This article has been accepted for publication in IEEE Transactions on Instrumentation and Measurement. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TIM.2025.3602597

Thermocouples in Resistive and Induction Furnaces Operated in Strong Magnetic Fields (2025)

Zachary P. Tener, Steven Flynn, Alexander M. Donald, James J. Hamlin, Mark W. Meisel, Michele V. Manuel, Michael S. Kesler

***Abstract*— Thermomagnetic processing methods require an understanding of the *in-situ* temperatures experienced by the workpieces. When commonly used thermocouples are employed in induction furnaces, RF fields can contribute additional temperature uncertainties to the ones arising from the use of strong magnetic fields. Focusing on temperatures between 300 °C to 1000 °C produced by induction and resistive furnaces, the readings generated by Type-K thermocouples were contrasted to the ones produced by Type-S and Type-N sensors for magnetic fields up to 9 T. Overall, when comparing Type-K response to temperatures above 700 °C in both zero-field and high field (≤ 9 T), the differences amounted to less than 1%, and when continuously measured has a linear relationship to the strength of the applied field. The relative invariance of Type-N and Type-S thermocouples was confirmed. These findings suggest that the use of thermocouples in high magnetic fields remains a viable option for applications, although the precision depends on the type used.**

***Index Terms*— Thermomagnetic processing, thermocouples, high temperature, strong magnetic fields.**

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) Industrial Efficiency & Decarbonization Office (IEDO) award number DE-EE0009131. A portion of this work was performed at the National High Magnetic Field Laboratory (MagLab), which was supported by National Science Foundation (NSF) Cooperative Agreement No. DMR-1644779 and the State of Florida. *Corresponding author: Michael S. Kesler*.

This paper was produced by a collaboration between research teams at Oak Ridge National Laboratory and the University of Florida.

Z. P. Tener (present address Savannah River National Laboratory, Aiken, SC) and M. S. Kesler are previous and current members of the Thermomagnetic Processing Laboratory, Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN.

S. Flynn (present address Department of Chemistry, Johns Hopkins University, Baltimore, MD), A. M. Donald, J. J. Hamlin, and M. W. Meisel (also a member of the National High Magnetic Field Laboratory) are previous or current members of the Department of Physics, University of Florida, Gainesville, FL.

M. V. Manuel (presently U.S. Steel Dean, Swanson School of Engineering, University of Pittsburgh) was previously Chair of the Department of Materials Science and Engineering, University of Florida, Gainesville, FL.

Notice: This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan.

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org

I. INTRODUCTION

THE effects of magnetic fields on the responses of thermocouples (TCs) that contain magnetic components have received considerable attention below 180 °C [1-5]. This temperature range encompasses the upper limit (152 °C) of the ferromagnetic behavior of Alumel, a standard component of Type-K TCs (see **Table 1**). However, even above the magnetic transition temperature, the use of TCs containing Alumel or other magnetic components can generate doubt in the accuracy and precision of thermocouple readings in the presence of an applied magnetic field, and expensive substitutes are used to eliminate a perceived but often uncharacterized source of error. These include platinum Resistance Temperature Detectors (RTDs) [6] and Fiber-Bragg Grating (FBG) [7, 8] sensors, which are considered to be magnetic-field independent. Both options eliminate magnetic components but have their own detriments.

More specifically, RTDs typically consist of pure elements whose temperature dependent resistivity has been calibrated and magneto-resistivity is known or assumed to be negligible. The Pt-based non-magnetic variety are not typically used above 660 °C due to the Pt-uptaking impurities from its surroundings, typically from a metal sheath. Contrastingly, FBGs are optical sensors commonly employing etched glass fibers acting as gratings for a designated range of wavelengths of light. Since the filtered light depends on physical characteristics of the fiber, changes in mechanical stress or temperature result in changes to the optical response. The main limitation of FBGs is the specificity and complexity of their manufacture lead to increased costs.

With the development of thermomagnetic processing using induction furnaces in magnetic fields up to 9 T and as high as 1000 °C [9-15], the magnetic field-induced shifts of TC calibration curves require renewed scrutiny, especially since these techniques are actively being scaled to industrially relevant sizes. Large magnetic fields at high temperatures also impact multiple research fields, from high-energy physics to material development and characterization, alongside more conventional circumstances such as high current transitions in electrical operations. The alternatives of RTDs and FBGs are effective, but these represent a greater financial investment beyond the ones associated with Type-K and Type-N TCs and a potential barrier to the adoption of high-field thermal processing. Consequently, an understanding of the magnetic field-induced shifts of high temperature readings is crucial, and the use of inexpensive, easily calibrated TCs are required.

Authorized licensed use limited to: Florida State University. Downloaded on September 02,2025 at 14:16:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. All rights reserved, including rights for text and data mining and training of artificial intelligence and similar technologies. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Instrumentation and Measurement. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TIM.2025.3602597

This work seeks to understand the behavior of TCs in the previously underexplored high field, high temperature regime. Herein, the responses of unshielded Type-N, Type-K, and Type-S TCs operated in resistive and induction furnaces to temperatures up to 1000 °C in magnetic fields up to 9 T are reported. Type-S vs. Type-K investigations were performed at Oak Ridge National Laboratory (ORNL) while Type-N vs. Type-K studies were performed at the University of Florida (UF).

II. Experimental Configurations and Protocol

A. Thermocouples

An initial expectation regarding TC thermometry within magnetic fields is informed by whether the TC consists of any magnetic materials. Herein, Type-K and Type-N are considered economical choices next to the expensive Type-S version. The TC constituents and their compositions are shown in **Table 1**.

The constituents of the Type-S and Type-N TCs are often considered to be non-magnetic or weakly paramagnetic, but subtle stronger magnetic effects are known to exist [16]. The Alumel and Chromel of Type-K TCs possess ferromagnetic properties, with a known Curie temperature of 154 °C for Alumel [3]. Contrastingly, Chromel magnetic measurements in the literature suffer from the occurrence of slight Cr oxidation

TABLE I

Thermocouple Types and Respective Compositions[17]

Type	Positive leg		Negative leg	
Accuracy	Comp. Name	Wt. %	Comp. Name	Wt. %
K *(±2.2 °C or ±0.75%)*	Chromel	0.1 Cr 0.9 Ni	Alumel	0.01 Si 0.02 Al 0.02 Mn 0.95 Ni
N *(±2.2 °C or ±0.75%)*	Nicrosil	0.001 Mg 0.014 Si 0.144 Cr 0.80 Ni	Nisil	0.001 Mg 0.044 Si 0.955 Ni
S *(±1.5 °C or ±0.25%)*		0.10 Rh 0.90 Pt		1.00 Pt

("green rot") in high temperature, low oxygen environments, altering the Curie temperature. When measured via heat capacity, the Curie temperature at 10 wt. % Cr in Ni is reported to be -48 °C [18]. However, some articles report the Curie temperature of a Type-K TC to be 354 °C, though this likely arises due to a magnetic transition of elemental Ni [4]. In heating applications, magnetic effects may be observed up to the Curie temperature of Alumel, and expectations suggest these effects would be more prominent in applied fields. Other factors influencing TC performance within magnetic fields include TC orientation relative to field orientation [4], workpiece temperature relative to TC component Curie temperature, thermal hysteresis of Cr-containing TCs [19, 20], and thermal and magnetic gradients along the wires [12]. In the induction

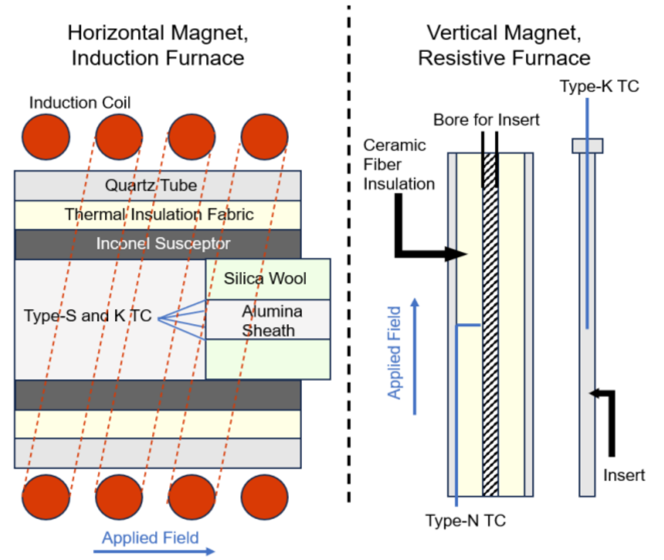

Fig. 1 Schematics for furnace setups used for thermocouple investigation. (left) Induction furnace setup utilized at ORNL, and (right) resistive furnace setup utilized at UF.

furnace scenario, there is an additional AC-generated magnetic field generated parallel to the static DC applied field.

Additionally, this study explored the behavior of TCs at the beginning of their useful lifetimes, as the materials employed were as received from the manufacturer. Naturally, TCs can degrade over time due to a variety of factors, including chemical environment, mechanical stress, and overheating beyond the TC's rating for extended periods of time (Type K = -270 – 1372 °C; Type N = -270 – 1300 °C; Type S = -50 – 1768 °C [17]). Although repeated use in a magnetic field might also impact the response, there are currently no studies of this interaction over long thermocouple lifetimes available in the literature. The studies performed herein represent temperature ranges well within the rating of the TC materials.

In this work, the induction furnace scenarios have TCs oriented parallel to the combined AC and DC magnetic field direction and passing through thermal and field gradients into the homogenous field. It shows how the TCs have variable response depending on TC type, and how Type-K shows significant variation even above the Curie temperatures of its constituents at higher fields. This result is compared to the resistive furnace scenario, where Type-K variation is relatively suppressed but still significant. Type-S and N thermocouples are used as field-independent comparisons, though minor effects on N thermocouples are observed and presented alongside the more impacted Type-K.

B. Induction Furnace

For the induction furnace studies at ORNL, the zero-field response of a Type-S TC was used by a temperature controller (Yokogawa model UT150) to regulate an RF power supply (Ameritherm (now Ambrell) HotShot 2, 2 kW) operating at 170

Authorized licensed use limited to: Florida State University. Downloaded on September 02,2025 at 14:16:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. All rights reserved, including rights for text and data mining and training of artificial intelligence and similar technologies. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Instrumentation and Measurement. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TIM.2025.3602597

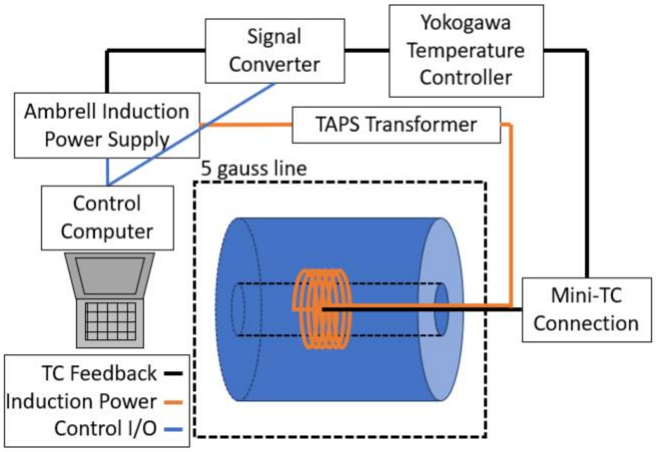

Fig. 2 Schematic of circuitry and thermometry layout in the induction furnace heating scenario.

– 180 kHz. In zero-field, the melting point of aluminum was used to provide a fixed-point calibration for the Type-S TC. Further offset calibration was performed using an Omega brand CL3515R Calibrator Thermometer for all TC types. A testing assembly was formed by TCs encased in a central alumina sheath surrounded by silica wool, where the regulating Type-S and Type-K TCs were coaxially inserted into the central region of a 1.0″ (2.54 cm) diameter cylindrical Inconel susceptor, which was wrapped by thermal insulation fabric and encased in a quartz tube, represented in **Error! Reference source not found.**, left. The TCs were 24″ (60.96 cm) long, which was sufficient to traverse the full thermal gradient, and were connected by mini-thermocouple connectors to appropriate extension wires (**Fig. 2**).

The assembly was placed in the center of a 2.0″ (5.08 cm) diameter, water-cooled ¼″ (0.635 cm) copper tubing wound in 10 turns to serve as the induction coil located in the homogeneous magnetic field region. The field was generated by an American Magnetics, Inc. 9 tesla superconducting magnet with a warm-bore of 5″ (12.7 cm) diameter. Care was taken to ensure the TC wiring was oriented parallel to the magnetic field and was constrained to keep the sensor regions as close to each other as possible without electrical contact.

Studies were performed without altering the position of the TCs, such that the TC experienced each setpoint at each static magnetic field in ascending order (0, 0.5, 1, 2, 5, 7, 9 T). At each setpoint, the temperature was held nominally for 10 min to achieve sufficient thermal equilibrium. In between magnetic field changes, the sample was allowed to furnace cool to room temperature, see **Error! Reference source not found.**. **Error! Reference source not found.**In the induction furnace, the temperature of the Type-S TC is shown for several applied magnetic field values. These data do not indicate the presence of any significant influence of the magnetic fields on the Type-S unit. Since the reading from the Type-S unit is used to control the temperatures, the output of the power supply is analyzed to infer if any subtle magnetic field-induced influences affect the Type-S output, see **Fig. 4,** where the output of the power supply at zero-field (PS(0)) is compared to the output at a static positive field (PS(B)) and normalized to PS(0). The detected, subtle trends do not appear to be systematically

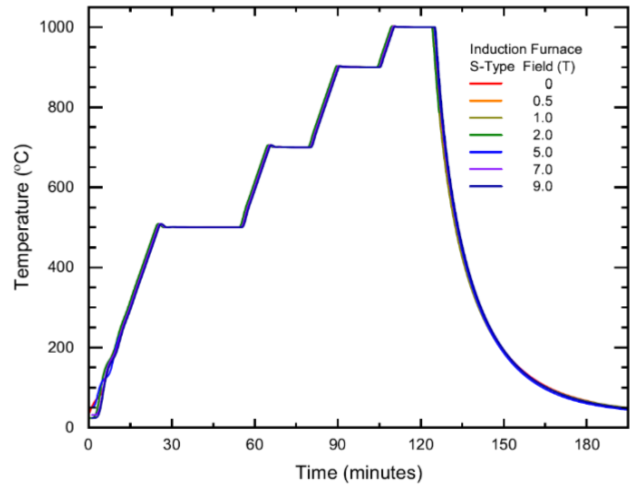

Fig. 3 TC readout inside the induction furnace's AC field and the applied DC field using a Type-S TC. The curves overlap closely, indicating there is minimal impact of the applied magnetic field

correlated to an increase of the power needed to raise the temperature. Field dependence trends toward negative values compared to zero-field runs, which may indicate a slight influence of the magnetic field. In another experiment, the magnet was ramped to 7 T, the setpoint adjusted to 1000 °C, and temperature was allowed to equilibrate. The magnetic field was then ramped down to 0 at a constant rate, (**Fig. 4**-pink curve).

C. Resistive Furnace

The resistive furnace used on the UF BxT system (**Fig. 1**-right), which consists of an in-house developed chilled-water jacketed insert that operates in a 90-mm, room-temperature bore of a repurposed Oxford 400 MHz (9.4 tesla) NMR superconducting magnet [21]. A 2″ (5.08 cm) diameter cylindrical ceramic fiber heater (Watlow, VC400J12A) with 0.5″ (1.27 cm) diameter inner bore was wrapped in a layer of 0.25″ (0.635 cm) thick ceramic fiber blanket and affixed inside the cooling jacket in the homogenous field region of the magnet. A Type-N TC inside an alumina sheath was run between the ceramic fiber wrap and the outer wall of the heater, then inserted at a 90° angle into a hollow TC port (I.D. 0.14″ (0.3556 cm)) extending radially from the outer wall into the hollow core of the furnace at its vertical midpoint. The tip of the Type-N TC was carefully positioned at the edge of the inner bore of the heater and fixed in place with additional insulation packed into the TC port. The response of the Type-N TC was passed to a temperature controller (Watlow, F4SH-FAA0-01RG) used to regulate the DC current generated by a power supply (Kepco ATE 500 W, 150 V, 3.5 A). The melting points of pure aluminum and copper in zero-field were used to calibrate any offset of the Type-N TC resulting from its radial displacement from the center of the furnace.

Authorized licensed use limited to: Florida State University. Downloaded on September 02,2025 at 14:16:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. All rights reserved, including rights for text and data mining and training of artificial intelligence and similar technologies. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Instrumentation and Measurement. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TIM.2025.3602597

An alumina tube (5/8″ (1.5875 cm) I.D.) with a lip was designed to allow a square cut-out in its wall to be positioned at the exact height of the TC port when it is inserted into the heater

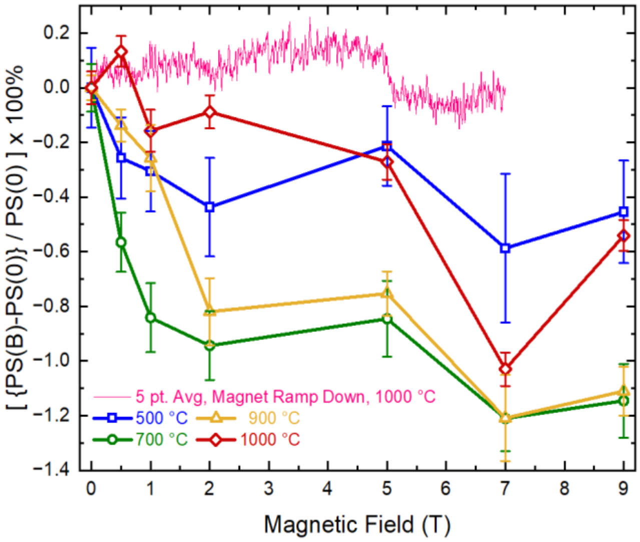

Fig. 4 The normalized difference in power supply output at zero and positive static magnetic field needed to obtain temperature equilibrium at a constant setpoint. Temperatures were collected with a Type-S TC in the induction heating system. The pink curve was held at 1000 °C (pink) and the field was ramped continuously from 7 T to zero-field.

from the top. A Type-K test TC was packed into the tube with ceramic fiber insulation and fixed in place at the center of the square cut-out. The assembly was lowered vertically into the furnace, ensuring minimal displacement from the Type-N TC. The readings from both TCs were recorded on an NI-9214 + TB-9214 input module, connected to a cDAQ-9171, then linked via USB to a computer equipped with LabView software used to read and record the data. Studies were typically performed at a constant field value while the furnace was ramped through a series of setpoints in a manner replicating the protocols used for the induction furnace work, with the exception that the minimum-maximum setpoints were 300 °C – 900 °C. The data are shown in **Fig. 5** as a function the measured temperature at zero-field ($T_N(0)$), compared to the measured temperature at a static positive field ($T_N(B)$), and normalized to $T_N(0)$. Once more, the trends do not appear to be systematically correlated to an increase in applied field strength, though there is some observable pattern at higher fields.

III. Results and Discussions

A. Type-S response in magnetic fields – Induction Furnace

Since the zero-magnetic field response of the Type-S TC was used by the temperature controller, the power required to maintain thermal equilibrium at the setpoints was analyzed, see **Fig. 4**. The maximum deviation from the zero-field in power supplied occurs at 7 T at 900 °C (neither the maximum temperature measured, nor the maximum field explored). While a consistent trend is difficult to define, there is a greater difference in response of the Type-S due to field as temperature increases from 500 °C to 700-900 °C, and then a return to lower levels of response at 1000 °C, similar to the response for the 500 °C setpoint. This kind of response cannot be associated with a monotonic increase of temperature or RF power.

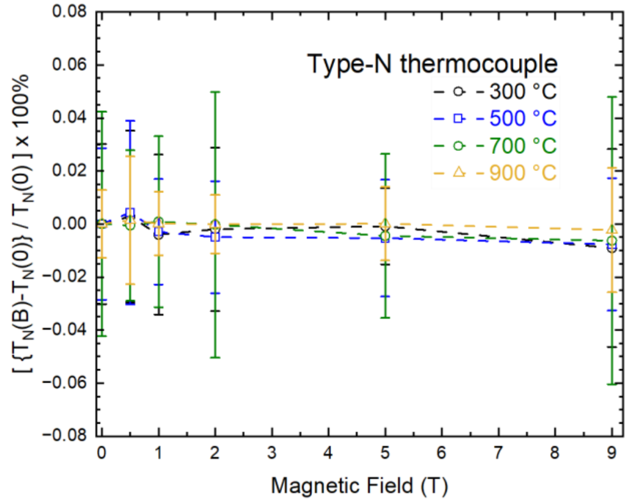

Fig. 5 The normalized difference in effective temperature of the Type-N TC at zero and positive static magnetic field, represented as a percent in the resistance furnace system.

However, we present two possible, and potentially concurrent, explanations. A crystallographic ordering of a Type-S thermocouple has been observed at 150 °C and 600 °C [22], where the sign of the EMF variance due to the ordering is opposite of that caused by rhodium experiments performed at static applied field with increasing temperature each time. Rh_2O_3 formation may cause the deviation in the 700 and 900 °C data. Additionally, Rh_2O_3 has a gradual allotropic phase transition (hexagonal → orthorhombic) between 900-1000 °C, which may partially account for the non-monotonic behavior [23, 24].

B. Type-N response in magnetic fields – Resistive Furnace

The radial position of the Type-N TC, which was offset from the concentric center, resulted in long thermal relaxation times, and consequently, the power supply output possessed large variance when moving from setpoint to setpoint. Nevertheless, the data indicates almost no response due to the applied magnetic field for temperatures above the Curie point (427 °C) of Alumel [3], **Error! Reference source not found.**, in which the value plotted is the mean of thirty consecutive data collected at each set point.

C. Type-K response in magnetic fields

The magnetic field effects on the response of a Type-K TC were studied in both induction and resistive furnace configurations, and the combined results are shown in **Error! Reference source not found.**.

Notable is the linear data, collected continuously during a magnet ramp-down from 7 T to 0 T (**Fig. 6**-pink curve). The linear data is opposed to the individual data points, determined at stable field as temperature was ramped. The linear data collection eliminates contributions from effects caused by susceptor heating, overshoot, and stabilization, but it clearly results in a greater temperature difference from 0 T (as

Authorized licensed use limited to: Florida State University. Downloaded on September 02,2025 at 14:16:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. All rights reserved, including rights for text and data mining and training of artificial intelligence and similar technologies. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Instrumentation and Measurement. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TIM.2025.3602597

compared to the temperature-stable data shown in red at 1000 °C).

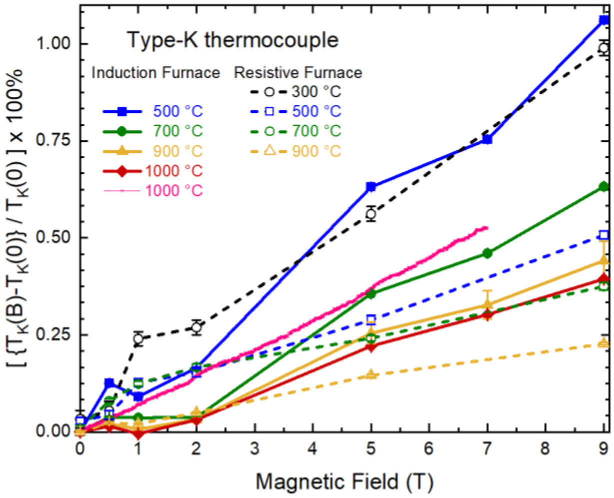

Fig. 6 The normalized difference in effective temperature of the Type-K TC at zero and positive static magnetic field, represented as a percent. Uncertainty levels are shown or are smaller than the size of the symbols.

IV. Conclusions

The data indicate that, at temperatures above material Curie temperatures and in parallel orientation to the field, Type-K TCs possess a positive (increasing response) in a field-dependent deviation, **Fig. 6**, compared to Type-S TC in an induction system, **Fig. 4**, and a Type-N TC in a resistive furnace, **Fig. 5**. The trends suggest the influence of a static magnetic field is weak below 2 T and induces a detectable, approximately linear effect at higher values as magnetic field is increased. Additionally, both heating scenarios show the greatest deviation of the Type-K TC at the lowest measured temperature, with the deviation decreasing as the temperature increases. This result may be due the rapid decrease of heat at distances moving away from the hot zone. Lower-temperature hot-zones will cause a thermal gradient that reaches the Alumel Curie temperature (154 °C) *physically closer* to the hot zone, resulting in an increased length of the thermocouple wire that is responsive to the applied field, whereas higher-temperature hot-zones result in less of the wire being both below the Curie temperature and within the applied magnetic field. An additional observation is that at similar temperatures, the deviation from zero-field readings is reduced in the resistive furnace compared to induction heating, suggesting the presence of RF fields may be contributing.

It is recommended that any thermomagnetic process design carefully weighs the presented options. In induction scenarios, if temperature accuracy is necessary within 6 °C, it is necessary to use either the Type-S or the more affordable Type-N thermocouple, though Type-N was not evaluated against the RF fields. However, it remained stable in resistive heating scenarios up to the maximum temperature and fields. In the same vein, in resistive heating scenarios, if accuracy is necessary within 3 °C, Type-S or Type-N is recommended.

However, should Type-K be the only available option and accuracy within the 6 and 3 °C ranges is allowable, Type-K can be utilized in fields of 9 T and 1000 °C so long as it remains parallel to the applied field. Deviation of Type-K from the Type-S or Type-N temperature is particularly limited below 2 T fields.

References and Footnotes

[1] D. B. Richards, L. R. Edwards, and S. Legvold, "Thermocouples in Magnetic Fields," *Journal of Applied Physics,* vol. 40, no. 9, pp. 3836-3837, 1969, doi: 10.1063/1.1658280.

[2] K. Schröder and M. Otooni, "Effect of magnetic fields on the absolute Seebeck coefficient and the resistivity of thermocouple wires," *Journal of Physics D: Applied Physics,* vol. 4, no. 10, pp. 1612-1616, 1971, doi: 10.1088/0022-3727/4/10/321.

[3] J. L. Horton, T. G. Kollie, and L. G. Rubin, "Measurement of B versus H of Alumel from 25 to 180 °C," *Journal of Applied Physics,* vol. 48, no. 11, pp. 4666-4671, 1977, doi: 10.1063/1.323530.

[4] T. G. Kollie, R. L. Anderson, J. L. Horton, and M. J. Roberts, "Large thermocouple thermometry errors caused by magnetic fields," *Review of Scientific Instruments,* vol. 48, no. 5, pp. 501-511, 1977, doi: 10.1063/1.1135063.

[5] S. Beguš, J. Bojkovski, J. Drnovšek, and G. Geršak, "Magnetic effects on thermocouples," *Measurement Science and Technology,* vol. 25, no. 3, 2014, doi: 10.1088/0957-0233/25/3/035006.

[6] *Industrial platinum resistance thermometers and platinum temperature sensors*, I. E. Commission, Geneva, Switzerland, 2022.

[7] K. O. Hill and G. Meltz, "Fiber Bragg grating technology fundamentals and overview," *Journal of Lightwave Technology,* vol. 15, pp. 1263-1276, 1997.

[8] A. Othonos, "Fiber Bragg gratings," *Review of Scientific Instruments,* vol. 68, no. 12, pp. 4309-4341, 1997, doi: 10.1063/1.1148392.

[9] L. Bao-Tong, Q. Sheng-Ru, and S. Xiao-Yan, "Exploration on repairing fatigue damage of steel specimens with magnetic treatment," *Scripta Materialia,* vol. 40, no. 7, pp. 767-771, 1999, doi: 10.1016/s1359-6462(99)00010-x.

[10] J. K. Choi, H. Ohtsuka, Y. Xu, and W. Y. Choo, "Effects of a strong magnetic field on the phase stability of plain carbon steels," *Scripta Materialia,* vol. 43, no. 3, pp. 221-226, 2000, doi: 10.1016/s1359-6462(00)00394-8.

[11] S. Asai, "Application of high magnetic fields in inorganic materials processing," *Modelling and Simulation in Materials Science and Engineering,* vol. 12, no. 2, pp. R1-R12, 2004, doi: 10.1088/0965-0393/12/2/r01.

[12] Z. H. I. Sun, M. Guo, J. Vleugels, O. Van der Biest, and B. Blanpain, "Strong static magnetic field processing of metallic materials: A review," *Current Opinion in Solid State and Materials Science,* vol. 16, no. 5, pp. 254-267, 2012, doi: 10.1016/j.cossms.2012.08.001.

Authorized licensed use limited to: Florida State University. Downloaded on September 02,2025 at 14:16:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. All rights reserved, including rights for text and data mining and training of artificial intelligence and similar technologies. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Transactions on Instrumentation and Measurement. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TIM.2025.3602597

[13] A. Smalcerz and R. Przylucki, "Impact of Electromagnetic Field upon Temperature Measurement of Induction Heated Charges," *International Journal of Thermophysics,* vol. 34, no. 4, pp. 667-679, 2013, doi: 10.1007/s10765-013-1423-1.

[14] D. Weiss *et al.*, "Thermomagnetic Processing of Aluminum Alloys During Heat Treatment," *International Journal of Metalcasting,* vol. 15, no. 1, pp. 49-59, 2020, doi: 10.1007/s40962-020-00460-z.

[15] M. S. Kesler *et al.*, "A rapid heating and high magnetic field thermal analysis technique," *Journal of Thermal Analysis and Calorimetry,* vol. 147, no. 13, pp. 7449-7457, 2021, doi: 10.1007/s10973-021-11010-y.

[16] H. J. Albert and L. R. Rubin, "Magnetic Properties of the Platinum Metals and Their Alloys," in *Platinum Group Metals and Compounds*, (Advances in Chemistry, 1971, pp. 1-16.

[17] *Standard Specification for Temperature-Electromotive Force (emf) Tables for Standardized Thermocouples*, A. International, West Conshohocken, PA, 2024.

[18] E. Ortiz, J. F. Jurado, and R. A. Vargas, "The specific heat of alumel and chromel alloys near their magnetic transitions," *Journal of Alloys and Compounds,* vol. 243, no. 1-2, pp. 82-84, 1996, doi: 10.1016/s0925-8388(96)02366-3.

[19] S. Arajs, "Paramagnetic Behavior of Nickel-Rich Nickel-Chromium Alloys," *Journal of Applied Physics,* vol. 38, no. 7, pp. 2946-2948, 1967, doi: 10.1063/1.1710028.

[20] N. Spooner, J. M. Thomas, and L. Thomassen, "High Temperature Corrosion In Nickel-Chromium Alloys," *Journal of Metals,* 1953.

[21] S. Flynn *et al.*, "Synthesis of Cobalt Grown from Co-S Eutectic in High Magnetic Fields," *arXiv:2504.00788 [cond-mat.mtrl-sci],* 2025, doi: 10.48550/arXiv.2504.00788.

[22] E. Webster, "Trials of Pt-20%Rh versus Pt thermocouples between 157 °C and 962 °C," *Metrologia,* vol. 57, no. 1, 2020, doi: 10.1088/1681-7575/ab5622.

[23] H. Leiva, R. Kershaw, K. Dwight, and A. Wold, "Magnetic and Electrical Properties of Rhodium(III) Oxide (III)," Office of Naval Research, 1982.

[24] S. Gossé, S. Bordier, C. Guéneau, E. Brackx, R. Domenger, and J. Rogez, "Thermodynamic assessment of the rhodium-ruthenium-oxygen (Rh-Ru-O) system," *Journal of Nuclear Materials,* vol. 500, pp. 252-264, 2018, doi: 10.1016/j.jnucmat.2017.12.034.

Authorized licensed use limited to: Florida State University. Downloaded on September 02,2025 at 14:16:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. All rights reserved, including rights for text and data mining and training of artificial intelligence and similar technologies. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.