INL/RPT-22-66384-Revision-0

High-Temperature Irradiation-Resistant Thermocouple (HTIR-TC) Qualification Work

March 2022

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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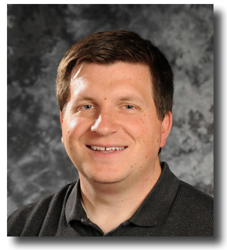

Introduction

The high-temperature irradiation-resistant thermocouple (HTIR-TC) has successfully passed through the design, calibration, and qualification phases, following the guidelines for sensors developed under the Nuclear Energy Enabling Technologies (NEET) Advanced Sensors and Instrumentation program [1]. The qualification test needs were laid out in a qualification document [2], and the HTIR-TC underwent in-reactor testing for over a year in the Advanced Test Reactor (ATR)'s high-neutron-flux (a perturbed thermal flux of up to ~2.8×10^{14} nv and a fast flux of up to ~2.25×10^{14} nv), high-temperature (up to 1550°C) environment as part of the Advanced Gas Reactor (AGR) 5/6/7 fuel test. In this test, several HTIR-TCs were placed at various locations in the test fixture, which was designed for evaluating the performance of new advanced fuels designed specifically for the AGR program.

The following is an overview of how the HTIR-TCs followed the qualification guidelines and processes [1], their performance results from the aforementioned reactor qualification test, and their performance features, including measurement range, accuracy, repeatability, drift, and end of life (EOL).

Qualification Guidelines and Processes

The qualification guidelines for instrumentation developed at Idaho National Laboratory (INL) [1] are based on accepted procedural and quality assurance standards for product development. They are intended as a useful resource for INL instrumentation R&D by referencing and consolidating guidelines pertaining to NASA, Nuclear Quality Assurance (NQA)-1, International Organization for Standardization metrology, and nuclear industry standards in a manner pertinent to INL's sensor system development process.

The overall product development and quality assurance processes described in the qualification guidelines are divided into three main phases:

- Design Phase
- Calibration Phase
- Qualification Phase.

HTIR-TC Performance Demonstration in the ATR

Construction and calibration of the HTIR-TCs used in the AGR-5/6/7 test followed the guidelines presented in the preliminary build and calibration reports, as well as specific controlled documents pertaining to each build [3-5]. Furthermore, the performance requirements were based on the function and operation requirements report [6].

Of the five capsules in AGR 5/6/7, only capsules 1 and 3 contained installed HTIR-TCs for measuring experimental temperatures. However, the lead wires for each TC needed to exit the reactor core by passing through designated channels in the upper capsules. This means, for example, that the HTIR-TCs positioned for temperature measurement in capsule 1 had to pass through the high-thermal-neutron-flux regions of the reactor core reflected in capsule 3 (i.e., the reactor height midplane). Thus, although the HTIR-TCs in capsule 1 measured a lower temperature (as expected), the drift caused by thermal- and fast-neutron-flux-induced changes in the cable thermoelements would be similar for every TC located in capsules 1 and 3.

The test fixture also had provision to pass a small adjustable He-Ne mixture gas flow around the TCs in order to maintain a constant temperature and minimize the effect of power fluctuations on the TC temperature readings [7].

The gas flow was maintained at a minimal value and did not remove heat via convection. It merely provided a high thermal conduction path to the cooler high water flow of the reactor coolant outside the capsule housing serving as a heat sink for the capsule.

HTIR-TC Drift Model

Generally speaking, all TC types eventually drift after use. There are two major sources of TC drift during irradiation tests: temperatures exceeding design parameters and thermoelement transmutation. Both have been modeled to capture the apparent drift seen in AGR 5/6/7. Regarding high-temperature drift, it was observed, even in out-of-pile testing, that HTIR-TCs drift when temperatures approach within 400°C of the heat treatment and calibration temperatures. With thermoelement transmutation, the thermal neutron flux is captured by the thermoelements in the TC, resulting in signal drift.

A common misconception about TC sensors is that the temperature measurement is generated in the junction

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Table 1. Comparison of the calculated and the observed HTIR-TC drifts in the ATR test.

HTIR-TC #	Time at High Temperature (EFPD)	Operating Temperature [°C]	Drift Calculated by HTIR-TC Drift Model [%]	Observed Drift of HTIR-TC in ATR Test [%]	Difference between Calculated and Observed Drift [%]
1-12	125	1293	-3.29	-3.33	~ -0.03
1-13	125	1293	-3.29	-3.33	~ -0.03
1-14	125	1381	-3.50	-3.48	~ 0.02
3-5	125	1500	-8.65	-8.67	~ -0.02

(i.e., where dissimilar wires are joined together). In actuality, however, the EMF is generated in the length of thermoelement.

Concerning the effect that the two sources of drift had on the HTIR-TC cable during the AGR 5/6/7 test, both were modeled and summed so that the calculated drift could be compared to the observed drift, as shown in Table 1. The empirical model, which extends out over 125 effective full-power days (EFPD) aligns with what was observed over the same duration for the four HTIR-TCs installed in AGR 5/6/7. The localized temperature over the actual length of the HTIR-TC cable was utilized from the experiment model [8].

Table 2. Summary of HTIR-TC general requirements.

Parameter	Requirement	Measured
Temperature Range Min [°C] Max [°C]	Room Temp 1550	Room Temp 1550
Accuracy [%]	±1	±0.4 >100 ±1 <100
Repeatability [%]	±1	<±0.3
Total drift in ATR [%]	-3.5	-3.5[2]
Drift[3] in BWR/PWR [%]	-1	-0.86[2]
Thermal Transients[4]	10	14 – 19

[1]For 125 EFPDs of exposure when operating at less than the heat treatment temperature
[2]Calculated from drift model
[3]For 18-month refueling cycle.
[4]Greater than 50°C/hour.

Conclusions

Based on the HTIR-TC drift model and the results of the HTIR-TC qualification test, in which the TCs were installed as part of the AGR 5/6/7 experimental test fixture, the present HTIR-TC design should be considered qualified for the following three applications:

1. Standalone TC in a well-moderated commercial power reactor (i.e., a boiling-water reactor [BWR] or pressurized-water reactor [PWR]), used for measuring reactor temperatures of <1050°C throughout a full 18-month refueling interval, as long as the temperature change during normal startup/shutdown is controlled and kept below ~50°C/hour. The drift for this application (using the conservative HTIR-TC neutron absorption coefficient of ~2.3 barns) is expected to be <0.9%. Because the HTIR-TC is really designed to measure high temperatures, it is unlikely to be used as the primary temperature sensor, but as a back-up sensor for monitoring the commercial power reactor inlet and outlet temperatures that could result if there was a loss of coolant accident.

Note that the 1050°C value is >650°C higher than the core outlet temperature for these reactors, and well below the heat treatment temperature of the HTIR-TCs. In this application, the HTIR-TC can, in the event of an accident, also be used to measure core temperatures of up to ~1550°C for a short period (i.e., approximately 1200 hours) before the reactor is shut down and the temperature cools, without entailing any drift concerns during the presumably short duration of this high-temperature transient. There have already been several cases in which NPPs have made inquiries regarding the use of HTIR-TCs.

2. Standalone TC in any commercial non-nuclear facility, used for measuring temperatures of <1050°C over a prolonged period. The drift for this application should be <0.5%, since drift does not stem from neutron fluence effects. Accurate measurements should also be possible at up to 1550°C for at least a short time (i.e., approximately 1200 hours) during high-temperature transients. As with the previous application, the temperature change during normal startup or shutdown should be kept below ~50°C/hour.

3. TC in a test fixture for conducting fuel experiment tests in a test reactor (e.g., the ATR). For such applications, if the max temperature is controlled to within 1%, temperature measurements of up to 1550°C are feasible over a period of 125 EFPDs, with a drift of <4% when the peak thermal flux is ~2.8×10^{14} nv and the fast flux is ~2.3×10^{14} nv. Also, provisions should be made for accurate temperature and neutron flux profile calculations and/or measurements along the length of the TC cable. For this application, the number of severe thermal transients due to rapid startup/shutdown should be kept below five.

See Table 2 for a summary of the HTIR-TC general requirements.

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References

[1] Dayal, Y., Jensen, C. 2019. "Guidelines for Developing and Qualifying Instrumentation Systems at Idaho National Laboratory," Idaho National Laboratory, GDE-947 Rev 0.

[2]. Skifton, R. 2021. "High Temperature Irradiation Resistant Thermocouple Qualification Requirement Report," Idaho National Laboratory, INL/EXT-21-63269.

[3] Skifton, R. 2021. "High Temperature Irradiation Resistant Thermocouple Preliminary Design Report," INL/INT-20-60511, Idaho National Laboratory, INL/EXT-21-63198.

[4] Skifton, R. 2021. "High Temperature Irradiation Resistant Thermocouple Preliminary Calibration Report," INL/INT-20-60512, Idaho National Laboratory, INL/EXT-21-63172, 2021

[5] Palmer, A.J. 2017. "HTIR Thermocouples for AGR-5/6/7," Idaho National Laboratory, SPC-1963, Rev 3.

[6] Skifton, R. 2021. "High Temperature Irradiation Resistant Thermocouple Function and Operation Report," Idaho National Laboratory, INL/EXT-21-63173.

[7] Scates, D., Reber, E.L., Miller, D. 2020. "Fission gas monitoring for the AGR-5/6/7 experiment," Nuclear Engineering and Design, 358. https://doi.org/10.1016/j.nucengdes.2019.110417.

[8] T Pham, C.B., Sterbentz, J.W., Hawkes, G.L., Scates, D.M. Palmer, J. 2020. "AGR-5/6/7 Experiment Monitoring and Simulation Progress," INL External Report, INL/EXT-19-55429. https://www.osti.gov/servlets/purl/1689160.