Optimized High-Temperature Irradiation-Resistant Thermocouple for Fast-Response Measurements

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***Abstract*—The high-temperature irradiation-resistant thermocouple is the only temperature probe proven to withstand the high-temperature (>1290°C), high-radiation (a fluence of up to ~1 × 10^{21} n/cm^2) environments of nuclear reactor fuel design testing and/or over-temperature accident conditions. This report describes the improved performance of a molybdenum and niobium thermocouple by utilizing a coaxial design (i.e., a single wire grounded to the outer sheath). This optimized high-temperature irradiation-resistant thermocouple features a simplified design yet allows for more robust individual components. The niobium and molybdenum thermoelements can be used interchangeably in either the sheath or wire, depending on the intended application. Via a plunge test in flowing water, the response time of the coaxial build of the high-temperature irradiation-resistant thermocouple was determined to be 30x faster than that of the comparable ungrounded type-K thermocouples, and 10x faster than the grounded type-K thermocouples and traditional ungrounded high-temperature irradiation-resistant thermocouples (i.e., two-wire configurations). Furthermore, by capitalizing on the coaxial design, a multi-core high-temperature irradiation-resistant probe with multiple "single-pole" wires along the length of the sheath was proven feasible. This multi-core, thermocouple design was dubbed a "demicouple." The high-temperature irradiation-resistant demicouple is primarily applied during fuel experiments to record multiple fuel-pin centerline temperature measurements using a single compact sensor. Furthermore, the shared "common" leg between demicouple junctions reduces error propagation in secondary measurements such as temperature differentials.**

***Keywords* —Thermocouple, Irradiation-Resistant, In-pile, Sensor**

I. Introduction

THE high-temperature irradiation-resistant thermocouple (HTIR-TC) is proven to survive periods of temperature and irradiation exposure never approached by any other thermocouple (TC). Recent irradiation tests during the Advanced Gas Reactor 5/6/7 experiment demonstrated the HTIR-TC's lifetime to be on the order of 10^{21} n/cm^2 at temperatures of up to 1500°C [1]. Such a lifetime is sufficient for commercial application during a nuclear power plant's typical 18-month refueling cycle, as well as in consideration of the high temperatures expected to be generated by advanced nuclear reactor concepts.

There is a need to continually improve the HTIR-TC so as to achieve longer lifetimes, improved form factors, faster time responses, etc. All deviations from the traditional HTIR-TC concept must be built, tested, and qualified for nuclear application—adding to the repertoire of high-temperature sensors capable of withstanding high doses of radiation.

II. Background

The basic working principle behind any TC is the generation of electromotive force (EMF) by heating one end of a circuit of two dissimilar metals [2, 3]. The EMF is a measurement of electrical potential (usually in mV), as determined via the material specific Seebeck effect. For a basic overview of how a TC operates and behaves during an irradiation test, see the appendix at the end of this report.

Conventional base metal TCs (e.g., type-K TCs) are commonly used in pressurized-water reactors (PWRs) to measure the reactor core exit temperature. These core exit TCs (CETs) generally do not provide input to the reactor trip system; thus, they are not subject to the same stringent response time and calibration requirements as, for example, safety-related narrow-range reactor coolant system resistance temperature detectors. At minimum, PWRs require two operable CET channels per reactor quadrant to enable radial temperature gradient indications. With two CETs per channel, this means that a minimum of 16 operable CETs are required from an inventory of more than 60 installed CETs [4]. In general, CETs are declared inoperable or out of service if they read an unrealistic temperature (e.g., one that is off the scale) or suffer from erratic spiking on the output signal. The cause of the CET failure may be due to the TC itself, or to a cable/connector issue—as is often the case [5]. Aside from these failure modes, CETs have not been shown to suffer from systematic calibration drift under normal PWR operation conditions—mainly due to the low temperature and low neutron flux regions they reside. However, it is generally understood within the advanced nuclear reactor community that both base metal and noble metal TCs may experience calibration drift (i.e., decalibration); thus, they may be unsuitable for long-term operation in the high-temperature, high-radiation environments expected in next-generation nuclear power plants.

Further, direct temperature measurements of core fuel—either at a centerline or cladding location—may reduce temperature uncertainties by an order of magnitude. This could provide reactor operators a better envelope in which to operate. Of course, temperature is not the only metric to be considered, but it plays a significant role in the thermal, mechanical, and neutronics of the core.

III. Optimized HTIR-TC Design

The HTIR-TC was recently redesigned as an optimized coaxial cable—a TC built using an outer sheath wrapped around an individual wire. By using the sheathing material as a “live” thermoelement, the sheathing is integral to the generated EMF. In contrast, the traditional HTIR-TC build utilizes two dissimilar wire thermoelements housed in an outer “dead” sheath housing.

The coaxial build was then further iterated by forming a multipoint TC, referred to here as a “demicouple” (DC). Up to five “coaxial” wires can be integrated into the sensor while still maintaining the same overall diameter as the traditional single-wire HTIR-TC build.

A. Coaxial HTIR-TC

A cartoon schematic/cutaway of the coaxial HTIR-TC is shown in Fig. 1, with the outer sheath (shaded red) composed of the niobium (Nb) thermoelement, and the inner wire (shaded green) composed of the molybdenum (Mo) thermoelement. (Though not shown, the sensor can also be built in an inverted manner, with Mo for the outer sheath and Nb for the inner wire). With the Nb sheathing thermoelement now a “live” part of the sensor, the EMF generated within the sheath is part of the overall sensor EMF output. In Fig. 1, the metal-oxide insulation between the thermoelements is shown as yellow, and its purpose is to electrically insulate the two thermoelements from each other along the length of the cable. At one end of the TC, a single junction would be formed by swaging the outer sheath onto the inner wire. This junction—to the right of the schematic shown in Fig. 1—would be the location of the temperature measurement. The cabling and lead wires going to the data acquisition (DAQ) module is shown as going to the left of the schematic in Fig. 1.

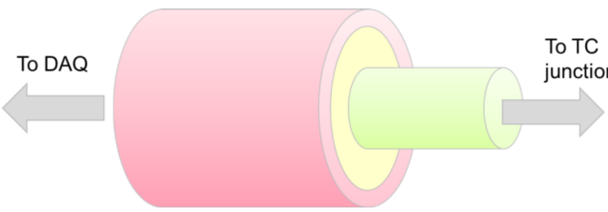

Fig. 1. Cartoon schematic of the coaxial HTIR-TC infrastructure (not to scale). The inner core (green) is one thermoelement conductor; the outer sheath (red) is another. The insulation (yellow) between the two conductors is typically comprised of a metal oxide (i.e., alumina). The sensor would continue on to the right to the measurement location and to the left to the Data Acquisition System (DAQ).

There are several advantages to building the HTIR-TC according to a coaxial design, rather than the traditional two-wire design: (1) the smaller outer diameter of the sensor can lead to less disruption of the sensing environment; (2) the additional material (i.e., mass) comprising both thermoelements, individually, within the sensor cross section enhances their robustness; (3) less overall lengths of material are needed to manufacture the TC, thus reducing costs and lead times; (4) manufactured spools of coaxial HTIR-TC cabling are mass-producible, (5) the sensor can be cut to length from the mass-produced spool, as opposed to the one-off builds for the traditional two-wire HTIR-TC. One major disadvantage—contrary to these five advantages listed—is the inability to be electrically isolated from the surroundings due to being inherently grounded. As with all grounded thermocouples, this must be considered to avoid erratic noise in the measurement.

An abbreviated cross-section view of the coaxial design is shown in Fig. 2, taken from an x-ray radiograph. In the figure, the outer sheath—seen at the top and bottom of the image—is comprised of Nb, while the inner wire is Mo. The lighter gray area between the outer sheath and inner wire is alumina—an electrical insulator.

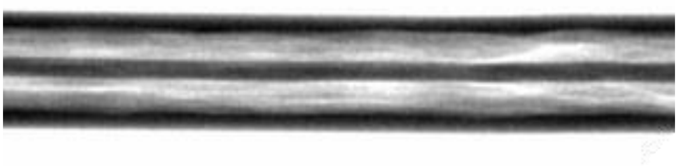

Fig. 2. Abbreviated cross-section view—using x-ray radiography—of the coaxial HTIR-TC. The inner-wire core is composed of Mo, while the outer sheath is made of Nb (top and bottom of image). The insulation between the two conductors is comprised of alumina.

B. Multipoint HTIR-DC

The coaxial build can be integrated into a DC by using only “half” (corresponding to the prefix “demi-”) the number of wires required for a traditional TC. Multiple identical thermoelement legs are inserted into the insultation and are terminated at the desired locations for temperature measurement. A cutaway example of a 5-point DC is seen in Fig. 3, with one of the five wires shown as a TC junction being swaged onto the inner wall of the TC sheath. The other four wires continue along down the cabling to form junctions elsewhere.

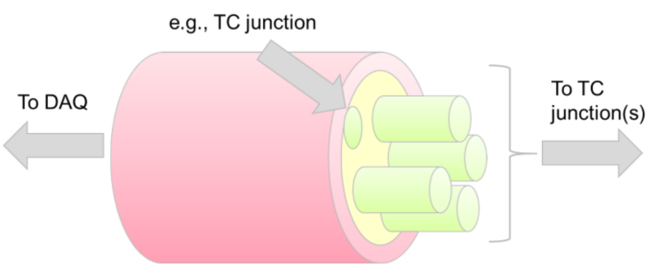

Fig. 3. Cartoon schematic/cutaway of the HTIR-DC (not to scale). An example TC junction is seen at the figure cut plane, while four other unique thermoelements continue along down the length of the cable to form TC junctions elsewhere.

IV. Experimental Setup, Testing, and Results

Two major tests (i.e., a long-term drift test and a time response plunge test) were performed on the coaxial HTIR-TCs, along with the expected proof-of-concept tests.

A. Long-term drift test

The coaxial HTIR-TC was implemented in Idaho National Laboratory's high-temperature longevity furnace, remaining there for thousands of hours at 1250°C. The furnace control TC was periodically checked by inserting a type-B TC with National Institute of Standards and Technology (NIST) traceable calibration into the furnace thermal well. This method alleviated drift within the furnace Type-B TC and ensured that the furnace itself did not drift over time.

The results of the longevity furnace test for the coaxial HTIR-TC are seen in Fig. 4. HTIR-TC A and B were both identical in build using Mo as the center wire, alumina (Al_2O_3) insulators, and a Nb alloy with 1% zirconium (Zr) balance for the outer sheath. HTIR-TC C varied only in the insulator material where hafnia (HfO_2) was utilized instead. Both HTIR-TC A and B drifted upwards no more than 5% over the course of the test—with HTIR-TC B performing slightly better. For HTIR-TC C, the drift was essentially 0%. This appears to show a slight edge using hafnia over alumina for the coaxial build.

For all three TCs, a downward trend was expected, such normally being the case when these TC types drift due to exposure to excessive heat. These drift results show that the designated channels that the TCs were installed in were perhaps slowly increasing in temperature (e.g., gas flow, TC movement, or conduction paths), or perhaps the thermocouple cabling was becoming contaminated with time due to its surroundings through solid state diffusion at these elevated temperatures. As a final note to the observed temperatures, a great deal of confidence is found in the overall furnace set up with the type-B TC temperature spot check not showing any sign of temperature variation.

B. Plunge test

A TC's response time can be directly measured by suddenly plunging it from air into flowing water—both being at different temperatures. This is known as the "plunge test." Using the definition of a first-order system, the TC's response time can be obtained as a time constant, τ, by simply calculating the time it takes the TC output signal to reach 63.2% of its final value, following this step change in temperature. The plunge test principal concept is illustrated in Fig. 5, with the TC being plunged from air into stirred or flowing water (left). The time constant, τ, of the new plunge temperature is accurately measured [6].

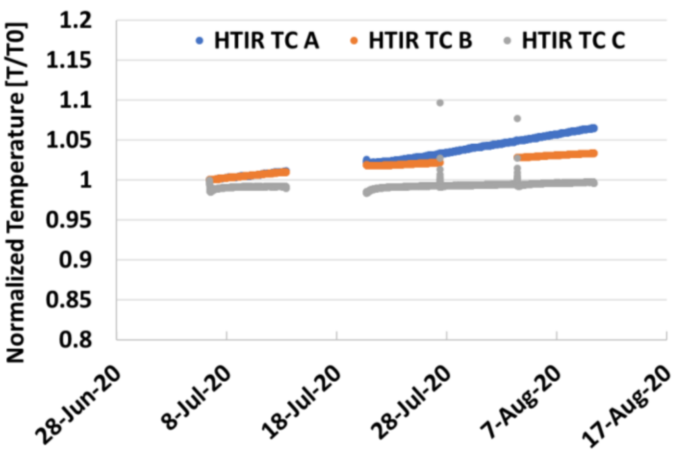

Fig. 4. Longevity test for the coaxial HTIR-TCs, showing <5% drift over a period of 1000+ hours. One set of TCs included Nb1%Zr.

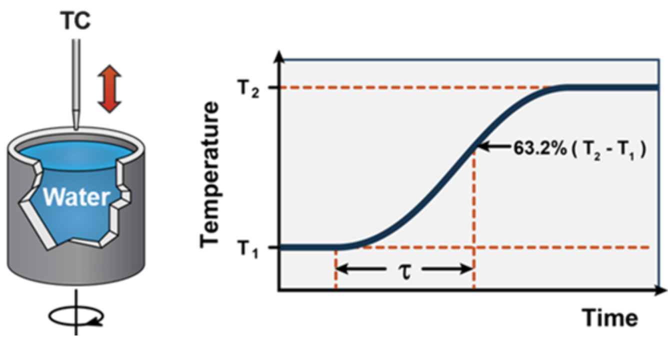

Fig. 5. A typical plunge test for determining the time constant, τ, of a new TC sensor to obtain a baseline comparison with other TCs available on the market.

Note that the TC's response time under these test conditions will not equal that when subjected to other conditions (e.g., different fluids, temperatures, or flow rates). However, this test is typically performed by sensor vendors wanting to establish a baseline comparative response time for a given sensor design, in hopes of potentially guiding potential buyers.

Three different types of HTIR-TCs were tested in the plunge test apparatus, along with two standard type-K TCs. The sensors varied in terms of the ground state, diameter, number of junctions, and base metals used. One HTIR-TC followed the optimized design, which was inherently grounded. Two HTIRs were DCs with two junctions each: one at the tip of the TC and another ~25 cm (10 in.) away from the tip. And one was a standard HTIR-TC ungrounded from the sheath. For comparative purposes, one of the type-K TCs was used in a

Table I
Results of the HTIR-TC Plunge Test

TC #	Number of Junctions	Junction Type	Probe Outer Diameter	Response Time [s]
HTIR				
#1	2*	Grounded	1.6 mm (0.0625 in.)	0.013
#2	1	Grounded	1 mm (0.040 in.)	0.038
#3	1	Ungrounded	1.6 mm (0.0625 in.)	0.144
#4	2*	Grounded	1.6 mm (0.0625 in.)	0.013
Type K				
#1	1	Grounded	1.6 mm (0.0625 in.)	0.160
#2	1	Ungrounded	1.6 mm (0.0625 in.)	0.440

*Tip and midpoint junctions are assumed to be similar.

ground state, whereas the other was ungrounded. Baseline response time test measurements were conducted in 20°C water flowing at 1 m/s.

The results of the plunge test show the response times of grounded coaxial HTIR-TCs to be 10–30x faster than those of comparative technologies. Though the coaxial design is inherently grounded, when compared with type-K grounded TCs, it is an order of magnitude faster. Even when compared to its ungrounded counterparts, the TCs are still much slower.

V. Conclusions

The coaxial HTIR-TC was demonstrated to be long-lasting and fast-responding. The drift test revealed a drift of ~0% throughout the entire course of the test by utilizing hafnia as the electrical insulator of the thermoelements (see HTIR-TC C above). The results of the plunge test show the coaxial HTIR-TCs/DCs to be 10–30x faster, respectively, than traditional type-K and HTIR TCs.

Appendix

The TC operates under the basic principle of EMF being generated as per the material specific Seebeck effect. By completing a circuit of two dissimilar metals, then heating one end of the circuit, electrical potential is generated, usually on the order of mV. The general equation is as follows:

$$EMF(T) = \int_0^L [S_1(T,x) - S_2(T,x)] \frac{dT}{dx} \partial x, \qquad \text{(A1)}$$

where $S_{1\&2}$ are the material dependent local Seebeck coefficients for the respective thermoelements; T is the local temperature along the length, x, of the thermocouple (TC) cable; and L is the overall length of the TC. The main takeaway from Eq. A1 is that it is necessary to calculate the local EMF generated in the TC thermoelement if material properties and/or temperature gradients are not constant.

Under irradiation, the Seebeck coefficient can be affected (i.e., "damaged") by thermal and fast neutrons [7], leading to sensor decalibration. The Seebeck coefficient can be substituted in Eq. A1 by:

$$S^*(T,x) = S(T,x) \times Reduction\ Factor, \qquad \text{(A2)}$$

where S^* is the local irradiated Seebeck coefficient and the reduction factor is defined by:

$$Reduction\ Factor = e^{-(C_1 \varphi_{Thermal} + C_2 \varphi_{Fast})t}, \qquad \text{(A3)}$$

where $C_{1\&2}$ are constants that heavily depend on the thermal and fast neutron cross sections, respectively; φ is the local neutron flux, as labeled; and t is the total time under irradiation.

It is important to note that equations A1–A3 imply that the neutron irradiation present in any neutron field affects the entire length of TC cabling. The TC junction is simply the location of the temperature measurement, but the EMF is generated along the entire length of the TC cabling, which is bombarded by thermal and/or fast neutrons during reactor operation.

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