

Development of a Radiation- and High-Temperature-Tolerant LVDT-Thermocouple Integrated Instrumentation System for In-Pile Irradiation Testing at HANARO

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1. Introduction

Next-generation nuclear systems such as the innovative small modular reactor, the sodium-cooled fast reactor, the high-temperature gas-cooled reactor and the molten salt reactor expose fuels and structural materials to combined high temperature, high stress and high neutron fluence. When repeated power ramps associated with load-following operation are superimposed on this environment, swelling, irradiation creep and dimensional change are accelerated. Resolving such behavior requires high-precision in-pile instrumentation measuring displacement and temperature in real time rather than post-irradiation examination alone.

The Halden Boiling Water Reactor provided the international reference capability in this field, deploying more than two thousand linear variable differential transformers (LVDTs) for fuel elongation, cladding creep and fission gas release measurements until its shutdown in 2018. Idaho National Laboratory has since developed LVDT-based creep test rigs for the Advanced Test Reactor and high-temperature irradiation-resistant thermocouples with the associated drift models [1, 2]. In Korea, instrumented capsules and the fuel test loop of HANARO have employed thermocouples, LVDTs, heaters and self-powered neutron detectors since 1995 [3], but these systems were designed primarily for steady-state irradiation. Long-term stability has not been demonstrated in a combined 700 °C and 300 MPa environment, signal degradation is expected above the Curie point of conventional LVDT materials, and displacement and temperature channels have been operated as independent instruments, so that thermal-expansion compensation and synchronized acquisition are not performed systematically.

This work, initiated in 2026 as part of a national program on advanced neutron irradiation testing technology, develops an integrated LVDT-thermocouple instrumentation system for in-pile testing at HANARO, targeting a displacement accuracy of 1 μm or better out-of-pile and 20 μm or better in-pile, with a temperature accuracy within 2%. This paper reports the design requirements, the reference sensor and data acquisition configuration, and the preliminary performance evaluation planned for the integrated system.

2. Requirements and System Configuration

2.1 In-pile environment

The reference irradiation position is a large-diameter vertical hole of the HANARO core, CT or IR2, where the thermal and fast neutron fluxes reach the order of $10^{14} \text{ n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$. The instrumentation must therefore withstand a specimen temperature of up to 700 °C, an applied stress of up to 300 MPa, gamma heating and a megagray-level accumulated dose, while transmitting low-level signals over a cable run of several tens of meters to the instrument room.

2.2 LVDT

A commercial extreme-environment LVDT of the RDP Group unguided LIN series has been selected as the reference sensor of the first phase. The selected model provides a nominal stroke of $\pm 5 \text{ mm}$, an operating temperature range from -220 °C to 600 °C, a maximum radiation dose of 1 GGy and a linearity error of $\pm 1 \%$ of full scale. The transducer weighs 150 g in total with an armature weight of 7 g, so the inertial and frictional load imposed on the specimen assembly remains negligible. It is supplied with a mineral-insulated (MI) cable of AISI 316L sheath, 3.0 mm outer diameter, four nickel conductors and magnesium oxide insulation, rated up to 800 °C. The sensor is wired as a three-lead half-bridge, which becomes a decisive constraint on the signal conditioning design described below.

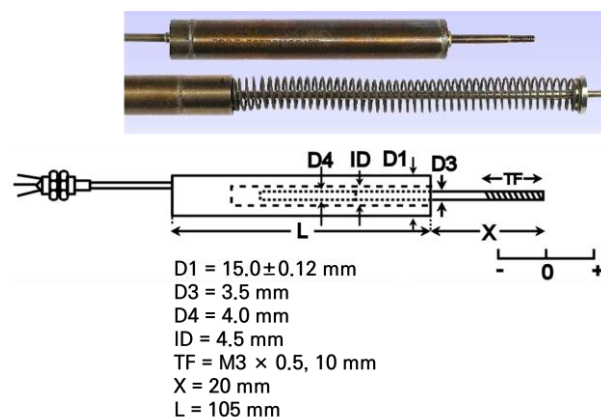


Fig. 1. LVDT specification (LIN56, RDP Group)

2.3 Thermocouple

Type N thermocouples with Nicrosil and Nisil thermoelements in a mineral-insulated construction were selected for the first phase. Type N was preferred over the more widely used Type K because its thermoelement composition suppresses the short-range ordering drift that de-calibrates Type K in the 315-593 °C range, and because published irradiation drift models place Type N within about 0.5 % drift at a fluence of 10^{21} n·cm⁻² for temperatures below 1100 °C [4, 5]. Within the 700 °C envelope of the present work Type N therefore approaches the stability of dedicated high-temperature irradiation-resistant thermocouples without demanding refractory thermoelements or a stabilization heat treatment.

2.4 Integrated data acquisition

A single PXIe chassis platform is adopted so that displacement and temperature are sampled on a common timebase with microsecond-level synchronization. An NI PXIe-4340 module (24-bit, synchronous demodulation, excitation in the 2.4-5.0 kHz band) is used for the LVDT and an NI PXIe-4353 module with a TC-4353 terminal block (32 thermocouple channels, 24-bit delta-sigma conversion, cold-junction compensation) for the thermocouples. Two issues have been identified at the design stage. First, the LVDT module supports only four- to six-wire connections with physically separated primary and secondary coils, so the three-wire half-bridge sensor cannot be connected directly. An external bridge completion network satisfying $Z_1/Z_2 = R_1/R_2$ is therefore designed, and its temperature coefficient must be small enough not to alias into the displacement reading. Second, the open-thermocouple detection circuit will be disabled, since its detection current becomes a significant noise source when the lead resistance of long MI cables is high. Instrument control, acquisition and signal processing are implemented either in LabVIEW or through the NI-DAQmx Python application programming interface, and both routes are evaluated so that the temperature-based correction of the raw displacement can subsequently be embedded in an automated test sequence.

3. Preliminary Performance Evaluation Plan

The first campaign is limited to bench-scale characterization of the sensors and modules before capsule integration. At room temperature the sensor is mounted on a micrometer stage to obtain sensitivity, linearity over the full stroke, hysteresis, repeatability and null-position stability, and to optimize the excitation frequency and amplitude, the filter bandwidth and the reference phase. The phase shift and attenuation of the MI cable are measured as a function of cable length and the bridge completion resistors are trimmed accordingly. The thermocouple channels are verified for electromotive force versus temperature, response time

and insulation resistance, after which crosstalk between the displacement and temperature channels is quantified.

Stepwise elevated-temperature tests in a tube furnace (room temperature, 300, 500 and 600 °C) will then quantify sensitivity and offset drift and calibrate a COMSOL Multiphysics model coupling the electromagnetic response of the coil and core with thermal expansion, including the temperature dependence of core permeability and coil resistance. MCNP calculations of neutron flux and gamma heating at the irradiation position will feed the same model to estimate nuclear heating and the transmutation-induced change of the Seebeck coefficient, which underlies the in-pile drift correction to be validated later in the project.

4. Conclusions

An integrated LVDT-thermocouple instrumentation system is under development to extend real-time in-pile measurement capability at HANARO. The reference configuration comprises an extreme-environment commercial LVDT rated to 600 °C and 1 GGy, Type N thermocouples and a synchronized PXIe acquisition platform with the bridge completion network required by the three-wire sensor topology. Bench characterization of this hardware will establish the baseline against which the in-house high-temperature sensors and the temperature-compensated displacement algorithm will be evaluated before capsule integration.

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