown in Figure 3. A value of ~40 ohms, as measured at 500 °C for LVDT B1, seems unreasonably low. In contrast, temperatures exceeded 400 °C 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 $1x10^6$ ohms at 500 °C. These results also favor selection of Vendor A LVDTs for use in ATR irradiation experiments.

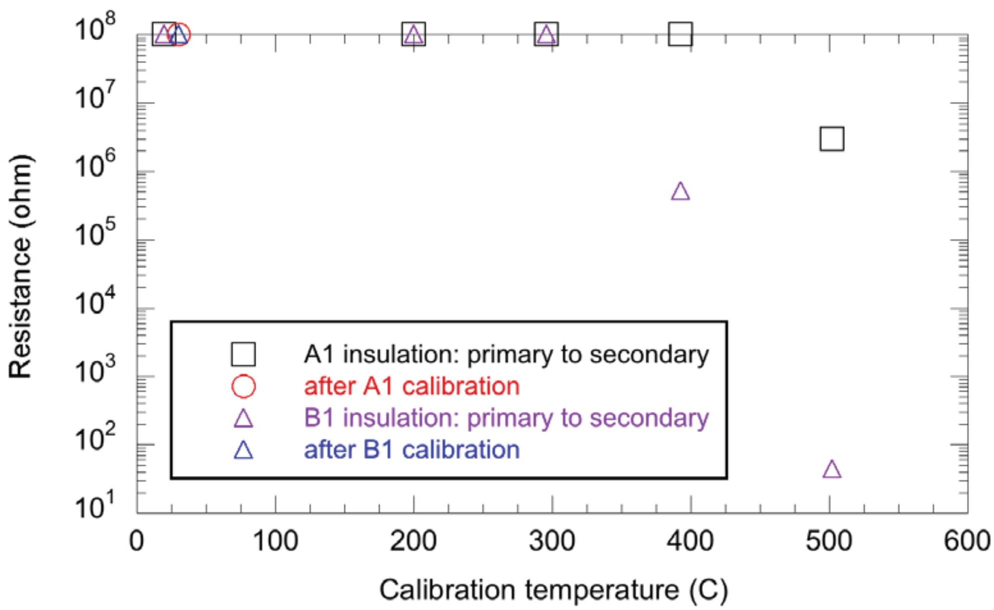

Figure 4. Comparison of LVDT insulation resistances as a function of temperature.

Long duration testing of LVDTs from both vendors was deemed necessary to reveal any tendencies for signal degradation or oscillation over time. Corresponding long duration results for all four tested LVDTs are compared in Figure 5. (Note that perfectly stable sensors should register 0% deviation throughout this test. Also note that an unplanned power outage interrupted data collection during the time period between ~700 and ~760 h. However, the best information available indicates high temperature furnace control was unaffected.)

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. However, some periodic fluctuations in the response of Vendor A LVDTs began to appear thereafter. Those fluctuations, primarily affecting LVDT A2, remained relatively small until a time just before the unplanned power outage (at ~700 h). LVDT A2 fluctuations then 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, which can be alleviated through more rigorous heat treatment.

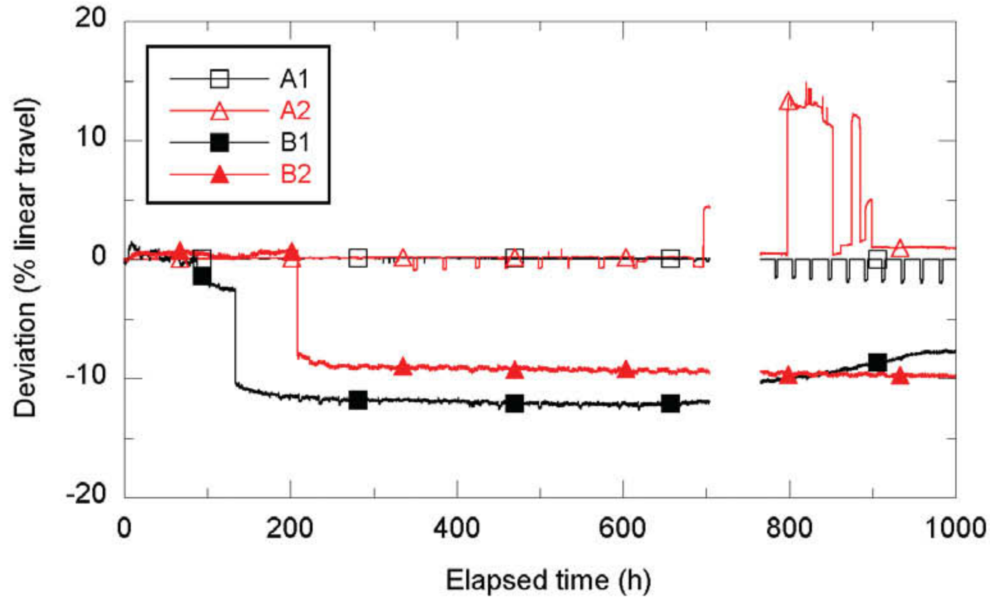

Figure 5. Comparison of LVDT response during long duration testing at 500 °C.

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 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. Like calibration, sensitivity, and resistance evaluations, these results also favor selection of Vendor A LVDTs.

3 CURIE POINT EVALUATION

Based on results from initial evaluations (as discussed above), Vendor A LVDTs were found to be the preferred design for use in ATR irradiation experiments. However, there are concerns because these LVDTs are known to experience an abrupt change in their output signal near 360 °C corresponding with passing through the Curie point for the copper nickel wire used in the windings. An evaluation of this effect was needed because these LVDTs may be used in ATR test loops operating at pressurized water reactor conditions (or ~15 MPa and ~300 °C). Consequently, temperatures could be an issue depending on the in-core position of the sensor and the corresponding gamma heating levels. This evaluation was therefore needed to determine the Curie point temperature, the affected temperature range, and the output signal change.

Four heatup tests were completed in this Curie point evaluation using the setup shown in Figure 6. The LVDT response shown in Figure 7 is representative of the behavior observed during each test. Results from all tests have been summarized in Table III. In this table, the Curie point temperature was taken to be the temperature corresponding with the largest LVDT output signal change observed. (From Figure 7, the largest output signal change clearly occurs at a temperature of ~379 °C.) The affected temperature range starts and ends where the change in LVDT output voltage starts and ends. (From Figure 7, the affected temperature range is between ~377 and ~381 °C.) Finally, the output signal change is calculated relative to the output signal just before Curie point effects begin. (From Figure 7, there is an output signal change of ~64%, which is estimated as 100 x [-0.393-{-0.646}/-0.393].)

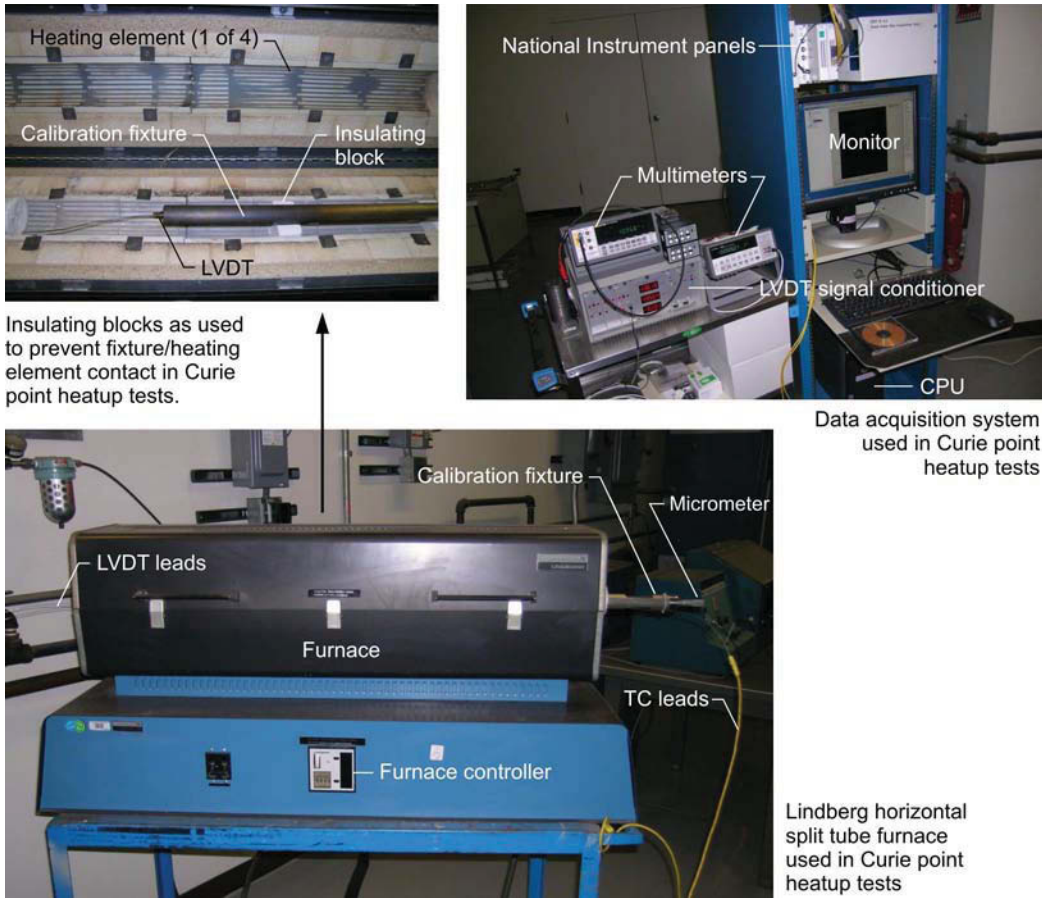

Figure 6. Setup for Curie point evaluation.

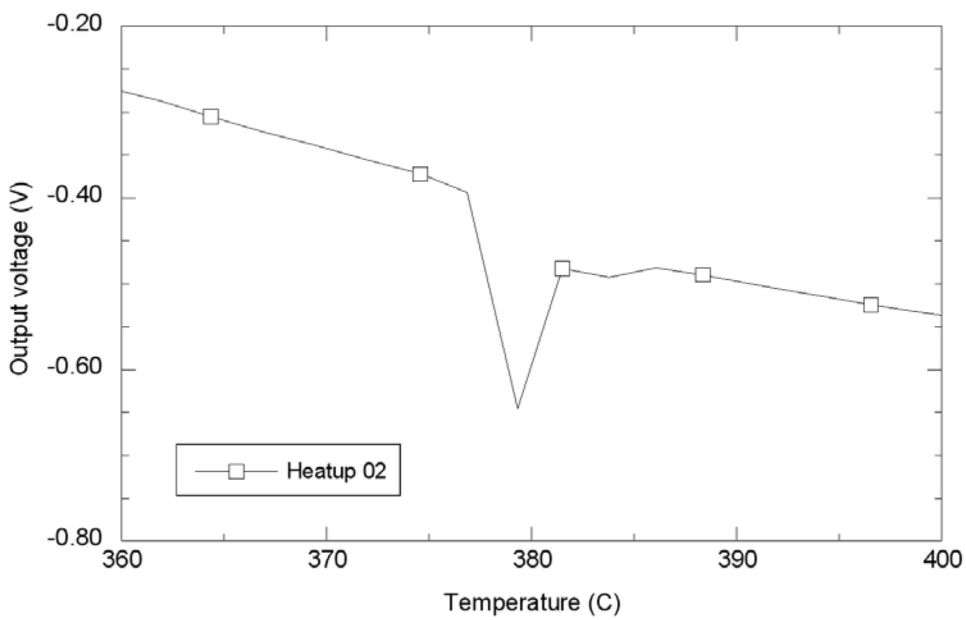

Figure 7. Heatup test 2 in the Curie point evaluation.

Table IIII. Curie point evaluation summary.

Test	Temperature at maximum signal change (°C)	Temperature range of signal change (°C)	Signal change (% relative to lowest unaffected temperature)
1	402	8 (406-398)	-32
2	379	4 (381-377)	-64
3	389	4 (390-386)	-10
4	379	4 (381-377)	-51

The results indicate the Curie point occurs at a temperature between ~380 and ~400 °C, which is somewhat higher than the Vendor A estimate of ~360 °C. This discrepancy could be minimized (or eliminated) if the heatup rate were reduced to a point where all heated components remain in quasi-thermal equilibrium throughout the tests. In addition, results indicate the Curie effect could alter the LVDT output by as much as ~60%, although the impact of such an output variation would be realized only if the LVDT was used within ±2 °C of the actual Curie point. These results support the position that the existence of the Curie point would be of concern only if a Vendor A LVDT was operated at (or very near) its affected temperature.

4 CURRENT EVALUATION OF AG LVDTS

As previously indicated, Vendor A postulated that instabilities observed during later portions of the initial long duration high temperature tests may be related to degradation of the LVDT insulation. In response, Vendor A supplied new LVDTs with refined heat treatment during fabrication for additional testing. The new LVDTs also included an alternate silver alloy wire in the windings, which eliminates Curie point issues. Like the initial evaluation, testing of the new LVDTs 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. Although two new LVDTs were supplied and tested, the following focuses primarily on only one of the LVDTs because results for the sensors were very similar.

Calibration data for LVDT A3 at 500 °C are given in Figure 8. Although there is some asymmetry as shown, deviation from linearity (at +0.04 mm, -0.00 mm) is comparable to the linear deviation of LVDT A1 (at ±0.02 mm as indicated in Figure 1). Results provided in Figure 8 were collected after continuous operation for 1000 h at 500 °C. It should be noted, however, that this post-long duration calibration was essentially unchanged from the calibration completed before long duration testing. A good indication of this sensor repeatability can be seen though comparison of the LVDT sensitivities provided in Figure 9. In this figure, sensitivities before and after long duration testing are shown to be nearly equal at room temperature and also at 500 °C. These results indicate that the new sensors should be able to function reliably after thermal cycling.

Insulation resistance measurements were also collected as shown in Figure 10. As indicated, primary to secondary insulation resistances for LVDT A3 remained relatively high over the tested temperature range. Although there was some apparent degradation in insulation resistance at room temperature following long duration testing, the behavior of the new LVDTs is comparable to LVDT behavior observed in the initial evaluation.

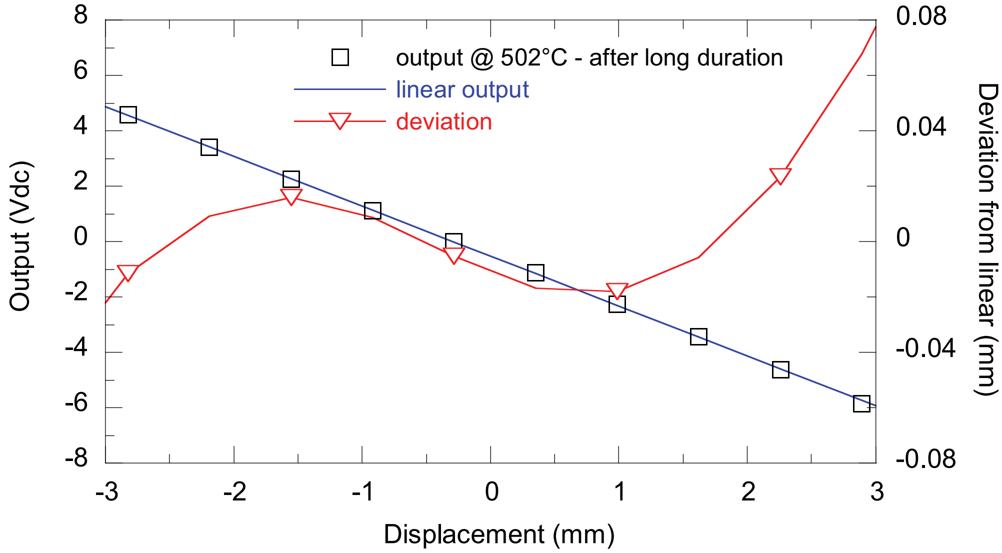

Figure 8. Calibration data for LVDT 3 from Vendor A (LVDT A3) at 500 °C.

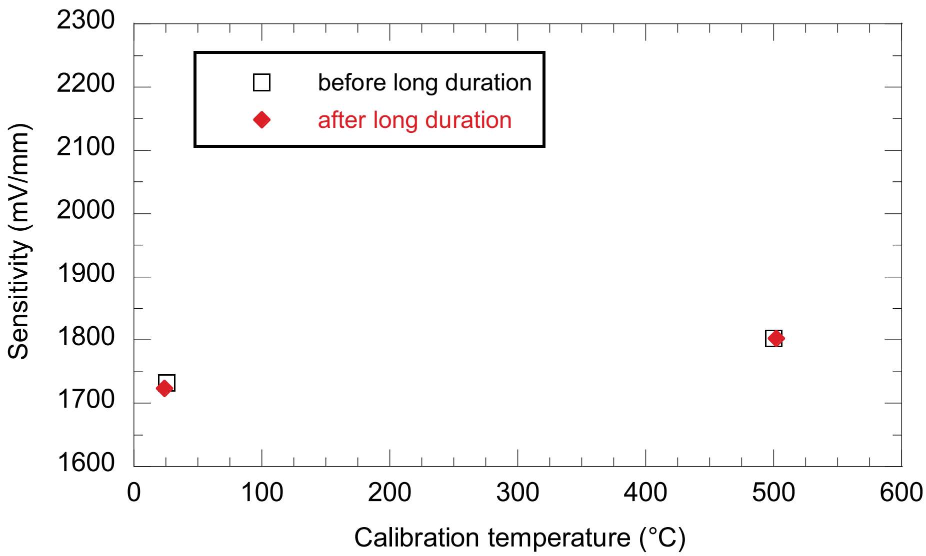

Figure 9. LVDT A3 sensitivities as a function of temperature.

High temperature long duration testing of the new LVDTs was completed to reveal any tendencies for signal degradation or oscillation over time. The corresponding results are provided in Figure 11. Like the initial evaluation, perfectly stable sensors should register 0% deviation throughout this test. As indicated, the new LVDTs were found to be very stable relative to results from the initial evaluation (compare Figures 5 and 11). In fact, the new LVDTs have a maximum deviation over 1000 h that is less than 0.4% (equivalent to a total displacement of less than 0.01 mm). Elimination of the long duration instabilities (observed in the initial LVDT evaluation) represents a major step forward. Consequently, the new LVDTs are now recommended for use in ATR irradiation experiments.

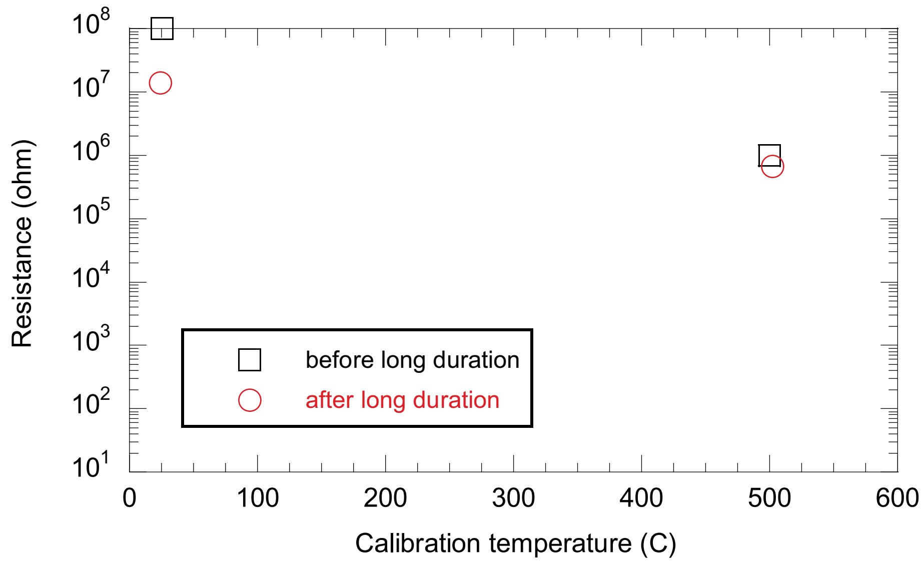

Figure 10. LVDT A3 insulation resistances as a function of temperature.

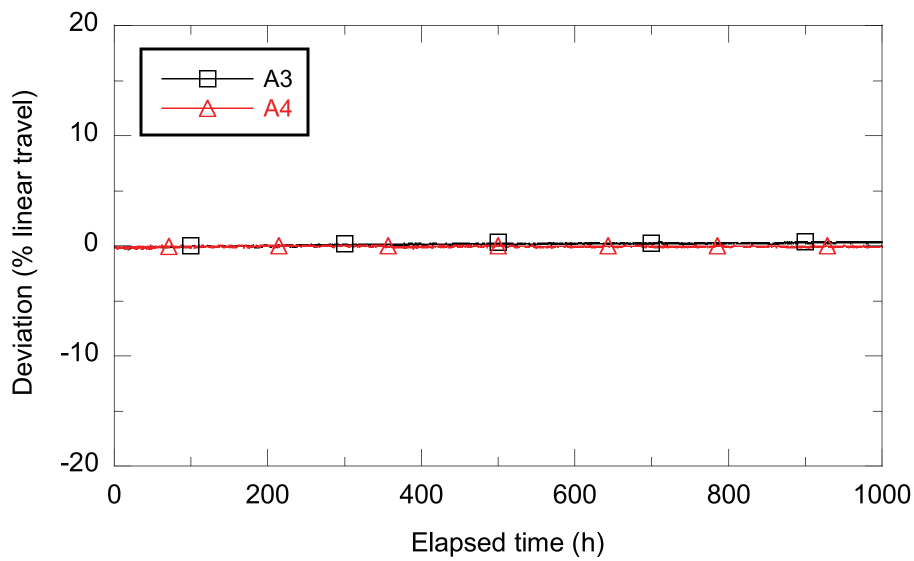

Figure 11. LVDT response during long duration testing at 500 °C.

5 SUMMARY AND CONCLUSIONS

The INL recently completed initial 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). These initial 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. 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 °C considered here) while Vendor B LVDT sensitivities decrease beyond 300 °C. 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 °C for ~300 h. In contrast, Vendor B LVDTs show considerable noise, oscillation, and large 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.

Having selected the Vendor A LVDT for ATR use, additional testing was needed to evaluate the effects of a material-specific Curie point and to resolve stability issues that were observed in the later portions of the initial long duration high temperature test. The Curie point temperature, the affected temperature range, and the associated output signal change were determined as part of the Curie point evaluation. The results indicate the Curie effect could alter the LVDT output by as much as ~60%, although the impact of such an output variation would only be realized if the LVDT was used within ±2 °C of the actual Curie point. These results support the position that the existence of the Curie point would be of concern only if a Vendor A LVDT was operated at (or very near) its affected temperature.

Based on a review of the initial evaluation results, Vendor A postulated that instabilities observed during later portions of the initial long duration high temperature tests may be related to degradation of the LVDT insulation. In response, Vendor A supplied new LVDTs with refined heat treatment during fabrication for additional testing. The new LVDTs also included an alternate silver alloy wire in the windings, which eliminates Curie point issues. Like the initial evaluation, testing of the new LVDTs 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. Results indicate the new LVDTs can operate in a very stable manner for long periods (1000 h) at high temperatures (500 °C). In addition, degradation of the LVDTs following high temperature operation was found to be insignificant. Consequently, Vendor A LVDTs are recommended for use in ATR irradiation experiments.

6 ACKNOWLEDGMENTS

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7 REFERENCES

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