Performance Test of Mini LVDT – ELVIS

[INL/RPT-24-80631]

Advanced Sensors and Instrumentation

Milestone M3CT-24IN0703032

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ABSTRACT

The Institute for Energy (IFE) Technology has been a pioneer in the development of Linear Variable Differential Transformers (LVDTs) for in-pile testing, deploying over 2,200 units in various reactor environments with less than a 10% failure rate after five years of operation. This report focuses on the performance testing of IFE's Mini LVDT, a compact sensor ideal for material test reactor experiments. The Mini LVDT, with a limited range of +/- 1.5 mm, offers excellent performance comparable to larger LVDTs, making it valuable in space-constrained applications. The development of an Enhanced Linear Variable Intrinsic Sensor (ELVIS) with internal temperature monitoring capabilities represents a significant advancement, addressing the critical need for real-time, accurate measurements in high-radiation and high-temperature environments. Two ELVIS prototypes were evaluated in terms of both temperature and displacement, showcasing promising results, though challenges with noise during temperature measurements were identified. This report summarizes the rigorous testing performed at Idaho National Laboratory (INL) and highlights the potential applications of Mini LVDTs and ELVIS in nuclear and other high-precision industries.

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ACRONYMS

ATR	Advanced Test Reactor
CANDU	Canada Deuterium Uranium
CT	computed tomography
DAS	data acquisition system
ELVIS	enhanced linear variable intrinsic sensor
IFE	Institute for Energy
INL	Idaho National Laboratory
LINAC	linear accelerator
LVDT	linear variable differential transformer
MSL	Measurement Sciences Laboratory
NIST	National Institute of Standards and Technology
TC	thermocouple
TREAT	Transient Reactor Test Facility
LVDT	linear variable differential transformer

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Performance Test of Mini LVDT – ELVIS

1. INTRODUCTION

The Institute for Energy (IFE) Technology has been at the forefront of linear variable differential transformer (LVDT) development for in-pile testing. Their Halden Boiling Water Reactor has seen the installation of over 2,200 distinct LVDTs since the initiation of in-core measurements. Remarkably, these LVDTs have exhibited a commendable failure rate of less than 10% even after 5 years of continuous operation under the demanding simulated conditions of boiling water reactors, pressurized-water reactors, and CANDU (Canada Deuterium Uranium) reactors [1, 2]. Over the years, IFE has developed many variants of LVDTs. Some of these variants include the Short, Small and Mini. Figure 1 illustrated some of the LVDTs that have been used by INL in experiments at Transient Reactor Test (TREAT) and Advanced Test Reactor (ATR). The Mini LVDT is one of IFE’s most recent production releases. It has the advantage of a very small size and although it is limited in range to +/- 1.5 mm its performance is comparable to the other LVDTs. The smaller size of the Mini LVDT makes it attractive for use in material test reactor experiments where space is extremely limited and valuable.

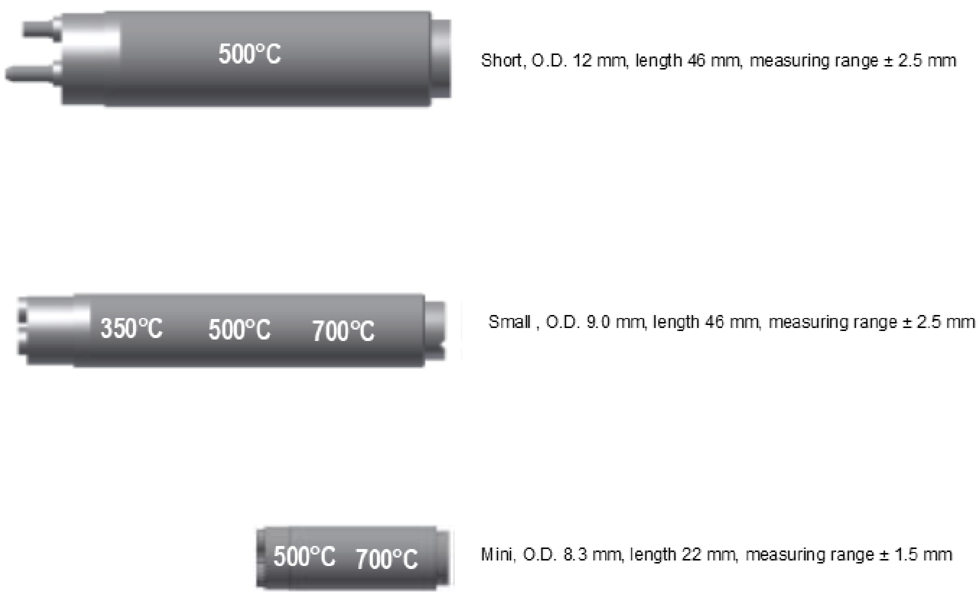

Figure 1. LVDTs produced by IFE and used by INL. Temperatures shown represent specific models and their maximum operating temperature.

Task 1 of Milestone M3CT-24IN0703032 was to develop a Mini LVDT with inherent temperature monitoring capabilities. The Enhanced Linear Variable Intrinsic Sensor (ELVIS) is the direct result of this effort. Two prototypes, ELVIS I and ELVIS II, were designed and constructed. A provisional patent [3] has been filed that protects the intellectual property of this design.

In the field of nuclear fuel research, real-time measurements of pressure and dimensional changes in both the fuel and its cladding during irradiation play a pivotal role in unraveling critical phenomena. These include the elongation of fuel and cladding, the accumulation of "crud," pressurization stemming from fission gas release, and interactions between the pellet and cladding. The repercussions of these phenomena can significantly impede fuel performance. Hence, it is imperative to employ in situ measurements to advance our understanding of the effects of irradiation on fuels and cladding materials.

Achieving micron-scale accuracy in these measurements is essential for a comprehensive assessment of fuel performance. LVDTs stand as established sensors renowned for their exceptional resolution, especially in high-radiation environments.

In irradiation tests conducted within material test reactors, an LVDT with internal temperature sensing can address several critical challenges: Material test reactors can reach extremely high temperatures during irradiation tests. These elevated temperatures can cause thermal expansion or contraction in components, potentially leading to inaccuracies in measurements. An LVDT with internal temperature sensing can compensate for these thermal effects, ensuring precise measurements even in the presence of gamma heating. Irradiation tests often run for extended periods, ranging from weeks to months or even longer. Throughout this time, temperature variations can occur, potentially affecting the accuracy of measurements. An LVDT with temperature sensing will maintain stability and reliability over the course of the test, ensuring consistent and accurate data collection. Accurate measurements are fundamental to meaningful research outcomes. An LVDT with internal temperature sensing contributes to high-quality data, enabling researchers to analyze material behavior with greater confidence and accuracy.

An LVDT with internal temperature sensing can solve several problems related to applications that require precise measurements in environments with varying temperatures. Here are some scenarios where such a device would be beneficial:

- In manufacturing, especially in industries like automotive and aerospace where precision is crucial, temperature variations can impact measurement accuracy. An LVDT with internal temperature sensing can correct for temperature-induced changes.
- In aerospace applications, especially for flight control systems, precise measurements are critical for safe and efficient operation. Temperature variations in the high-altitude environment can significantly affect measurements. An LVDT with temperature sensing can maintain accuracy in extreme conditions.
- In medical equipment such as Linear Accelerators (LINACs) used for cancer treatment, precise beam positioning is vital. Temperature and radiation fluctuations can affect beam placement. An LVDT capable of withstanding high-radiation environments, and with temperature compensation, could result in a great leap forward in accurate beam placement.
- In research and development labs, where experiments often involve precise measurements in fluctuating temperatures, an LVDT with internal temperature sensing can mitigate these effects.

This report provides a performance history of the Mini LVDTs at INL and a comprehensive record of the rigorous testing undergone for ELVIS I and ELVIS II. It does not delve into intellectual property details or present results that may infringe on the provisional patent. A separate document, currently being prepared, will provide detailed information on this technology and include data from the testing. Access to this document may require a nondisclosure agreement between INL and interested parties.

2. BACKGROUND

LVDTs are reliable sensors that convert the mechanical movement of a specimen into an electrical output. A schematic of a five-wire LVDT (INL's baseline for in-pile testing) is shown in Figure 2. Three coils are used, a single primary coil and two secondary coils. 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 magnetic coupling with the primary coil. As the core moves, this coupling changes, causing voltages induced in the secondary coils to experience a corresponding change. This change is measured using a demodulation function, D, represented by:

$$D = \frac{V_a - V_b}{V_a + V_b} \quad (1)$$

where V_a and V_b are the voltages induced on each of the secondary coils. Demodulation can then be correlated to a movement when the core is attached through a pushrod.

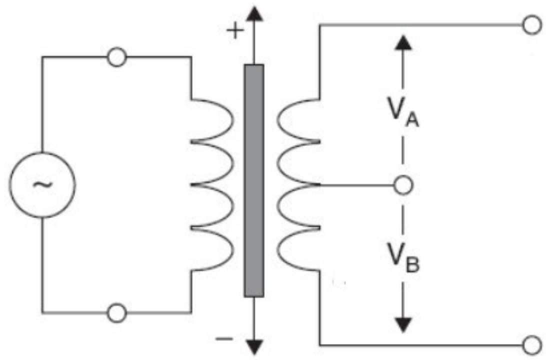

Figure 2. Five-wire LVDT schematic.

LVDT linearity refers to the degree to which the relationship between the physical displacement of the LVDT's core and the corresponding electrical output signal is linear. In other words, it assesses how accurately the LVDT converts mechanical motion into an electrical signal across its specified range of operation.

Ideally, in a perfectly linear LVDT, the output demodulation would change in a perfectly proportional manner with respect to the mechanical displacement of the core. For instance, if the core moves by 1 millimeter, the demodulation should change by a consistent amount, as determined by the sensitivity of the LVDT.

In reality, however, there can be some nonlinearity due to factors like manufacturing imperfections, material property variations, and mechanical tolerances. This means that the actual relationship between core displacement and output demodulation may deviate slightly from perfect linearity.

It is important to note that high linearity is desirable in applications where precise and accurate measurements are crucial. In situations where nonlinearity can be tolerated or compensated for, an LVDT with lower linearity may still be suitable. Most commercially available LVDTs achieve a linearity of 0.5%.

In the context of this study, linearity was determined through a non-standard approach. The LVDT core was moved through its stroke while simultaneously measuring displacement, demodulation, and temperature (ordinarily, a voltage is recorded in lieu of demodulation). Given the temperature sensitivity of LVDTs, measurements were conducted at various temperatures to comprehensively evaluate performance. Figure 3 showcases the calibration data amassed at 20°C for the testing of ELVIS I.

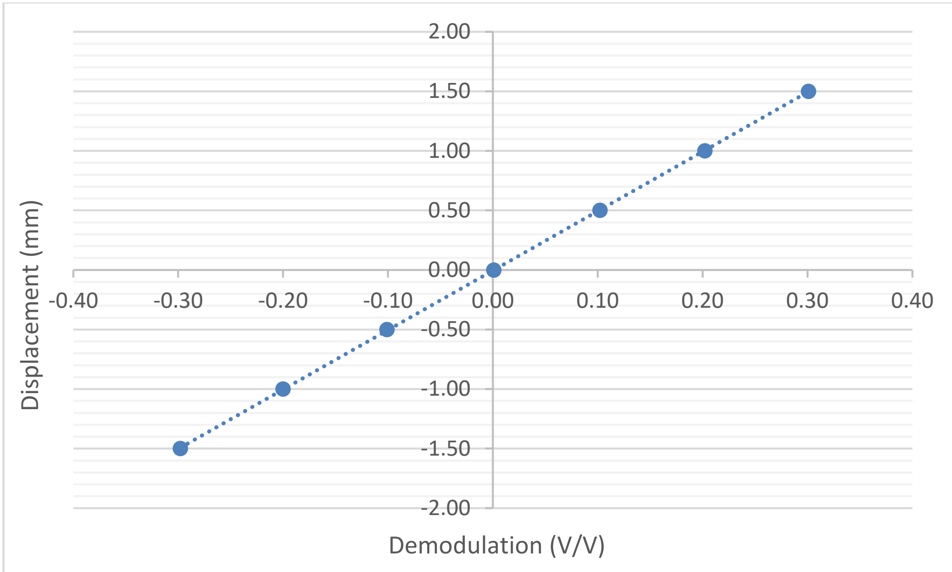

Figure 3. Calibration data for Mini LVDT used in ELVIS II test at 20°C in vertical orientation.

Seven equidistant data points were captured along the stroke, which spanned from -1.5 mm to +1.5 mm, yielding a 3 mm stroke. A linear curve fit was then applied to the collected data. Subsequently, the LVDT core was maneuvered across the stroke, generating another set of seven data points. Each measured position was compared to the position extrapolated from the curve fit. Linearity at each position was computed using the following formula:

$$\frac{Measured\ Position - Calculated\ Position}{Stroke} 100\% \tag{2}$$

After this was completed, the linearity was reported as the maximum value of the seven calculations. A linearity of 0.5% or less was targeted.

Sensitivity was also evaluated as part of this testing. LVDT sensitivity denotes its capacity to accurately translate mechanical displacement into an electrical signal. It quantifies the change in LVDT output in response to a specific mechanical input or displacement. Sensitivity is derived from a linear curve fit and is the inverse of the slope of the line illustrated in Figure 3.

LVDTs are typically deployed as position sensors across various industrial applications, excelling in the precise measurement of linear displacements. Sensitivity is typically expressed in volts (V) per unit of displacement (usually millimeters). For this testing, the electrical output of demodulation (V/V) was employed in lieu of volts (V). For instance, an LVDT with a sensitivity of 0.125 (V/V)/mm signifies that demodulation will change by 0.125 (V/V) for every millimeter of movement.

A higher sensitivity LVDT can detect smaller displacements with greater accuracy, making it suitable for applications requiring high-precision measurements. Conversely, a lower sensitivity LVDT would be used for applications where coarse measurements are acceptable or where the range of motion is larger.

3. USE OF MINI LVDTS AT INL

A total of five Mini LVDTs have been deployed at TREAT [4, 5] and two were extensively tested at Measurement Science Laboratory (MSL) as part of the ELVIS I and ELVIS II evaluations. Table 1 provides evaluation data for these Mini LVDTs. High-quality commercial LVDTs typically have a linearity of 0.5% or less—the lower the number, the better the performance. Although the Mini LVDTs used in the TREAT testing exhibited higher linearity, they were still acceptable for use. Out of the seven Mini LVDTs tested, one failed during calibration, but none failed during test execution at TREAT. IFE determined that this failure was caused by an unexpected change in the chemical composition of the ceramic glue used in the Mini LVDT rated for 700°C. This issue has been resolved, and future Mini LVDTs should not encounter the same problem.

The average sensitivity of a Short IFE LVDT is approximately 0.065 V/V/mm, while the average sensitivity for the Mini LVDTs tested was 0.151 V/V/mm. This suggests that the Mini LVDTs may offer higher resolution than the Short LVDTs. However, their shorter measurement range (3 mm versus 5 mm) may limit their application.

All of the TREAT LVDTs were used as pressure transducers, as shown in Figure 4. To calibrate these pressure transducers, a displacement calibration was first performed to ensure accurate placement of the LVDT body within the pressure transducer. Linearity and sensitivity were then calculated from the displacement calibrations. Figure 5 presents test results for the LVDT pressure transducer used in the THOR-M experiment, showing that this transducer performed exceptionally well and closely tracked the NIST-traceable Honeywell pressure transducer.

Table 1. INL use of Mini LVDTs. Linearity and sensitivity were evaluated at 20°C.

Experiment/Test	Measurement	Linearity (%)	Sensitivity (V/V/mm)
THOR	Pressure	0.6	0.139
THOR-C3	Pressure	1.0	0.133
THOR-M	Pressure	0.9	0.136
THOR-MOXTOP-1	Pressure	0.9	0.159
THOR-MOXTOP-2	Pressure	0.8	0.137
ELVIS I	Temperature	N/A	N/A
ELVIS II	Temperature/Displacement	0.3	0.201

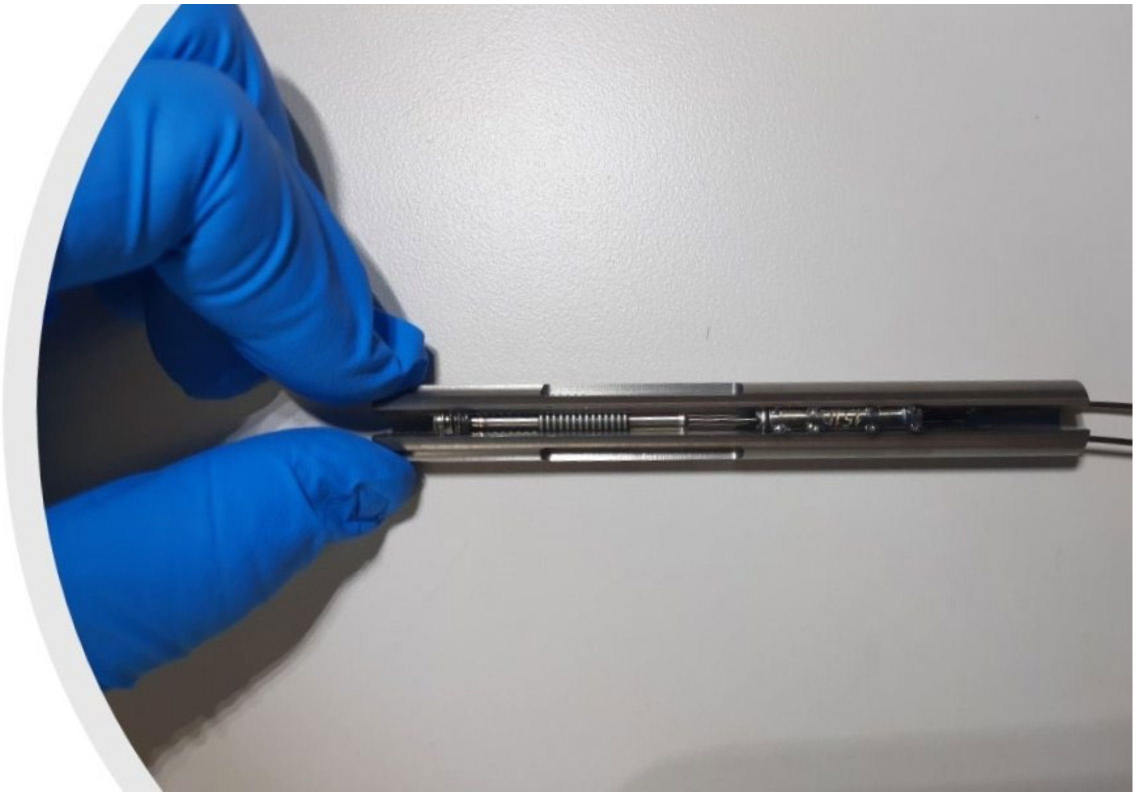

Figure 4. THOR pressure transducer based on the Mini LVDT provided by IFE.

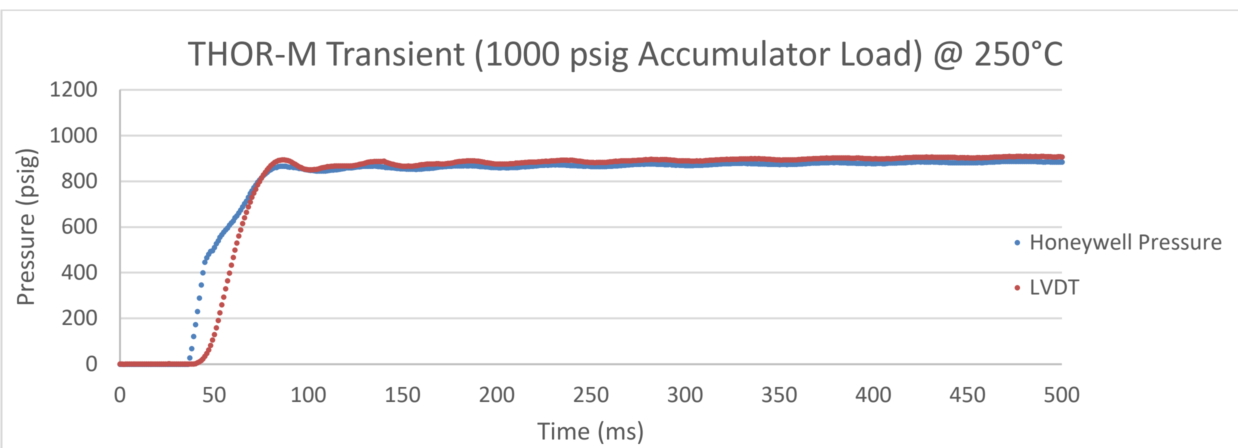

Figure 5. THOR-M pressure transient ran on the MSL LVDT Test and Calibration Rig.

4. EVALUATION OF ELVIS I AND ELVIS II

Two prototypes, ELVIS I and ELVIS II, were evaluated using the MSL LVDT Test and Calibration Rig (see Figure 6). ELVIS I was evaluated solely in temperature measurement mode, while ELVIS II was tested in both temperature and displacement modes simultaneously. Neither prototype was evaluated with electromagnetic field (EMF) shielding, and the LVDT body was not bonded back to the circuit board. Significant noise was observed during temperature measurements, but no excessive noise was detected during elongation measurements for ELVIS II. This temperature noise was mitigated using onboard averaging and post-processing techniques.

Temperature tests ranged from 20°C to 700°C, with ultrapure argon flowing at a rate of 2 l/min for all testing. A snug-fitting NIST-traceable thermocouple (TC) was placed inside the LVDT body for temperature measurement. Normally, the TC is placed on the outside of the LVDT body in loose contact. Interestingly, subsequent testing of ELVIS II revealed up to a 10°C difference between these two types of TC placements, likely due to internal heat generation by the coils when driven. The coils were not active during ELVIS I testing.

Figure 7 shows a photograph of ELVIS I. Calibration curves were generated using furnace set points of 20°C, 100°C, 300°C, and 500°C. Thermodynamic equilibrium was achieved before collecting calibration data, which required approximately 12 hours. After generating the calibration curves, the system was re-run at the temperatures shown in Table 2 to evaluate performance. Thermodynamic equilibrium was again achieved before collecting data. Performance was found to be exceptional, comparable to a K-type thermocouple.

Table 2. ELVIS I test results.

TC (°C)	ELVIS I (°C)	Error (°C)	Error (%)
22.3	22.7	0.4	2.0
301.8	303.3	1.5	0.5
196.9	195.9	-1.0	-0.5
405.2	404.9	-0.3	-0.1

.

Figure 6. MSL LVDT Test and Calibration Rig.

Figure 7. ELVIS I prototype.

Figure 8 presents a photograph of ELVIS II. Calibration curves were generated using furnace set points of 20°C, 100°C, 300°C, and 500°C. Unlike the ELVIS I tests, ELVIS II's coils were active during calibration, and calibration curves were generated for both temperature and displacement simultaneously. As with previous tests, thermodynamic equilibrium was achieved before collecting calibration data, requiring approximately 12 hours. After generating the calibration curves, the system was re-tested at the temperatures shown in Table 3 to evaluate performance. Note that the upper test point of 685.3°C was an extrapolation of the temperature curve. Performance was similar to that of ELVIS I.

Excessive noise was observed during the calibration and evaluation of ELVIS II's temperature capabilities. However, this noise was significantly reduced by fine-tuning the onboard circuitry and post-processing the temperature data. Additional test runs were performed at 20°C and 100°C with the LVDT coils turned off to determine if the coils were contributing to the noise in the temperature readings. These tests showed that the energized coils did not contribute to the noise. The source of the noise needs to be identified and reduced before the ELVIS series sensors can be released for use by external customers.

Additional tests were conducted to assess ELVIS II's impact on the generation of the displacement calibration curve. Calibrations were performed with and without ELVIS II in the system. The results showed identical calibration curves, with no impact on linearity or sensitivity. This positive outcome indicates that ELVIS II can be integrated into an existing data acquisition system (DAS) without affecting its performance.

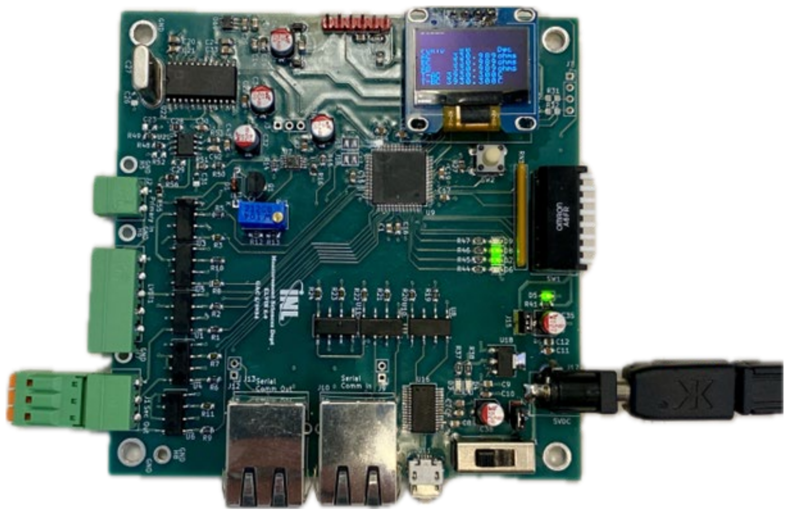

Figure 8. ELVIS II prototype.

Table 3. ELVIS II test results.

TC (°C)	ELVIS II (°C)	Error (°C)	Error (%)
24.9	25.3	0.35	1.4
294.0	288.6	-5.36	-1.8
685.3	678.4	-6.98	-1.0

5. CONCLUSION

The performance evaluation of IFE's Mini LVDT and the ELVIS prototypes demonstrates their suitability for use in demanding environments such as material test reactors. The Mini LVDT offers high sensitivity and linearity despite its compact size, making it a valuable tool for precise measurements in space-constrained applications. The development of ELVIS I and ELVIS II, with integrated temperature sensing, addresses critical challenges in nuclear fuel research by providing accurate real-time data in fluctuating temperature environments. Although noise issues were observed during temperature measurements, the performance of ELVIS II, particularly in displacement measurements, was excellent. Future improvements to reduce noise will enhance the utility of these sensors for broader commercial applications. Overall, the Mini LVDT and ELVIS series have the potential to advance measurement capabilities in high-radiation, high-temperature environments, contributing to safer and more efficient operations in nuclear research and other industries.

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