Contents

Scope

This instruction covers the use, design, and specifications of thermocouples used at the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

General

A thermocouple is a temperature measurement sensor that consists of two dissimilar metals joined at one end (a junction) that produces a small thermo-electrical voltage when the wire is heated. The change in voltage is interpreted as a change in temperature. [i]

Although there are many configurations of thermocouples, there are five important factors to consider when using thermocouples for fire applications: temperature range, ruggedness, response time, wire tolerance limit, and grounded or ungrounded.

Temperature Range : The temperature range of a thermocouple is defined by the type and thickness of the metals used in their construction. The type of thermocouple is described using a letter nomenclature. Typical thermocouple types are J, K, T and E. For most fire applications, Type-K thermocouples with a maximum temperature range of approximately 1250 ºC (2282 ºF) are used. [1]

Ruggedness: The resistance of a thermocouple to environmental conditions is largely dependent on the type of junction and the wire insulation. Typically, thermocouples have either exposed or sheathed junctions. Exposed junction thermocouples have a faster response time but the junction is unprotected from the environment. Sheathed junction thermocouples are protected inside of a metal sheath, commonly constructed of Inconel, that provides environmental and abrasion resistance. However, sheathed thermocouples have a slower response time and a lower maximum temperature range because thinner wires are used within the metal sheathing. The ruggedness of thermocouples is mainly a function of the wire insulation material. Glass braid insulation has a temperature range of -73 ºC to 260 ºC and Nextel braid insulation has a temperature range of -73 ºC to 1204 ºC. Inconel is listed with a maximum temperature of 1150 ºC. [i, Page H-5-7]

Response Time: The response time of a thermocouple is characterized by its "time constant" that is defined as the time required to achieve 62.3% of an instantaneous change. Factors that affect response time are wire gage, sheathed versus exposed junction, and grounding. For a 0.015 mm (0.001 inch) gage wire, the response time in a "still" air environment is approximately 0.05 sec [i, Table 2, Page A-18].

Wire Tolerance Limit: Thermocouple wire is generally available in more than one grade. The grade of wire refers to the tolerance limit specified for a particular thermocouple type. For example, one manufacturer sells two grades: standard and special limits of error (SLE) [i]. Unless otherwise specified, Type-K SLE thermocouple wire is used at the ATF Fire Research Laboratory which has a minimum accuracy of the greater of 1.1ºC or 0.4% of the temperature reading over 0ºC. When there is a specific experiment requirement for a different level of accuracy, the actual measured thermocouple accuracy shall be documented in the "TC Type" FireTOSS input field.

Grounded Thermocouples: The difference between grounded and ungrounded thermocouples is that the junction of a grounded thermocouple is welded directly to the protective sheathing where as an ungrounded thermocouple junction is isolated from the sheathing. Grounded thermocouples are recommended for measurements of corrosive substances or in high pressure environments. Because the junction of a grounded thermocouple is welded to the sheath, the response time is faster than ungrounded thermocouples. However, a concern with grounded thermocouples is that many instruments can have ground loop problems.

Uncertainty and Accuracy

In a thermocouple measurement, the reported temperature is that of the junction, or bead. Generally, however, the temperature of the thermocouple junction is different from the temperature of interest. In fire tests, the temperature of interest is typically that of the gases surrounding the thermocouple junction. The uncertainty associated with the measured junction temperature can be estimated based on specifications for a particular thermocouple and an analysis of the measurement system. The difference between the junction temperature and the temperature of the surrounding gases can be significant and is highly dependent on conditions associated with a particular experiment. The analysis that follows is divided into two sections: first, an analysis of the uncertainty associated with the junction temperature measurement (measurement error) and second, an analysis of the error associated with the differences between junction temperature and environment temperature (insertion error).

Measurement Error

The uncertainty associated with the measured junction temperature is a primarily a function of the thermocouple/extension wire and any additional junctions such as when the thermocouple wire transitions to extension wire. The measurement system illustrated in Figure 1 is a common set-up used at the FRL. The analysis provided here is based on manufacturer specifications for Type-K thermocouples [i].

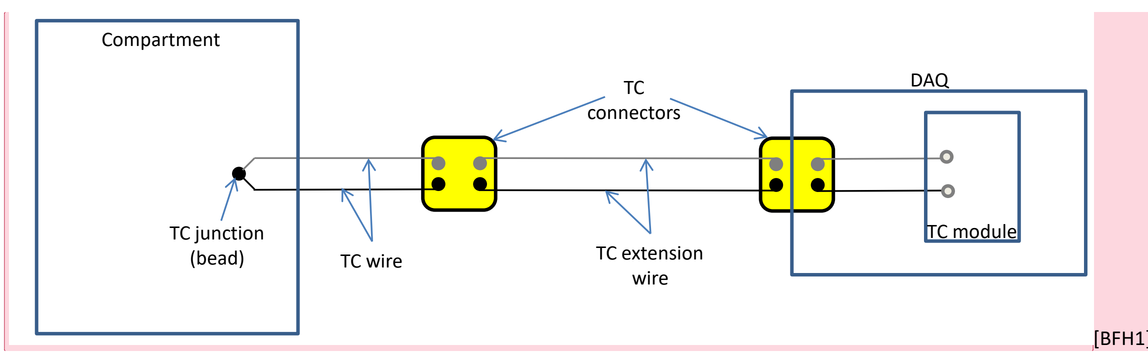


Figure 1. Thermocouple measurement system

Thermocouple wire can be specified as having either standard or special limits of error. The limit of error for standard Type-K thermocouples is the greater of 2.2°C or 0.75% of the temperature reading over 0°C. Special limit of error (SLE) Type-K thermocouples can be specified with a corresponding error limit that is the greater of 1.1°C or 0.4% of the temperature reading over 0°C. The maximum specified temperature of a Type-K thermocouple is 1250°C. At this temperature, the error associated with standard and SLE type-K thermocouples is 9.38°C and 5°C, respectively. [i, page H4] The FRL uses SLE thermocouple wire.

Thermocouple extension wire is fabricated from the same material as the thermocouple wire, and is also available in standard or SLE grades. The error associated with standard and SLE grades are, respectively, ±2.2°C and ±1.1°C. This error is valid in a temperature range is between 0°C – 200°C. The error due to extension wire is only considered if there is a temperature gradient across the length of the extension wire.

Thermocouple connectors are commonly used to transition from the thermocouple to extension wire or extension wire to the data acquisition system. These junctions introduce uncertainty in the measurement if there is a temperature gradient across the junction and the junction is made of a different material than the thermocouple wire. This error is approximately the same as the temperature difference across the junction [ii]. Junctions are generally small and are often insulated. The connectors used at the FRL are made of the same material as the thermocouple wire and are therefore ignored in this analysis.

Excessive wire lengths and the data acquisition system are other sources of error. However, these errors are generally small and are not considered in this analysis.

This analysis considers two scenarios. In the first scenario a SLE Type-K thermocouple is placed in a high temperature environment (1000°C), such as inside a compartment fire. The thermocouple lead extends outside the compartment where it is connected to standard Type-K extension wire that runs to the data acquisition system, shown in Figure 1. In this scenario the environment outside the compartment is between 0°C – 200°C and is conditioned such that there is no temperature gradient between the TC/extension connection and the data acquisition system.

In this scenario, because there is no temperature gradient at any of the junctions or across the extension wire, the connections and extension wire can be ignored in the uncertainty analysis. The measurement error is only associated with the error of the thermocouple wire.

For SLE K-type wire at 1000°C, the corresponding error is 0.4%, or 4°C. Assuming a square probability distribution, the standard uncertainty is obtained by dividing by $\sqrt{3}$. The result is a standard uncertainty of, u_{TC} = 2.3°C.

The second scenario is identical to the first, with the exception that there is a temperature gradient between the ends of the extension wire. In this case, the error associated with the extension wire must be considered. This is accomplished by combining the errors from the thermocouple wire and extension wire in quadrature:

$$u_c(T) = \sqrt{u_{TC}^2 + u_{EX}^2} \qquad (1.1)$$

Where $u_c(T)$ is the combined standard uncertainty, and u_{TC} and u_{EX} are, respectively, the standard uncertainties of the thermocouple wire and extension wire. Assuming that the extension wire is standard grade, the standard uncertainty is u_{EX} = 1.27°C. The combined standard uncertainty is then, $u_c(T)$ = 2.64°C.

Insertion Error

Insertion errors are those that arise from differences between the thermocouple junction temperature and the temperature of the surrounding fluid. The two types of errors considered are conduction errors and radiation errors.

Conduction Error

Conduction error, as the name suggests, results when heat is conducted away from the thermocouple junction through the wire, causing a reduction in the junction temperature. Conduction errors are minimized by using small gauge wire and relatively long insertion lengths. For wire diameter, D, and insertion length, L, a general rule is that conduction errors can be neglected in conditions for which L/D > 50 [iii]. Considering 24 AWG wire with a diameter of 0.5 mm, the corresponding minimum insertion length is 2.5 cm.

Radiation Error

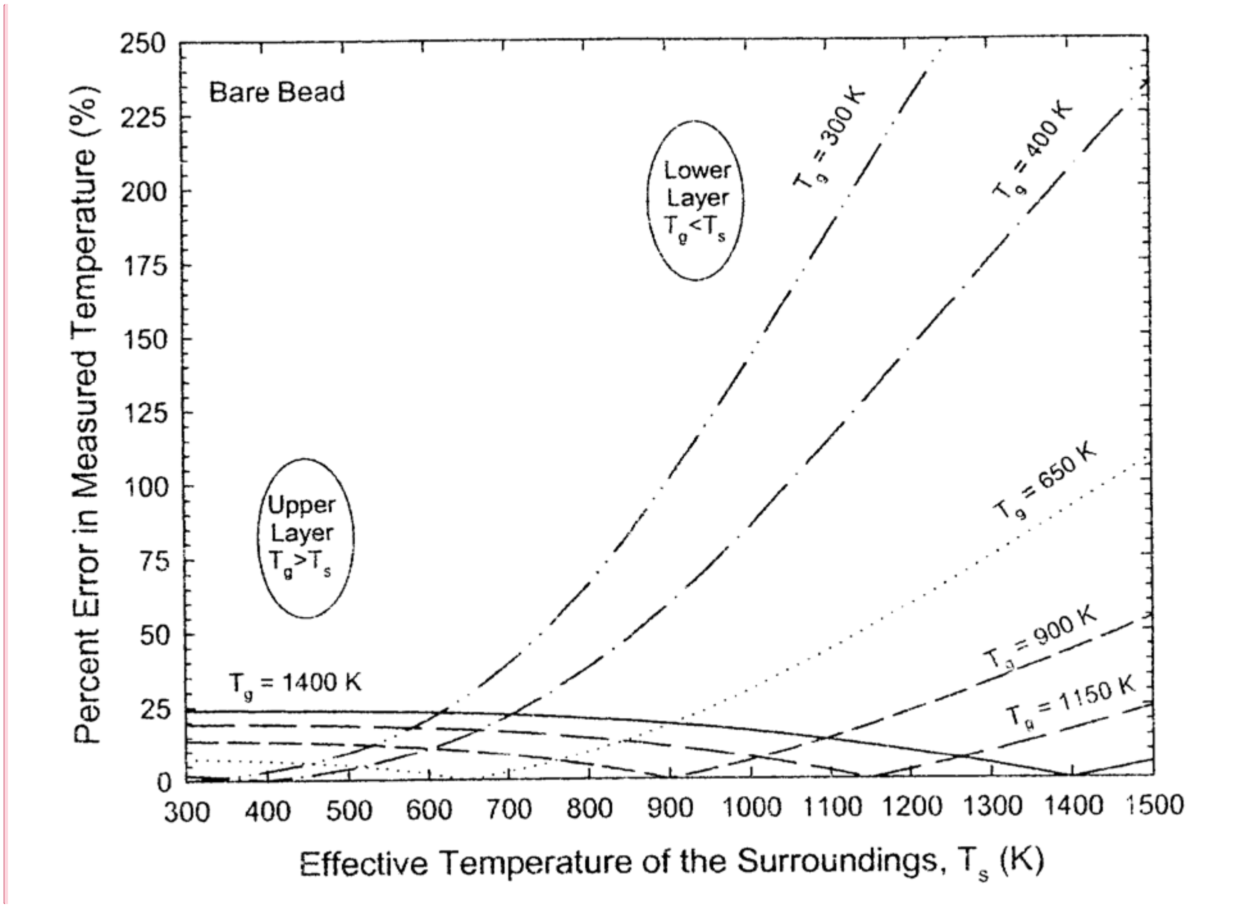
In fire environments, radiation error can be significant. Radiation error can be quantified by considering a thermocouple junction in a fluid environment that exchanges energy through convection with the local medium and through thermal radiation with the surroundings. A First Law analysis simplifies to:

$$T_g - T_j = \frac{\varepsilon\sigma}{h_c}\left(T_j^4 - T_s^4\right) \qquad (1.2)$$

Where T_g is the gas temperature, T_j is the junction temperature, T_s is the temperature of the surroundings, ε is the probe emissivity, σ is Boltzmann's constant and h_c is the convective heat transfer coefficient [iv]. The left hand side of Eqn. 1.2 is the difference between the gas temperature and the junction temperature, which represents the error. This error is highly dependent on the conditions of a particular experiment. In conditions where the gas and surrounding temperature are in equilibrium, the net radiant exchange is zero and the radiation error is eliminated. Fire experiments tend to be highly transient, particularly in the developing stage, and the T^4 dependence in the radiation term can drive significant errors in the temperature measurement.

The largest errors are encountered with thermocouples in low temperature regions that are exposed to an intense radiant flux. This is a condition often encountered in a developing enclosure fire in which cool air is drawn into a compartment through the lower area of a door and a sooty, hot upper layer is developing below the ceiling. Radiation from the hot upper layer heats the thermocouple junction, resulting in temperature readings that can be significantly higher than the actual temperature of the gases in the lower layer. One study documented errors as high as 225°C in extreme cases [4].

Radiation errors are greatest in the lower region where the gas temperature is lower than the temperature of the surroundings. The error decreases with a reduction in the temperature of the surroundings and as the gas temperature increases. Errors are typically reduced in the upper layer where gas temperatures are higher than the temperature of the surroundings. However, even in the upper layer, errors can be on the order of 25% [4]. Figure 1 shows a chart of calculated radiation errors for a range of conditions assuming an idealized bare bead thermocouple with a diameter of 1.5 mm [4].



[BFH2]

Figure 2: Calculated percentage errors for an idealized bare-bead thermocouple with 1.5 mm diameter bead [4].

Operating Instructions

Requirements

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. The data acquisition instrumentation shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.
3. All thermocouples shall be constructed from thermocouple wire with a minimum accuracy of the greater of 1.1°C or 0.4% of the temperature reading over 0°C.
   3.1. Exception: When there is a specific experiment requirement for a different level of accuracy, the actual measured thermocouple accuracy shall be documented in the “TC Type” parameter in FireTOSS laboratory report.
4. If thermocouple extension wire is used, the wire shall be used in the range specified.
   4.1. The minimum accuracy of Type-K extension wire shall be 2.1 C between 0 ºC and 200 ºC.

4.2. The temperature gradient between the ends of the extension wire and any additional junctions shall be minimized.

Procedure

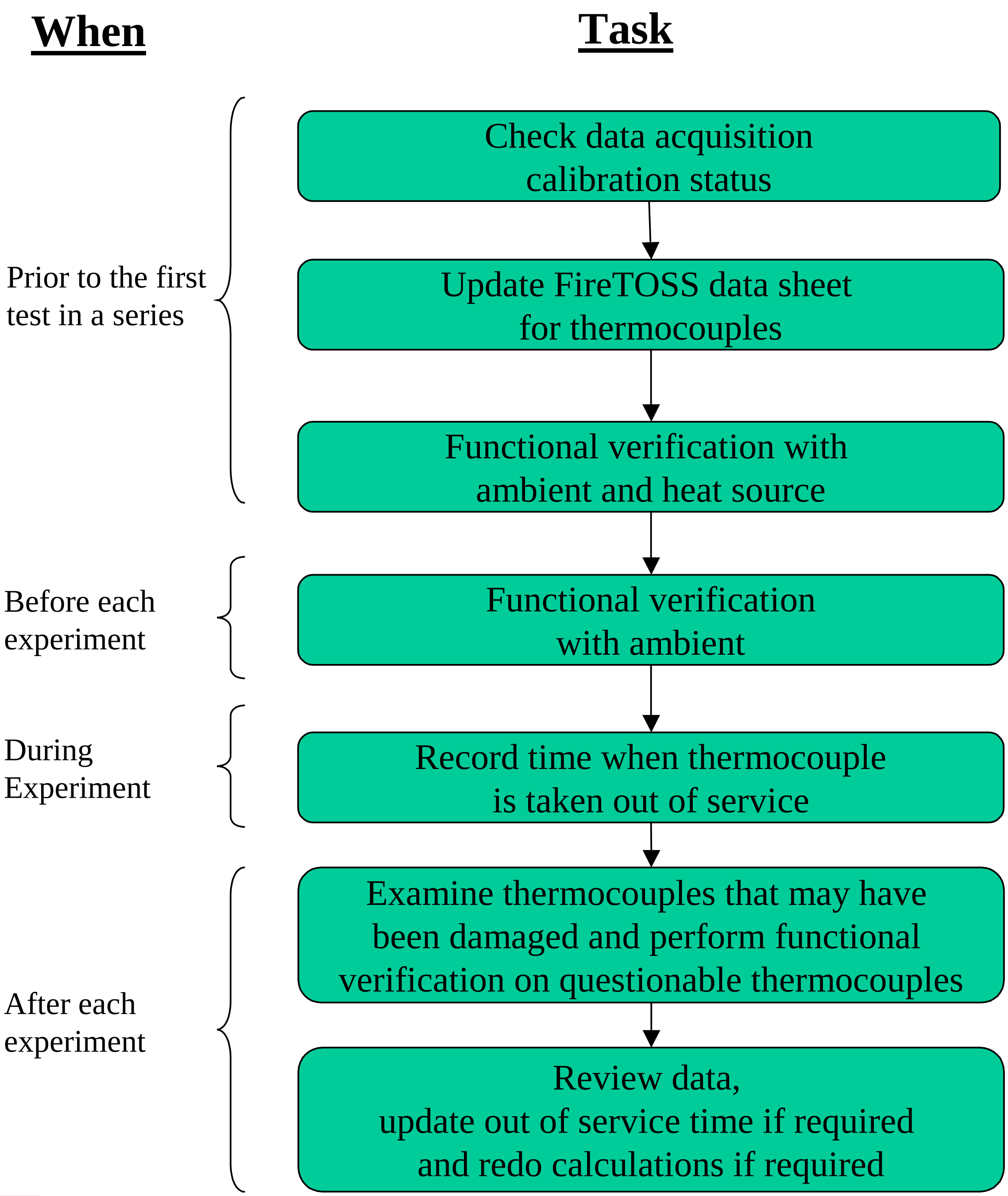
1. Prior to the first test in a series
   1.1. Operation of the thermocouples shall be verified in two ways.
      1.1.1. The thermocouple reading shall be verified against ambient temperature
      1.1.2. A heat source shall be applied and the resulting rise in temperature verified.

2. Before each test in a series
   2.1. The thermocouple reading shall be verified against ambient temperature to ensure operability.

3. During the Test
   3.1. The output of the thermocouple shall be recorded for the duration of the experiment.
      3.1.1. Exception – When the thermocouple must be removed prior to the end of the experiment due to experiment design or damage. The elapsed time at which the thermocouple was removed and the reason for removal shall be recorded.

4. Post Test
   4.1. After the experiment, the thermocouples in locations where they could have been damaged shall be examined for visible damage. Perform functional verification if necessary.
      4.1.1. If damage has occurred, the instrument shall be taken out of service at the time of the damage. The laboratory engineer shall review the data to determine if there is a noticeable event that marked the damage to the instrument. If not, the thermocouple shall be taken out of service for the entire test. After the thermocouple has been taken out of service, the calculations shall be redone.

Figure 3 shows a flowchart of the procedure that should be used for thermocouples.



[BFH3]

Figure 3. Thermocouple Process Flow Chart

Thermocouple Documentation Requirements

Thermocouples shall be documented using the FireTOSS experiment design program. The information that the user can document about the thermocouples is shown in Table 1. The first column in Table 1 shows the description of input parameter that will appear in the column heading of the FireTOSS experiment design program. The second column in Table 1 shows whether the parameter is required in all cases, and column three provides a description of the information to be supplied for the parameter.

Table 1. Data Acquisition Input Parameters

Parameter	Required	Parameter Description
Description	True	Description of the location of the thermocouple
Location X	False	X axis location of thermocouple
Location Y	False	Y axis location of thermocouple
Location z	False	Z axis location of thermocouple
TC Type	True	Identifies the type of thermocouple. Required information includes, thermocouple type, diameter, Inconel or beaded, grounded or ungrounded. Thermocouple accuracy shall be documented if required by the design of the experiment or if the accuracy is less than the FRL standard. Also, indicate if TC extension wire was used.
Tree ID	False	In conjunction with a diagram of the experiment set-up, this parameter is used to identify a horizontal or vertical traverse of instruments.
Room Number	False	Cross reference of instrument location
Chart	False	Allows the user to group instrument data onto different charts. If this parameter is left empty, data for similar instruments will be put on one chart.
Out of service time	False	Indicates the elapsed test time that the instrument was removed from the test. All calculations for the data on the instrument cease at this time.
Out of service reason	False	Specifies the reason that the instrument was removed from the experiment. Reasons typically include damage, impending damage, or test design
Initial Change Amount	False	Used in standardized testing to mark an event
Discontinuity threshold value	False	Value used to mark a discontinuity in the data. Typically, an data acquisition error has occurred.

References

1. Omega Temperature Measurement Handbook, 6th edition, Omega Engineering, Stamford, CT, 2007.

2. Nakos, J. T., “Uncertainty Analysis of Thermocouple Measurements Used in Normal and Abnormal Thermal Environment Experiments at Sandia’s Radiant Heat Facility and Lurance Canyon Burn Site,” SAND2004-1023, Sandia National Laboratories, Albuquerque, NM, 2004.

3. Figliola, R. S., and Beasley, D. E., *Theory and Design for Mechanical Measurements, Second Edition*, John Wiley and Sons, New York, 1995.

4. Pitts, W. M., Braun, E., Peacock, R. D., Mitler, H. E., Johnsson, E. L., Reneke, P. A., and Blevins, L. G., “Temperature Uncertainties for Bare Bead and Aspirated Thermocouple Measurements in Fire Environments,” *Thermal Measurements: The Foundation of Fire Standards,” ASTM STP 1427*, L. A. Gritzo and N. J. Alvares, Eds., ASTM International, West Conshohocken, PA, 2002.