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Uncertainty Analysis of Thermocouple Measurements Used in Normal and Abnormal Thermal Environment Experiments at Sandia's Radiant Heat Facility and Lurance Canyon Burn Site

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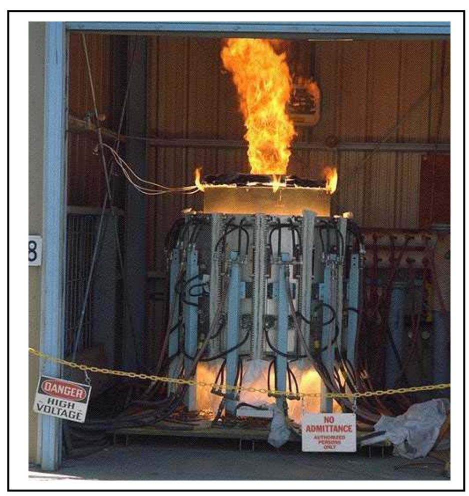

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Uncertainty Analysis of Thermocouple Measurements Used in Normal and Abnormal Thermal Environment Experiments at Sandia's Radiant Heat Facility and Lurance Canyon Burn Site

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Abstract

It would not be possible to confidently qualify weapon systems performance or validate computer codes without knowing the uncertainty of the experimental data used. This report provides uncertainty estimates associated with thermocouple data for temperature measurements from two of Sandia's large-scale thermal facilities. These two facilities (the Radiant Heat Facility (RHF) and the Lurance Canyon Burn Site (LCBS)) routinely gather data from normal and abnormal thermal environment experiments. They are managed by Fire Science & Technology Department 09132.

Uncertainty analyses were performed for several thermocouple (TC) data acquisition systems (DASs) used at the RHF and LCBS. These analyses apply to Type K, chromel-alumel thermocouples of various types: fiberglass sheathed TC wire, mineral-insulated, metal-sheathed (MIMS) TC assemblies, and are easily extended to other TC materials (e.g., copper-constantan). Several DASs were analyzed: 1) A Hewlett-Packard (HP) 3852A system, and 2) several National Instrument (NI) systems. The uncertainty analyses were performed on the entire system from the TC to the DAS output file. Uncertainty sources include TC mounting errors, ANSI standard calibration uncertainty for Type K TC wire, potential errors due to temperature gradients inside connectors, extension wire uncertainty, DAS hardware uncertainties including noise, common mode rejection ratio, digital voltmeter accuracy, mV to temperature conversion, analog to digital conversion, and other possible sources. Typical results for "normal" environments (e.g., maximum of 300-400 K) showed the total uncertainty to be about ±1% of the reading in absolute temperature. In high temperature or high heat flux ("abnormal") thermal environments, total uncertainties range up to ±2-3% of the reading (maximum of 1300 K). The higher uncertainties in abnormal thermal environments are caused by increased errors due to the effects of imperfect TC attachment to the test item. "Best practices" are provided in Section 9 to help the user to obtain the best measurements possible.

Acknowledgements

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Acronyms

ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
B	Bias or systematic uncertainty
CAP	Certification Augmentation Program
ch	channel
DAS	data acquisition system
DOF	degrees of freedom
DVM	digital voltmeter
EMF	electromotive force
ESCC	Experimental and Systems Certification Capabilities
FCU	Furnace Characterization Unit
FET	field-effect transistor
FS&T	Fire Science & Technology
HP	Hewlett-Packard
ISO	International Standards Organization
LCBS	Lurance Canyon Burn Site
MIC	Mobile Instrumentation Container
MUX	multiplexer
NBS	National Bureau of Standards
NIST	National Institute of Standards and Technology
NPLC	number of power line cycles

ppm	parts per million
PXI	PCI (Peripheral Component Interconnect) extensions for Instrumentation
RHF	Radiant Heat Facility
RSS	Root-sum square
S	Random uncertainty, one standard deviation
SCXI	Signal Conditioning eXtensions for Instrumentation
TAIII	Technical Area III
TC	thermocouple

1 Executive Summary

An uncertainty analysis was performed on several data acquisition systems (DASs) that use Type K (chromel-alumel) thermocouples (TCs). These measurements are made in typical experiments performed in Sandia's Fire Science and Technology (FS&T) Department 9132 facilities in Technical Area III (TAIII): the Radiant Heat Facility (RHF) and the Lurance Canyon Burn Site (LCBS). Components included in the analysis were Type K TCs, TC connectors, TC extension cable, several DASs (i.e., Hewlett-Packard (HP)-3852A and several National Instruments DASs), and the data reduction equation (voltage-to-temperature conversion). The analyses were performed assuming that error sources such as broken TCs, TC shunting, and other "major" issues have been eliminated.

These results will be important for applications ranging from system qualification efforts (e.g., the W76-1 and W80-3 lifetime extension programs (LEPs)) and code validation efforts (e.g., CALORE, the thermal response code and FUEGO, the fire environment code).

Results from the analysis show that, for "normal" environments up to a maximum of about 300-400 K, the uncertainty of a typical DAS is about ±1% of the reading in absolute temperature. For example, if one is measuring a process at 300K, the total uncertainty is about ±3K (±3°C). Assuming the TCs have the ANSI standard "accuracy" value (±2.2°C), the majority of the total uncertainty is due to this source.

Systematic errors caused by TC junction type (i.e., ungrounded, grounded, or exposed junction) and mounting scheme (i.e., strap welded, epoxy bonded, etc.) are usually negligible for normal environments. However, these same error sources can be much larger (e.g., ±2%) in abnormal thermal environments (i.e., 1300K). In addition, these mounting errors vary from experiment to experiment and are often difficult to accurately estimate.

Therefore, the total measurement uncertainty in abnormal thermal environment experiments is often much larger than that due to the hardware used to acquire the signal alone. It is therefore very important to quantify the uncertainties caused by installation effects or TC junction type for commonly used configurations so that the total uncertainty can be quantified to a higher degree of confidence. In addition, the uncertainty analysis can be used to identify the sources that dominate the total uncertainty. That identification can then be used for effective resource allocation if one decides to reduce the uncertainty.

Two examples are provided to show how to use the material in this report in practical applications.

2 Introduction

The entire DAS evaluated consists of a Type K TC, TC mounting to the surface being measured, TC connectors, TC extension wire, and the data acquisition hardware and software. Systems evaluated are listed in Table 2-1. Equipment does change and new systems are being purchased, but the HP and NI systems were purchased in 2002-2003 so will be likely be used for some time in the future. Legacy HP and IO Tech systems are still being used but only the HP 3852A systems will be evaluated. The IO Tech system will not be evaluated because the newer NI systems have replaced it.

Table 2- 1. Data Acquisition Systems Evaluated

Manufacturer	Model	Facility/Site Used	Comments
Hewlett-Packard	3852A	RHF and LCBS	Old systems – at least 10 years old and no longer supported by HP. However, these are still good systems and are used.
National Instruments	6052A DAQ[1] card, SCXI[2]-1102 TC cards	LCBS and RHF	System purchased 10/2001; DAQ in standalone PC; 16-bit
National Instruments	6062A DAQ card, SCXI-1102 TC cards	RHF	System purchased 8/2002; DAQ card in laptop computer; 12-bit
National Instruments	6070E DAQ (PXI)[3], SCXI-1102 TC cards	RHF	System purchased 8/2002; DAQ has imbedded PC. PXI[3] system has own PC; 12-bit
National Instruments	6036E DAQ card, SCXI-1102 TC cards	RHF	System purchased 3/2003; DAQ card is installed in laptop; 16-bit

3 Uncertainty Analysis Methods

There are a number of methods that can be used for the determination of measurement uncertainty. A recent summary of the various uncertainty analysis methods is provided in reference [1]. The American Society of Mechanical Engineers' (ASME's) earlier performance test code PTC 19.1-1985 [ref. 2] has been revised and was replaced by reference [3] in 1998. In references [2] and [3], uncertainties were separated into two types: "bias" or "systematic" uncertainties (B) and "random" or "precision" uncertainties (S). Systematic uncertainties are often but not always constant for the duration of the experiment. Random errors are not constant and are characterized via the standard deviation of the random variations, thus the abbreviation 'S.' In reference [2], the total uncertainty was expressed in two ways, depending on the "coverage" desired. First, the "additive" method is:

$$U_{ADD} = \pm[(B_T) + (t_{95}S_T)] \qquad \{3\text{-}1\}$$

Where B_T is the total bias or systematic uncertainty of the result, S_T is the total random uncertainty or precision of the result, and t_{95} is "Student's t" at 95% for the appropriate degrees of freedom (DOF). This method provides about 99% "coverage." "Coverage" here does not mean "confidence" because a statistical term (S_T) was combined with a non-statistical term (B_T) (see reference [1]).

The second choice was the root-sum-square (RSS) method [ref. 2]:

1 DAQ = data acquisition system
2 SCXI = Signal Conditioning eXtension for Instrumentation
3 PXI = PC extensions for Instrumentation

$$U_{RSS} = \pm[(B_T)^2 + (t_{95}S_T)^2]^{1/2} \quad \{3\text{-}2\}$$

A third method, adopted by the International Standards Organization (ISO) [ref. 4] and American National Standards Institute (ANSI) [ref. 5], separates uncertainty types into Type A and Type B. Type A sources are derived from statistical methods while Type B sources are not. The method of calculating total uncertainty in this model is as follows:

$$U_{ISO} = \pm K[(U_A)^2 + (U_B)^2]^{1/2} \quad \{3\text{-}3\}$$

where U_A and U_B are the Type A and B uncertainties, and K is a “coverage factor” used to obtain a level of confidence. K normally varies between 2 and 3 (this is analogous to 2σ for 95% coverage and 3σ for 99% coverage).

According to reference [1], one of the other uncertainty methods “will likely be proposed as a detailed model in the new U.S. National Standard by the ASME.” (Reference [1] was published in 1997, before the new ASME national standard was finalized in 1998.) These methods are almost identical, only differing in the constant. The first model is defined as follows:

$$U_{95} = \pm 2\,[(B_T/2)^2 + (S_T)^2]^{1/2} \quad \{3\text{-}4\}$$

The second is defined as:

$$U_{ASME} = \pm t_{95}\,[(B_T/2)^2 + (S_T)^2]^{1/2} \quad \{3\text{-}5\}$$

where t_{95} is determined from the number of degrees of freedom (DOF) in the data provided. Both methods provide about 95% coverage. For large DOF (i.e., 30 or larger) t_{95} is almost 2, so methods in equations {3-4} and {3-5} are the same. Also, reference [1] shows that the ISO method (equation {3-3}) and new ASME methods (equations {3-4} and {3-5}) are identical. Reference [6] also provides a comparison of the uncertainty methods available, and reference [7] provides the National Institute of Standards and Technology’s (NIST’s) method of estimating uncertainty.

Reference [1] recommends use of the U_{95} or U_{ASME} method (equation {3-4} or {3-5}). The new ASME PTC 19.1-1998 [ref. 3] recommends use of equation {3-4}. Because the ISO and ASME methods (equations {3-3} or {3-5} are identical, and because in FS&T Department 09132 we are involved with engineering mechanics, the ASME model recommended in equation {3-4} is the most relevant, and will be used in this analysis.

In all cases above, ‘S_T’ is given as one standard deviation. However, in practical terms, manufacturer’s specifications most often do not specify uncertainty types as systematic or random, or with any kind of confidence level (e.g., 95% or 99%). As a result, the practitioner has the challenge of trying to determine how to combine uncertainty values with incomplete information. If it is crucial to determine more about the uncertainties listed, it is best to call the manufacturer to understand what confidence level is specified. Most often, the uncertainties listed are maximum values (i.e., three standard deviations). In these cases, there may be a need to adjust the listed uncertainties to a smaller value, then use equation {3-4} to find the total uncertainty. Similarly, one might have to estimate the biases based on maximum values (i.e., 99% coverage) and reduce them to a 95% coverage value.

An alternative used in reference [8] arose because of the way manufacturers provide data on "accuracies," "errors," or "uncertainty" estimates. As noted above, most manufacturers do not specify uncertainty sources as systematic or random, nor do they provide confidence levels (i.e., $\pm 3\sigma$ [$\pm$99%] or $\pm 2\sigma$ [$\pm$95%] errors). Often "accuracies" or "errors" are provided as a maximum value or a percentage of the reading or a percentage of full scale. As a result, a rigorous uncertainty analysis (i.e., knowing the error to $\pm$95% or $\pm$99% confidence level) is often not possible.

According to reference [8], because the uncertainties provided by the manufacturers are often the maximum values possible, there is no need to use the student's t correction (t_{95}), and the total uncertainty may be expressed as:

$$U_{MAX} = \pm[B + R] \quad \{3\text{-}6\}$$

where R is the RSS of the "random" or "precision" uncertainties. 'R' is used rather than 'S' so as not to imply that in this case the random uncertainty is one standard deviation (it is often three standard deviations). 'B' is the maximum total systematic uncertainty. Because this method was not used in any of the other methods or described in any of the other references listed above, it will not be used here.

In all of the methods described above, the total systematic uncertainty B_R and total random uncertainty S_T are found using the RSS method:

$$B_T = (B_1^2 + B_2^2 + B_3^2 + \ldots)^{1/2} \quad \{3\text{-}7\}$$

$$S_T = (S_1^2 + S_2^2 + S_3^2 + \ldots)^{1/2} \quad \{3\text{-}8\}$$

where B_1, B_2, B_3 and S_1, S_2, S_3 are the individual uncertainty sources. Another method of combining the individual uncertainty sources is to add them. However, this overestimates the total uncertainty (assuming all B_i's are positive) as compared with the RSS method and is not normally used.

It is sometimes difficult to determine which type of uncertainty source (systematic or random) one is faced with. One-way to determine if a source is systematic or random is to ask the question: Can I eliminate or reduce this error [ref. 8]? If the answer is yes, the uncertainty type is systematic; if the answer is no, the uncertainty type is random. Another way to tell is if the uncertainty always skews the data in the same direction (i.e., + or –). If so, then it is systematic. A third way is to ask if the uncertainty is constant for the duration of the experiment, or if it contributes to data scatter. If constant, it is a systematic uncertainty; if it contributes to data scatter, it is random. A fourth way is to see if the uncertainty was statistically determined; if so, it is random.

Typical types of systematic uncertainties are mounting errors, non-linearity, and gain. Less commonly discussed systematic uncertainties are those that result from the sensor design (i.e., TC junction type) and coupling with the environment. Some typical examples are discussed in Section 4.0. A type of random uncertainty is common mode and normal mode noise. Reference [8] provides valuable information on how to effectively interpret manufacturer's specifications to obtain a total uncertainty estimate for TC measurements.

"Uncertainties" and "errors" are used to convey specific ideas. When making a measurement, one never knows what the "true" value is. The "error" is the difference between the true value and the measured value. Therefore, one never knows the true error. "Uncertainty" means that your measurement is uncertain; you can only say that the true value is within some uncertainty interval. More precise definitions of "error" and "uncertainty" are provided in reference [3].

In summary, the method outlined in reference [3] (ASME PTC 19.1-1998) and expressed in equation {3-4} above will be used in the analyses in this report.

4 Systematic Errors Resulting From Installation Method or TC Type

This section is presented here to highlight the importance of accounting for the TC installation or TC junction type uncertainty into any TC uncertainty analysis, especially for measurements in abnormal thermal environments.

It is the insidious nature of systematic errors that one can have a small random uncertainty and therefore believe your overall measurement has a small uncertainty, but have a large unknown systematic error. An example is the measurement of temperature in a gas stream in a pipe: the measurements can have small excursions about a mean temperature (small random uncertainties) but the mean temperature has a large systematic error that is not known unless the entire system is carefully analyzed (see reference [9]). In this case, the systematic error is a result of radiation-induced errors and errors caused by the gas stream velocity.

Several examples of systematic errors present in typical tests at the Radiant Heat Facility are provided later. These examples show that systematic errors caused by the installation or "mounting method" or TC type can be large (e.g., 2-5%) compared to the total combined uncertainty caused by all other sources, including the TC wire accuracy, extension wire, DAS hardware, and data reduction scheme (e.g., ±1%).

You will never know the systematic errors are present unless it is understood that different types of thermocouples (ungrounded junction, grounded junction, or intrinsic/exposed junction) have different systematic errors in various environments. Examples of systematic errors due to differing TC junction types are provided in reference [10]. Later sections and Appendix B provide more quantitative estimates of systematic errors in application typical of those in the RHF and LCBS.

5 Hewlett-Packard 3852A Data Acquisition System Uncertainty

5.1 Overall System Description

Figure 5-1 shows a sketch of the HP-3852A DAS. It consists of the following components:

1) a) Thermocouple, Type K, chromel-alumel

   b) Type K thermocouple connectors (male and female)

   c) Type K thermocouple extension wire

To standardize hardware and software, Type K TCs are often used at all temperatures.

2) Hewlett-Packard 3852A data acquisition system consisting of reference junction, multiplexer, and digital voltmeter.
3) Personal computer with software to convert digitized voltage to temperature.

This configuration is typical of several operable DASs used at the RHF and LCBS. A survey of the HP3852A DAQ systems used at the RHF and LCBS showed the following major components were used:

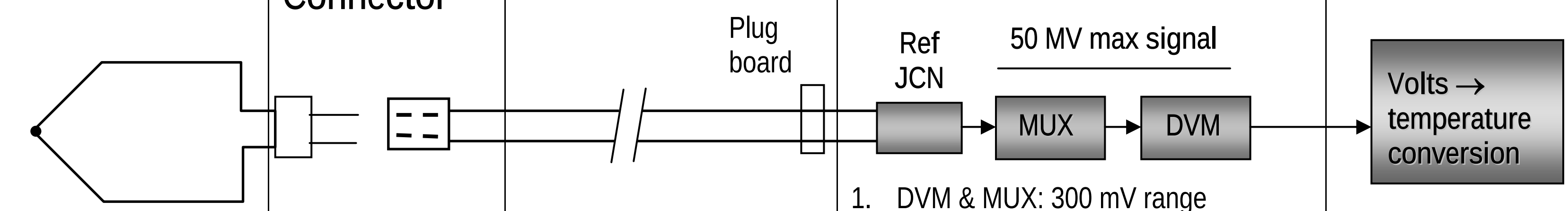
1) All had 44701A digital integrating voltmeters; no high-speed voltmeters were used.
2) A number of multiplexers (MUXs) were being used:
   - 44705A and 44708A relay MUXs,
   - 44710A, 44709A field-effect transistor (FET) MUXs,
3) 3853A extenders are used in systems with a large number of channels (over 140).
4) Each 3852A has eight slots for cards, one for the digital voltmeter, and seven for other cards. Cards usually have 20 channels each.

See Table 5-1 for a summary of the HP-3852A systems and their components.

Because of the large number of combinations available for use with the HP DASs, only the most commonly used combination will be analyzed: an integrating voltmeter with relay multiplexers. The analysis method for other combinations is the same, and results would be similar.

Table 5- 1. Components in HP-3852A DASs

Experimental Facility	Number of Channels	DVM Type	Multiplexer Type	Extender? (3853A)
Radiant Heat	200 channels (ch) TC, 40 ch voltage	44701A	44708A for TCs, 44705A for voltage	Yes
Radiant Heat	60 ch TC, 20 ch voltage	44701A	44708A (1) and 44710A (2) for TCs, 44710A (1) for voltage	No
Radiant Heat	100 ch TC, 40 ch voltage	44701A	44708A (4) and 44710A (1) for TCs, 44705A (2) for voltage	No
Burn Site	200 ch TC, 40 ch voltage	44701A	44708A (10) for TCs, 44705A (2) for voltage	Yes
Burn Site	40 ch TC, no voltage cards now	44701A	44708A (2) for TCs	No



Type K TC	TC Connector	Extension Wire	HP-3852A Hardware	Conversion to Temperature
±2.2°C or ±0.75% of reading (in °C), whichever is greater, from 0-1250°C (32 – 2300°F). Summary for TC B = ± 2.2°C or ± 3/4% of reading S = 0 TC Type or Installation Errors: S = 0 B = ±0-5% depending on application.	Approximate error is same as ΔT across connector Summary for TC connector B = ± ΔT of connector S = 0 See Appendix A	For cable temperature 0-200°C (32 - 400°F): ± 2.2°C Summary for extension cable B = ± 2.2°C S = 0 Notes: 1) B denotes 'bias' and S random. 2) NPLC = number of power line cycles. To achieve a faster scan rate use NPLC = 0.1. Use NPLC = 1.0 if accuracy is needed.	1. DVM & MUX: 300 mV range (NPLC=0.1) = 0.008% + 10 μV =11 μV or 0.3°C (assumes 40 mV signal [1000°C] and 40μV/°C); For 30 mV range: = 0.02% + 12 μV =20 μV or 0.5°C) (Bias) 2. 1-year spec = 0.01% (assume NA) 3. Temperature coefficient: (% of reading + volts) × degrees outside 18 to 28°C range. For 300 mV range, error = (0.0006% + 300 nV) × °C = 0.032% or 0.4°C(S) 4. Auto-zero off = 10 μV or 0.25°C (B) 5. Reference temperature uncertainty = 0.1°C (S) 6. Cross talk between channels -35 dB @ 100 kHz $\log^{-1}(-35/20) = e_0/e_i$ = 1.78% @ 40 mV e_o = 0.71 mV. (S) A change of 0.7 mV corresponds to over 20°C. See Appendix C. 7. Noise rejection 60 dB for normal mode noise = 0.10% or 1.3°C (S)	Summary for conversion B = ± 0.5°C = ± 0.9°F S = 0 Uncertainty of entire system at 1010°C : See example in Section 5.5

Figure 5- 1. HP-3852A DAS Schematic

5.2 Analysis Assumptions

Assumptions used in the HP-3852A uncertainty analysis are as follows:

1) The input signal from the TC is within the range of 0–50 mV. For a Type K thermocouple, 0–50 mV corresponds to 0-1230°C (32–2250°F, or 273-1503 K).
2) The input signal from the test item is low frequency, say in the range of 0.01 to 1 kHz.
3) The experiment's duration is long enough so drift is possible (say 8 hours).
4) There is no excitation (i.e., no bridge); the TC is a self-generating transducer.
5) Maximum operating temperature range where the DAS is located is 0–55°C (32–130°F).
6) Maximum operating temperature range where the extension cable is located is between 0-200°C (32–400°F).
7) There is no amplification of the signal (gain = 1.0).
8) Cross talk between channels can be neglected.
9) Uncertainty sources are uncorrelated[4]

5.3 Uncertainty Analysis

5.3.1 Thermocouple, Type K, Chromel-Alumel

Thermocouple manufacturers adhere to the American Society for Testing Materials (ASTM) specifications for calibration accuracy ("limits of error") for Type K TCs [ref. 11]:

0-1250°C (32-2300°F): ±2.2°C or 0.75% of reading in °C, whichever is greater.

This is normally considered a systematic uncertainty. Random uncertainties are "fossilized" into the calibration bias [refs. 11 & 12]. Specially calibrated thermocouple wire that can be purchased (extra cost) provides accuracy to ±1.1°C or ±0.4% of reading in °C, whichever is greater.

According to Reference [11], "the 'limits of error' stated are definitive, not statistical. Wire that does not conform to the stated limits is simply not Type K." As a result, the above uncertainties should be considered a maximum, or 3σ (99.7%) limits.

Summary for Type K thermocouples:

B (systematic uncertainty) = ± 2.2°C or 0.75% of reading in °C (99% coverage), whichever is greater, and
S (random uncertainty) = 0

[4] It is assumed in this analysis that uncertainty sources are uncorrelated. It is believed that this is not the case with channel-to-channel cross talk, but enough data are not available to quantify the degree of correlation, and the cross-talk uncertainty is small, so the effect of cross-correlation is considered negligible.

5.3.2 Thermocouple Connector

Refer to Appendix A for a detailed analysis of potential thermocouple connector errors. In the appendix, it was assumed that there was a 2°F change in temperature along the length of the pin of the TC connector, and that the TC connector pins are made of material close to but not the same as the TC. In this case, a 2°F ΔT along the TC connector pins corresponds to about a 2°F error (also see Reference [11], Section 3.2.2, page 35). This is a systematic uncertainty (B) because it can be reduced by reducing the ΔT along the connector pins. The analysis in Appendix A was performed assuming a 2°F ΔT in the connector (arbitrary but large value). For this analysis, it will be assumed that there is a smaller change in temperature across the connector of only 0.5°C, and that the uncertainty scales linearly so the uncertainty is also about 0.5°C.

Summary for Type K thermocouple connectors:

B = ±0.5°C, and

S = 0

5.3.3 Thermocouple Extension Wire

Refer to Appendix A for a discussion regarding potential thermocouple extension wire errors. TC extension wire is used for two reasons: (1) to improve mechanical properties and (2) to use material that is less costly. ASTM specifications for TC extension wire [Ref. 11, Table 3.10, page 36] are as follows: ±2.2°C (±4°F) between 0-200°C (32–400°F). Therefore, the extension wire uncertainty limits are the same as that for TC wire in the temperature range of 0-200°C (32–400°F). There is no guarantee that the error is ±2.2°C outside the 0-200°C range, and in fact the extension wire junction to the TC wire has to be kept "below the upper limit of the extension wires or considerable errors may be introduced." [Ref. 11, Section 4.5, page 73] Presumably, non-negligible errors could also be introduced if the extension wire were to be operated below 0°C (32°F). This could easily occur at the LCBS during the winter. For this example, it will be assumed that the extension wire is not operated below 0°C or above 200°C (400°F) so the ±2.2°C error limit applies. This is a systematic uncertainty (B).

Summary for Type K thermocouple extension wires:

B = ±2.2°C, and

S = 0

5.3.4 Thermocouple Installation Method or Type and Shunting Errors

Installation Method or Type
As stated in Section 4.0, there is often a significant systematic error related to the installation of the TC or TC type used. The temperature of the measuring junction of the TC is never equal to the temperature of the test item. The TC exchanges energy with the test item and with the environment so an error is always present. Estimating the error associated with mounting the TC to the test item is the key to accurate TC measurements in typical "abnormal" environments. This type of error can be called "mounting error" and is

a systematic error. In low temperature applications (i.e., normal environments) this type of error is negligible if the TC is properly mounted, but this error is significant in abnormal environments. In abnormal thermal environment applications, this is often the largest error source. For example, references [13] and [14] provide experimental data that show systematic errors when using various types of mineral-insulated, metal-sheathed (MIMS) TCs (i.e., intrinsic [exposed junction], grounded junction, and ungrounded junction) in radiant heat environments. The systematic errors caused by different junction types can be much more than the ANSI values quoted above (i.e., ±2.2°C or 0.75%). They can be steady state or transient. For example, Figure 5 in reference [13] shows the response of two TCs mounted on a flat steel plate during a constant temperature radiant heat test. After the initial transient, the “intrinsic” (i.e., exposed junction) TC reads higher than the “sheathed” (ungrounded junction) TC by about 36 K (36°C). At a nominal temperature of about 958 K (685°C), this is about a 3.8% error. This assumes the intrinsic TC provides the “true” temperature.

Similarly, from reference [14], a number of plots provide data on the differences between use of exposed junction, grounded junction, and ungrounded junction TCs. Examination of these data show systematic errors caused by TC type varying from a low of 2.9–4.8% for exposed vs. grounded junction TCs to 3.2–5.9% for exposed vs. ungrounded junction TCs at nominal temperatures between 1090-1310 K (817-1037°C).

Data taken recently in a series of experiments to accurately characterize the temperature of inconel shrouds at about 1000°C show similar patterns. Figures B-1 and B-2 show data from intrinsic, ungrounded, and grounded junction TCs on a flat inconel shroud where the TCs are located on the side facing away from the lamps. The intrinsic TC always reads the highest, and the ungrounded and grounded junction TCs read lower. Sometimes the ungrounded reads higher and other times the grounded junction TC reads higher. It is postulated that the differences between the intrinsic TCs and the others are due to the junction being displaced from the surface. The differences between the ungrounded and grounded junction TCs are thought to be due to slight differences in the junction placement inside the sheath.

Figures B-3 and B-4 show clear differences between TCs of the same junction type (i.e., ungrounded) but of different sheath diameters. It is clear that the smaller diameter TCs read higher, and the higher temperature is the more accurate value.

Additional data are available from reference [10] where extensive data were taken from a flat shroud. Twenty (20) TC pairs were mounted side-by-side where one was an intrinsic design and the other a mineral-insulated, metal-sheathed (MIMS) ungrounded junction design. The shroud was heated via a logarithmic profile to 1173K (5 minutes to rise to 800K). In these experiments, average steady state errors were about 2%, less than those in Refs [13] and [14], but still significant. The smaller errors were due to improved mounting techniques. Figures B-5 and B-6 show some of the data from reference [10], and Table B-1 summarizes the results. Table B-1 shows the average error to be about 16.7°C with a standard deviation of about 4.4°C. Therefore, with about 95% confidence the error is 25.6°C. For the lowest shroud temperature (800 K or 527°C) this is about 3.2% error, and for the highest shroud temperature this error is about 2.2%.

The above examples are for TCs mounted on a flat stainless steel plate or “shroud” at RHF in abnormal thermal environments, and for fiberglass sheathed TCs attached to a thin metal case and to foam in normal environments. There are other configurations (e.g., “flame” temperatures at the Burn Site) where the systematic error caused by the TC type or installation method has not yet been properly quantified. Because they can be the largest part of the total uncertainty, these types of errors should be quantified as part of the uncertainty analysis for each application.

Section 6.4.4.5 provides an analysis of systematic TC mounting errors for relatively low temperature environments (e.g., 100°C or 373 K). In that application the overall environment is relatively benign so the mounting error is negligible.

Shunting Errors
"Shunting" can cause large systematic errors [refs. 15, 16, 17]. TC shunting occurs when the resistance of the magnesium oxide insulation separating the chromel and alumel wires in MIMS TCs from the metal sheath is reduced at high temperatures, so the insulation is more conductive and "virtual" junctions form. Black and Gill [ref. 18] and Gill and Nakos [ref. 19] have modeled this problem and compared the model predictions with experimental data with good success. With care and preparation, shunting can be eliminated by actively cooling the TCs where they are exposed to high temperatures. In this application it will be assumed that shunting has been eliminated.

5.3.5 Summary for Type K TC, TC Connectors, and TC Extension Wires

For the Type K TC:

B = ±2.2°C or ± ¾% of reading in °C, which ever is greater, and

S = 0

For the Type K TC connectors:

B = ±ΔT on connector, and

S = 0

For the Type K TC extension wires:

B = ±2.2°C, and

S = 0

For the Type K TC type or installation method (for TCs on a shroud):

B = ±0-5% of reading, and

S = 0

5.3.6 Hewlett-Packard Model 3852A Data Acquisition System

A typical HP-3852A DAQ system consists of a patch panel, multiplexer(s), digital voltmeter(s), and PC. The digital voltage signal is converted to temperature by the PC. It will be assumed that the patch panel, composed of TC connectors in a mounting structure, does not introduce any error into the circuit because there is negligible ΔT across the patch panel.

Reference [20] provides the specifications for several combinations of HP multiplexers and digital voltmeters. One combination is an “Integrating Voltmeter with Relay Multiplexers,” another one is an “Integrating Voltmeter with FET Multiplexers, and a third is a “High Speed Voltmeter HP 44702A/B with High-Speed FET Multiplexers HP 44711A or HP 44713A.” “These specifications give you total system accuracy including all errors contributed by the voltmeters, system back-plane, ribbon cables, and function modules. Cross talk between channels is not included here, but is specified under the multiplexer descriptions” [20]. No mention is given in the reference as to whether these specifications are maximum (e.g., 99.7%), 95%, 68%, or something else. Confirmation was made via HP[5] [ref. 21] that these values are maximum, which here is assumed to be the 3σ (99.7%) values.

For each of the voltmeter/multiplexer combinations, four error sources are listed:

1) Overall error depending on the voltage range (90 days, 18-28°C, auto-zero on) (Section 5.3.6.1)
2) 1-Year stability specification (Section 5.3.6.2)
3) Operating temperature coefficient (Section 5.3.6.3)
4) Auto-zero off (Section 5.3.6.4)

In addition, the following sources can add uncertainty:

5) Reference junction temperature (Section 5.3.6.5)
6) Cross talk between channels (Section 5.3.6.6)
7) Noise (Section 5.3.6.7)

5.3.6.1 Overall Uncertainty Depending on the Voltage Range

Assuming the maximum input is 50 mV (1232°C), the 300-mV range would be used, so the error is specified as 0.008% + 8 μV for number of power line cycles (NPLC) of 1, or 0.008% + 12 μV for number of power line cycles (NPLC) of 0.1 [20]. Normally a specific range is set so a single value of accuracy is obtained. Assuming the input signal is 30 mV or less (720°C or 1330°F), the uncertainty is 0.02% + 8 μV for NPLC = 1 and 0.02% + 10 μV for NPLC = 0.1. NPLC is the number of power line cycles used for integrating the signal; an NPLC of 0.1 or 1 is normally used.[6]

This is a systematic uncertainty (B) (see reference [8]).
300 mV range:
B = $\pm$ 0.008% + 8 μV for NPLC of 1, or $\pm$0.008% + 12 μV for NPLC of 0.1
30 mV range:
B = $\pm$ 0.02% + 8 μV for NPLC of 1, or $\pm$0.008% + 10 μV for NPLC of 0.1, and
S = 0.

[5] Personal conversation with Ed Gunderson, Hewlett-Packard, February 1999.
[6] Personal conversation with Chuck Hanks, March 10, 2003. NPLC = 1 may slow the scan rate but is often used.

5.3.6.2 1-Year Stability Specification

This uncertainty is specified as follows: Add 0.01% of reading to 90-day specifications. This is a systematic uncertainty (B). Therefore, the overall uncertainty due to voltage range (Section 5.3.6.1) should be increased by 0.01% of the reading [ref 20].

B = ±0.01%, and
S = 0.

5.3.6.3 Temperature Coefficient

This uncertainty is stated as an "additional accuracy error using ± (% of reading + volts) per °C change outside 18 to 28°C, as long as the operating temperature is maintained between 0 to 18 or 28 to 55°C." The maximum amount the temperature can be "outside 18 to 28°C" is 27°C (55 minus 28) and still be in the ranges 0–18°C or 28–55°C. Therefore, the total error related to temperature coefficient is as follows:

1) For signals less than 30 mV: 0.002% + 30 nV
2) For signals greater than 30 mV but less than 300 mV: 0.0006% + 300 nV.

This is a systematic uncertainty (B) because it can be reduced (i.e., it is zero if the operating temperature is kept between 18–28°C). S = 0.

5.3.6.4 If Auto-Zero Not Used

If the auto-zero is not used, an additional uncertainty should be added, as often the case [ref. 20]. This assumes a stable environment, ±1°C, for 24 hours. The additional error is 10μV. This is a systematic uncertainty (B).

B = ±10 μV, and
S = 0.

5.3.6.5 Reference Junction Error

Reference [20] provides specifications for the relay multiplexers. There are two specifications of interest: the reference junction compensation accuracy and the channel-to-channel cross talk. The reference junction temperature is measured with is a thermistor located on the MUX card (e.g., 44708A) and can be sampled every time the TCs are sampled. There is one thermistor per MUX card.

The reference junction compensation accuracy is stated to be 0.1°C over the operating temperature range of 18–28°C. It is assumed to be a bias (B).

B = ±0.1°C, and
S = 0.

5.3.6.6 Cross Talk, Channel-to-Channel

The channel-to-channel cross talk is stated as "channel-to-channel, 50 Ω source, 1 MΩ termination, –35 dB (100 kHz)." As will be seen later, the NI DASs have a much better crosstalk specification (e.g., -75 dB). Fortunately, we do not normally encounter thermocouple signals of 100 kHz frequency because the –35 dB specification has a relatively large uncertainty:

$dB = 20 \log(\Delta V/V)$, so $\Delta V/V = \log^{-1}(-35/20) \approx 0.0178 \approx \pm 1.78\%$ {5-1}

This is a systematic uncertainty (B). ΔV may be interpreted as the voltage induced on channel 2 as a result of the difference in voltage (V) between channel 1 and channel 2. Substituting into the above equation and assuming the maximum difference between channels (V) is 50 mV, the crosstalk error ΔV would be:

$\Delta V = 0.0178*50 = 0.89 mV$.

Assuming a sensitivity of about 40μV/°C, this value is a large error. As a result, experimenters should be careful if using the HP-3852A relay multiplexers when taking thermocouple data with high frequency content (e.g., 100 kHz). Data from TCs on surfaces is almost a DC signal, and TCs that attempt to measure fire fluctuations are normally up to 100 Hz.

This magnitude of the cross talk was checked by inserting two "shorted" channels between adjacent TC channels reading temperatures up to 350-400°C. At a scan rate of once/second the crosstalk was negligible. See Appendix C for a complete description of the data.

5.3.6.7 Noise Rejection

Normal Mode
Specifications are provided for noise rejection when using the integrating voltmeter with relay multiplexers [20]. Noise rejection is specified in two ways: "normal mode" and "common mode." For "normal mode" noise, the "normal mode rejection" (NMR) is 60 dB (50-60 Hz) for any number of channels in the DAS. Therefore:

$NMR,\ dB = 20 \log(\Delta V/V)$, so $\Delta V/V = \log^{-1}(-60/20) \approx 0.001 \approx 0.10\%$ {5-2}

This is a random uncertainty (S).

B = 0, and
S = ±0.10%

Common Mode
The common mode rejection ratio (CMRR) is specified as 145 dB for 20 channels or less and NPLC = 1, 142 dB for 21-140 channels, and 128 dB for 141 channels or more for 50 or 60 Hz common mode voltage (CMV). For DC CMV the specifications are 120 dB (20 channels or less), 105 dB (21-140 ch) and 95 dB (141 ch or more). Assuming the number of channels is >140 and the CMV is AC (due to the AC power system), the 128 dB specification applies. The CMRR is defined as follows [8]:

$$CMRR, dB = 20\log(CMRR) = 20\log(gain * e_{cmv} / e^{e}{}_{cmv})$$
$$e^{e}{}_{cmv} = (e_{cmv} * gain) / \log^{-1}(CMRR, dB / 20) \qquad \{5\text{-}3\}$$

Where e_{cmv} = common mode voltage and $e^{e}{}_{cmv}$ = common mode voltage error.

For many TC measurements it is difficult to determine the source of common mode voltage. Common mode voltage (CMV) could occur due to potential voltage induced into long TC wires that act like an antenna (e.g., LCBS fire measurements), or from potential gradients due to thunderstorms. Although 120v AC is used, this is not thought to be a significant CMV source for TCs, and is addressed above for NMR for 50-60 Hz signals. The largest common mode voltage measured on TC circuitry was about 20V[7], but this only applies to high voltage sources (e.g., at the RHF). Therefore, assuming the maximum common mode voltage is 20 volts, and the gain is 1, an estimate of the common mode voltage error is:

$$e^{e}{}_{cmv} = e_{cmv} * gain / \log^{-1}(128/20) = 20 * 1 / \log^{-1}(6.4) = 8\mu V$$

This value (8μV) corresponds to an uncertainty of about 0.2°C. If the CMV was 20 VDC instead of AC, the CMRR is 105 dB and the common mode error would be 112μV, or about 2.8°C. Therefore, it is very important to keep the CMV as low as possible, and to use the smallest gain possible, or the common mode error will be large compared with other error sources. This is a bias.

B = ± 0.2°C, and

S = 0.

5.3.6.8 Summary of Errors for HP 3852A DAQ System (Reference Junction, Multiplexers, and Voltmeter)

a) *Overall error depending on the voltage range (90 day specification):*
   For signals less than 300 mV (corresponds to more than maximum output of Type K TC):
      0.008% of the reading in mV + 8 μV for NPLC = 1, or
      0.008% of the reading in mV + 12 μV for NPLC = 0.1

   For signals less than 30 mV (30 mV corresponds to 720°C or 1330°F):
      0.02% of the reading in mV + 8 μV for NPLC = 1, or.
      0.02% of the reading in mV + 10 μV for NPLC = 0.1

b) *1-Year stability specification:* add 0.01% to the 90 day specification.
   This adds to the 90 day specification as follows: for signals greater than 30 mV the overall error is 0.018% + 8 μV.

c) *Temperature coefficient:*
   For signals less than 30 mV: 0.002% + 30 nV
   For signals greater than 30 mV but less than 300 mV: 0.0006% + 300 nV

d) *If auto-zero not used:* 10 μV. At 40 μV/°C this is about 0.25°C.

[7] Per personal communication with John Bentz, 2/6/02. Common mode voltage measured at CYBL facility (near Building 6536) in Tech Area III.

e) *Reference junction:* ±0.1°C.

f) *Cross talk between channels:* assumed negligible

g) *Noise:* Normal mode noise: 0.10% of reading; Common mode noise: 0.2°C

5.3.6.9 Voltage-to-Temperature Conversion

Various voltage-to-temperature conversion equations, all polynomials of various orders, are used to reduce the data from mV to temperature. For example, a conversion equation used in the past came from an NBS document [ref. 21] and spans the temperatures of interest in two ranges:

1) 0–400°C
2) 400–1370°C

The equations are of the type:

$$T = a_0 + a_1E + a_2E^2 + a_3E^3 + a_4E^4, \quad \text{where E is in } \mu V \text{ and T is in °C.} \qquad \{5\text{-}4\}$$

This relation was taken from the National Bureau of Standards (NBS), now NIST, thermocouple reference tables in reference [21]. The maximum specified error for any of the temperature ranges was no more than ±0.6°C. This is a systematic uncertainty (B).

The present version uses a 9th order polynomial of the form [22]:

$$T = a_0 + a_1E + a_2E^2 + a_3E^3 + a_4E^4 + a_5E^5 + a_6E^6 + a_7E^7 + a_8E^8 + a_9E^9$$

The constants are as follows:

a_0 = 0.147
a_1 = 25.170885
a_2 = -0.38112846
a_3 = 8.0689821
a_4 = -7.9010641
a_5 = 4.0808749
a_6 = -1.2077814
a_7 = 2.0725446
a_8 = -1.9225205
a_9 = 7.4707981

Estimated maximum uncertainty of this equation is –0.2°C, +0.8°C over the range of 0-1370°C.

5.3.6.9 Electrical Noise from RHF Power System

When taking data at the Radiant Heat Facility, electrical noise from high power (100s of kW) levels for the radiant heat lamps can affect results if the DAS is not properly grounded. Fortunately, electrical noise concerns have been addressed during operations over the years. However, not all of the noise can be removed. This adds some random uncertainty into typical TC measurements. A similar problem exists in fires at the LCBS. Even though high power levels don't exist during fire tests, the fire environment is very "noisy" and proper grounding of the TC sheaths to the DAS chassis is very important.

Reference [13], Table VII, provides data on electrical noise levels induced into an older model HP DAS. This work was performed in 1980 using an older version of the HP DAS (no longer in use) (not the HP-3852A). The maximum noise levels, converted from μV to an equivalent temperature swing, ranged from ±0.3°C to 1.5°C (±0.5°F to ±2.7°F). The noise levels varied with the overall power level, being larger with higher power levels. Fortunately, newer DASs have much better noise rejection characteristics.

Noise levels were estimated during a recent set of experiments (ref. [10]) using the newer HP-3852A DAS. Results from reference [10] indicate noise was negligible. Additional experiments were recently performed (April 2003) during a set of foam characterization experiments. Results are described in Appendix D and show maximum noise "spikes" of about 0.5°C from total power levels ranging from 10-41 kW. Using data from Appendix D one can approximate the noise as a mean value and standard deviation of about 0.2°C and 0.1°C, respectively. Note that these values are at best estimates only, and more data are needed for grounded junction TCs, exposed junction TCs, and higher power levels. These are random uncertainties.

5.4 Total Uncertainty for HP-3852A DAS

Equation (3-4) is used to estimate the total uncertainty of the system. Recall that all of the uncertainty values provided by manufacturers are often maximums, and this is assumed to mean 3σ values or 99.7%. For a 95% confidence level (for example), the bias values should be converted to 2σ values, and the random ones to 1σ values, then combined using equation {3-4} to estimate the total uncertainty. An example is provided in the next section to illustrate the methodology.

The example below uses manufacturer supplied uncertainty values for each of the components. This method can over estimate the total uncertainty because maximum values are usually provided by the manufacturer [ref. 23] for each potential source. As will be shown with the National Instruments system example (Section 6.4), a better way to perform the uncertainty analysis is to do an end-to-end calibration. This calibration provides a known source input to the end of the extension cable. This input is provided by a TC calibration device (e.g., Fluke Model 5520A). Outputs are read at temperature levels spanning what is envisioned during the experiments. Multiple readings are taken for each channel (e.g., 600 readings/second for 1-2 seconds). Values of the mean channel reading, the error, and the standard deviation are supplied with the output. This type of calibration precludes having to laboriously estimate each of the individual sources listed above, except for TC uncertainty and TC mounting biases. Because the TC is not connected to the DAS, uncertainty associated with that component is not included in the analysis. This method also has the added advantage of being able to verify each channel used before and/or after the experiment. See the example in Section 6.4 below for details of this method. The example in Section 5.5 does not use the end-to-end calibration method, however, an end-to-end calibration was performed on the HP-3852A DAS and the results are shown in Appendix E. Results in Section 5.5 for the

DAS indicate a 95% coverage bias of about 0.7°C (uncertainty sources 5-11). Table E-2 shows average bias for channels 100-119 as about 0.10°C and 0.49°C for channels 200-218. Adding 2σ (2 standard deviations) to each value gives 0.25°C for channels 100-119 and 0.65°C for channels 200-218. Therefore, the end-to-end calibration provides a lower and more accurate value of channel bias.

5.5 Example

Problem: Estimate the total uncertainty with 95% confidence in a TC measurement if the MIMS TC is mounted on a flat shroud in a test at the RHF at a nominal temperature of 1010°C. Ungrounded junction, mineral-insulated, metal-sheathed TCs (1/16 in. diameter) are used to measure the shroud temperature. The TCs face the test unit. The shroud temperature is nominally 1283 K (1010°C). Extension cables are used and they are in ambient temperatures within the range of 0-200°C. Assume there is 20V, 60 Hz common mode voltage. Assume additional noise generated in the TC due to the power system is a maximum of 0.5°C.

Solution: Using information from Appendix B and Table B-1, one can estimate the systematic error associated with use of a 1/16-in.-diameter, ungrounded junction, sheathed TC as about -2% (95% confidence, negative sign indicates that the TC reads lower than the shroud temperature) at 1158K (885°C, close enough to 1010°C). Although data from Appendix B shows the error can be larger, improvements in TC mounting procedures have reduced this expected systematic error to the –2-3% range. At 1283 K, 2% is about –25.7 K or –25.7°C. This value is compatible with a 95% confidence level. Assuming there is only a 0.5°C ΔT across the connector, the uncertainty would be about 0.5°C. In all calculations below it is assumed that the TC sensitivity is 40 μV/°C.

1) TC mounting error: B = -2% or –25.7 K (95% confidence)
2) TC wire accuracy: B = ± 0.75% = ±9.6 K (99%) reduced to ±6.4 K (95%)
3) TC connector uncertainty: B = ± 0.5 K (99%), or ±0.3 K (95%)
4) TC extension cable uncertainty: B = ± 2.2°C = ± 2.2 K (99%), or ± 1.5 K (95%)
5) Overall error depending on the voltage range (includes 1 year stability specification):

At 1010°C (1283 K) from a Type K TC table the nominal output is 41657 μV (41.657 mV), so the uncertainty is found from the 300-mV range: 0.018% + 8 μV.

B = 0.00018*41.657 + 8 μV ≈ 15.5 μV = 0.39 K (99%) or 0.26 K (95%)

6) Operating temperature coefficient: It is assumed that the operating temperature is between 18-28°C so this uncertainty is zero.

7) Auto-zero not used: 10 μV uncertainties.

B = 10μV = ≈ 0.25 K (99%) or 0.17 K (95%).

8) Reference junction: ±0.1 K

B = ±0.1 K (99%), or 0.07 K (95%).

9) Cross talk between channels: negligible

10) Noise:
    a) NM noise: S = 0.10% = 0.001*41.657 = 42μV = 1.0 K (99%) or ±0.3 K (95%)
    b) CM noise: S = 8 μV or 0.2 K (99%) or 0.13 K (95%)

11) Voltage-to-temperature conversion: Maximum of 0.8°C = 0.8 K (99%) or B = ± 0.5 K (95%).

12) Electrical noise: Assumed to be no more than about ±0.3 K (random uncertainty), so S = ± 0.3 K.

Using equation {3-4} to combine the systematic uncertainties, the result is:

$$B_T = (B_1^2 + B_2^2 + B_3^2 + \ldots)^{1/2} \qquad \{3\text{-}7\}$$

Because the TC mounting error is one-sided, the results will have a larger uncertainty on the – (negative) side than on the + (positive) side. The negative and positive side systematic uncertainties are:

$$B_T- = (25.7^2 + 6.4^2 + 0.3^2 + 1.5^2 + 0.26^2 + 0.17^2 + 0.07^2 + 0.5^2)^{1/2} \approx -26.5 \text{ K, and}$$

$$B_T+ = (6.4^2 + 0.3^2 + 1.5^2 + 0.26^2 + 0.01^2 + 0.17^2 + 0.07^2 + 0.5^2)^{1/2} \approx +6.6 \text{ K.}$$

Similarly, for the random parts of the uncertainty, the result is:

$$S_T = (S_1^2 + S_2^2 + S_3^2 + \ldots)^{1/2} \qquad \{3\text{-}8\}$$

$$S_T = (\{0.33\}^2 + \{0.13\}^2 + \{0.3\}^2)^{1/2} \approx 0.5 \text{ K}$$

Using the method described in reference {3} for nonsymmetrical uncertainty intervals, the total uncertainty estimate is as follows:

1) Define $B = (B^+ + B^-)/2 \approx 16.6$ K
2) Define shift $= (B^+ - B^-)/2 \approx 10.0$ K

$$U_{95} = \pm 2\,[(B/2)^2 + (S_T)^2]^{1/2} \approx 16.6 \text{ K} \qquad \{3\text{-}4\}$$

$$U_{95} - = -U_{95} - \text{shift} \approx -26.6°\text{C, or 2.1\% of the reading in K, and}$$

$$U_{95} + = U_{95} - \text{shift} \approx 6.6°\text{C, or 0.5\% of the reading in K.}$$

It is apparent from this example that, for this case and all others where the TC type/installation method systematic error is large, the total uncertainty is dominated on the negative side (i.e., the TC reads lower than the true value). Other uncertainty sources accept the TC calibration and extension cable uncertainty can be neglected. **The TC type/ mounting error is by far the largest source of uncertainty.**

Note that conversion from the maximum uncertainties (3σ) provided by the manufacturer to 2σ values for use in equation {3-4} may not be justified. The 2% (25.7°C) systematic uncertainty for mounting method is by no means a statistical value (i.e., 2σ or 3σ). Therefore, although this value has been used in equation {3-4}, which is for a 95% confidence level, the confidence that the total uncertainty is really at 95% is questionable. The largest contribution to the total is from the mounting error, but this value is an approximation from the data in Table B-1 and may not be representative for all cases.

Coleman and Steele [24] suggest use of a measure of the relative contribution of each uncertainty source. In that way the most important sources and their relative contribution to the total uncertainty can be identified, and resources can be focused to reduce uncertainties where possible.

Begin the analysis by using the overall uncertainty relation from equation {3-4}:

$$U_{95} = \pm 2 * [\sum (B_R / 2)^2 + \sum S_R{}^2]^{1/2} \qquad \{3\text{-}4\}$$

Squaring both sides and dividing by the total uncertainty one arrives at the following:

$$1 = B_1{}^2 / U_{95}{}^2 + B_2{}^2 / U_{95}{}^2 + ... + (2S_1)^2 / U_{95}{}^2 + (2S_2)^2 / U_{95}{}^2 + ... \qquad \{5\text{-}5\}$$

Evaluating each of the terms in equation {5-5} allows one to assess the importance of each of the uncertainty sources to the total. Table 5-2 provides a summary of the uncertainty/error sources for the example, and provides the magnitude (in °C) and the relative contribution of each source.

Table 5- 2. HP-3852A Relative Contribution of Uncertainty Sources

Uncertainty Source	Uncertainty, K, 95% coverage	Relative Contribution to Total Uncertainty, Negative side/Positive side, %
1) TC mounting error (B)	-25.7	94.0/0.0
2) TC wire limits of error (B)	±6.4	5.7/94.0
3) TC connector (B)	±0.3	0/0.1
4) TC extension wire (B)	±1.5	0.3/5.1
5) Voltage range (B)	±0.26	0/0.1
6) Auto-zero (B)	±0.17	0/0
7) Reference junction (B)	±0.07	0/0
8) Normal mode noise (S)	±0.33	0/0.1
9) Common mode noise (S)	±0.13	0/0
10) Voltage-to-temperature conversion (B)	±0.5	0/0.5
11) Electrical noise (S)	±0.3	0/0.1
Totals	**-26.5, + 6.7**	**100/100**

It is evident from Table 5-2 that the TC mounting error is the largest source, followed by the TC wire accuracy.

5.6 Summary

In summary, for abnormal environments, the total uncertainty of a shroud TC measurement using the HP-3852A DAS is heavily dependent on the systematic uncertainty resulting from the mounting method or TC type used, and that uncertainty source can completely dwarf all other uncertainty sources. It is also one-sided. Table 5-2 shows the relative contribution of the uncertainty sources. It can be seen that, on the negative side, the largest source is the TC mounting error, followed by the TC wire accuracy. On the positive side, the uncertainty is dominated by the TC wire accuracy followed by the TC extension wire accuracy.

At a nominal temperature of 1283 K (1010°C), the 26.5 K (26.5°C) uncertainty is about 2.1%, while the 6.6°C uncertainty is about 0.5%. Key elements required to reduce the uncertainty are the TC mounting error, use of calibrated TCs, and avoidance of using extension wire. Unfortunately, this is typical of experiments at both RHF and the LCBS. Because this type of systematic uncertainties (TC mounting errors) is not well characterized, the resulting total uncertainty estimates may not have a high degree of certainty. This suggests a need for careful consideration of the mounting error in all abnormal thermal environment experiments.

6 National Instruments (NI) Data Acquisition Systems Uncertainty Analyses

This section analyzes the uncertainty of several data acquisition systems based on National Instruments hardware and LabView software.

6.1 Overall System Description

Figure 6-1 shows a schematic of a typical NI DAS. The first three components are the same as for the HP-3852A system: TC, TC connector, and TC extension cable. The next component is the plug board (TC-2095 or equivalent), the signal-conditioning card (SXCI-1102), and the data acquisition card. At present (February 2003) there are four DAQ cards available for use: Model 6036E, Model 6052E, Model 6062E, and Model 6070E. The TC reference junction is in the SCXI-1102 module. Terminal blocks are model TC-2095. Table 6-1 provides a comprehensive listing of the uncertainty sources in each of the four (4) types of cards, and the SXCI-1102 module. These data were taken from NI user manuals, references [25]-[29]. Two items are worth discussion at this time.

Least Significant Bit Accuracy

Models 6036E and 6052E DAQ are 16-bit cards. That means the overall DVM accuracy is as follows:

Accuracy = Peak-to-peak voltage/2^n, where n = number of bits.

For a 16 bit card used in a 100 mV (Type K maximum output is about 50 mV) range (or ±50 mV), the accuracy is about:

$100/2^{16}$ = 100/65,536 = 0.00153 mV or 1.53 µV.

Using about 40 µV/°C as a sensitivity, 1.53 µV corresponds to about 0.04°C which is negligible. However, one uses either the Model 6062E or 6070E cards, which are both 12 bit cards, the equivalent accuracy is:

$100/2^{12} = 100/4096 = 24.41\mu V$ or about 0.61°C. This value is not negligible in normal environments and in applications where results are particularly sensitive to TC uncertainties (e.g., heat flux from inverse conduction methods).

The HP-3852A system employs a different method to increase accuracy. That system depends on the "number of power line cycles" (NPLC) used to integrate the result. The more NPLC the higher the accuracy. There is no similar 12 or 16-bit specification as there are with the NI DASs.

Filter

All SXCI-1102 signal-conditioning cards have a 2 Hz low pass filter (always used). This means that the card will filter out anything above 2 Hz. In fact, 2 Hz is the "-3dB point," which corresponds to a 29% reduction in signal amplitude. There are no filters on the HP system.

For the majority of TC signals, especially surface measurements, filtering at 2 Hz is appropriate. For flame temperature measurements, this may not be appropriate as the flame temperatures may oscillate at frequencies of 100Hz.[8] In addition, "fire puffing" occurs at frequencies of about 1-10 Hz, so that information would be lost. Thermocouples normally used for "flame" or "fire" temperature measurements are 1/16 inch diameter, mineral-insulated, metal sheathed Type K designs, and the time constant of those MIMS TCs is about 1-5 seconds. These are used because smaller TCs often do not survive the fire, they are flexible and relatively robust, and larger TCs have slower time constants.

Because we normally have a number (e.g., 100 or more) of the 1/16" diameter, MIMS TCs to measure various important variables (test unit temperature, "flame" temperature, back face temperatures of calorimeters, etc.), and the test lengths are relatively long (e.g., 30 minutes), the available scan rate is limited to about once/second. The combination of the 2 Hz filter, slow response of the TC, and the slow scan rate of the DAS (1 Hz) as compared to the flame temperature oscillations (e.g., 100 Hz), may cause some aliasing (lower frequency results "masquerading" as real data). So lower frequency oscillations appear in the output, although they are not part of the input. Also, the magnitude of the flame temperature values recorded by the TC are likely not the true maxima and minima. Therefore, "flame temperature" values should be used with great care. Surface temperatures in normal environments; respond slowly, almost at a DC level. In this case, a 1 Hz scan rate is satisfactory.

Rather than individually discuss each one of the uncertainties present in the NI DASs (as was done with the HP-3852A DAS), an example will be presented. Similar uncertainty sources discussed earlier for the HP-3852A system apply to the NI systems. The example used for the HP-3852A DAS was for abnormal environments. The example for the NI system is provided using normal environments, to highlight differences, especially in the TC mounting error.

[8] Personal conversation with Sheldon Tieszen, 2002.

6.2 Analysis Assumptions

Assumptions used in the National Instruments DAS uncertainty analysis are as follows:

1) The input signal from the transducer is within the range of about 0–6.2 mV. For a Type K thermocouple, 0–6.2 mV corresponds to 0-150°C.
2) The input signal from the test item is low frequency, say less than 1 Hz.
4) The experiment's duration is long enough so drift is possible (say 8 hours).
5) There is no excitation (i.e., no bridge); the TC is a self-generating transducer.
6) Maximum operating temperature range where the DAS is located is 0–55°C (32–130°F).
7) No extension wires are used, cross talk may be present.
8) Gain = 100. (Note different gain than that used for the HP-3852A DAS (G = 1).)
9) There is no electrical noise from the RHF power system because the tests were performed elsewhere.

6.3 Component Uncertainties

Table 6-1 provides a detailed listing of all uncertainty sources for NI DASs available for use.

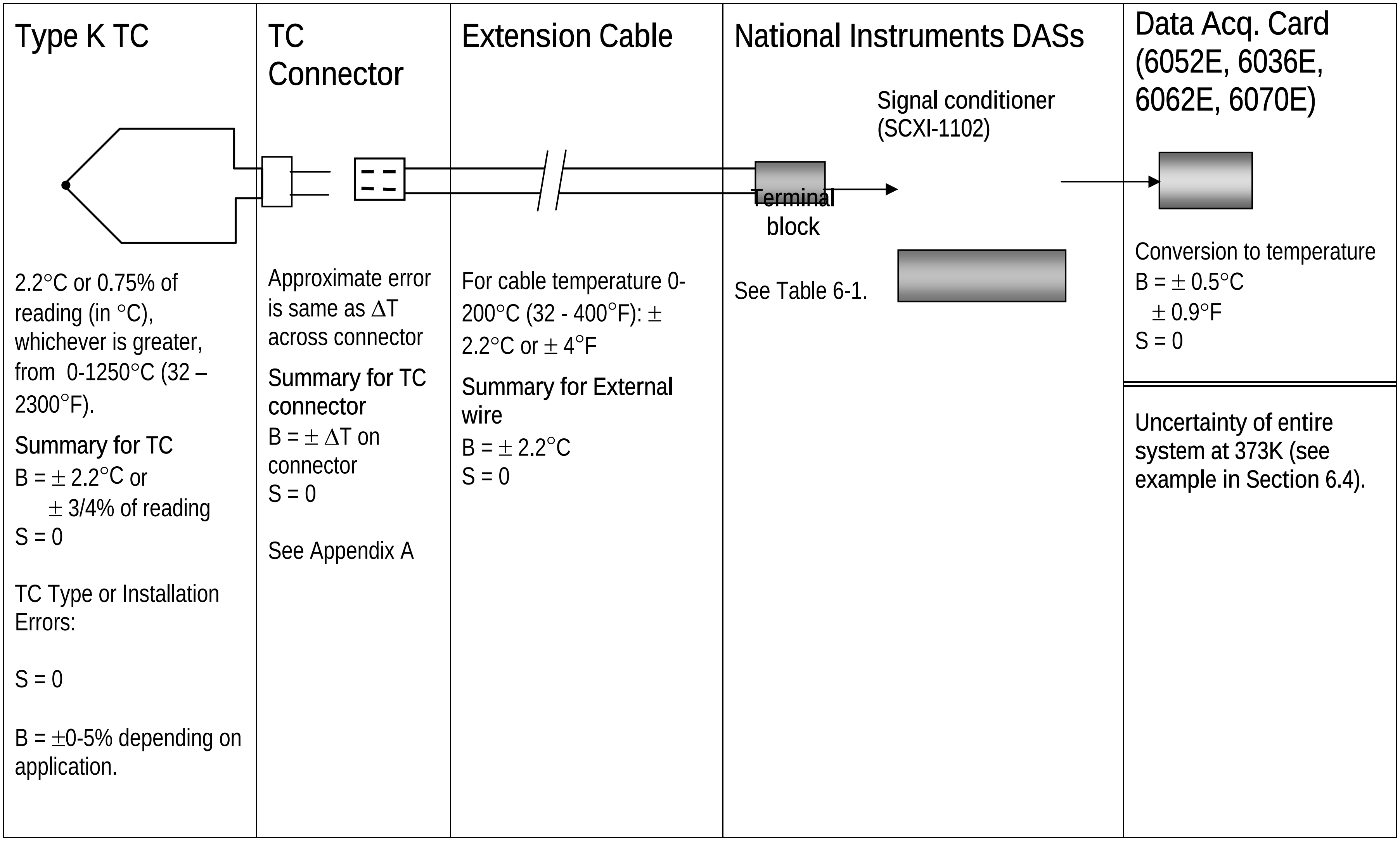


Figure 6- 1. NI DAS Schematic

Table 6- 1. Uncertainty Sources in National Instruments Data Acquisition Systems

Uncertainty Source	NI-6036E DAQ (Laptop @ RHF)	NI-6052E DAQ (LCBS)	NI-6062E DAQ (Laptop @ RHF)	NI-6070E DAQ RH	Comments	SCXI-1102 Signal Conditioning Card
Resolution	16-bit	16-bit	12-bit	12-bit		NA
1 LSB = ±5V or 0-10V ranges	153 µV for gain = 1 and 1.53µV for g=100	153 µV for gain = 1 and 1.53µV for g=100	244mV for g = 1, 24.41µV for g = 100	Same as for 6062E	***Large increase in accuracy for 16 bit DAS*** Note: 24.41 µV = about 0.61°C. 1.53 µV is about 0.04°C.	NA
Analog Inputs:						
1) Transfer characteristics						
a) Relative accuracy	±1.5 LSB[9] typical; ±3.0 LSB maximum	±1.5 LSB typical; ±3.0 LSB maximum	±0.5 LSB typical dithered[10], ±1.5 LSB maximum, undithered	Same as for 6062E		NA
b) Differential non-linearity (DNL)	±0.5 LSB typical; ±1.0LSB maximum	±0.5 LSB typical; ±1.0LSB maximum	-0.9, +1.5 LSB maximum	±0.5 LSB typical; ±1.0LSB maximum		0.005% FSR[11]
c) Offset error[12]	Pre-gain error after calibration: ±1.0µV max. Post-gain error after calibration: ±28.8µV.	Pre-gain error after calibration: ±1.0µV max. Post-gain error after calibration: ±76µV.	Pre-gain after calibration: ±16µV maximum. Post-gain after calibration:	Pre-gain after calibration: ±12µV maximum. Post-gain after calibration:	16 bit DAS much better.	300µV for gain =1 15 µV for gain = 100

[9] LSB = least significant bit

[10] "Dithering" is the addition of Gaussian noise to an analog input signal

[11] FSR = full scale range

Uncertainty Source	NI-6036E DAQ (Laptop @ RHF)	NI-6052E DAQ (LCBS)	NI-6062E DAQ (Laptop @ RHF)	NI-6070E DAQ RH	Comments	SCXI-1102 Signal Conditioning Card
			±1.0mV.	±0.5mV.		
d) Gain error	0.02% (±200 ppm) of reading, maximum for gain = 1.	0.00305% (±30.5 ppm) of reading, maximum for gain = 1.	±0.02% of reading maximum for gain = 1.	±0.02% of reading maximum for gain = 1.	16 bit DAS an order of magnitude better	0.015% of reading max for gain = 1, 0.020% for gain = 100
2) Amplifier characteristics						
Common mode rejection ratio (CMRR), dB	85 dB for gain = 0.5, 1.0 96 dB for gain = 10, 100	92 dB for gain=0.5, 97 dB for g=1, 101 dB for g=2, 104 dB for g=5, 105 dB for g ≥10	85 dB for g ≤1, 95 dB for g=2, 100 dB for g≥5	95 dB for g=0.5, 100 dB for g=1, 106 dB for g ≥2		110 dB 50-60 Hz 75 dB DC gain = 1 100 dB DC gain =100
3) Dynamic characteristics						
a) Bandwidth	Small signal (-3 dB): 413 kHz Large signal (1% THD[13]): 490 kHz	Small signal (-3 dB): 480 kHz Large signal (1% THD): 500 kHz	Small signal (-3 dB): 1.3 MHz Large signal (1% THD): 300 kHz	Small signal (-3 dB): 1.6 MHz Large signal (1% THD): 1MHz	Bandwidth larger for 12 bit DASs	2Hz
b) Settling time for full-scale step	±4 LSB, 5 µs typical ±2 LSB, 5 µs max.	± 1 LSB: 10-15 µsec. (depends on gain)	± 1 LSB: 3 µsec.	± 1 LSB: 1.5-2.0 µsec. (g = 100)	Settling time greater for 16 bit DAS	To 0.1% of max: 1 sec; To 0.01% of max: 10 sec
c) System noise	6.0 LSB RMS for gain = 100	4.2 LSB RMS[14] for gain = 100	1.0 LSB RMS for gain = 100	±0.9 LSB RMS for gain = 100	Noise higher for 16 bit DAS	RTI: 50 µV RMS g = 1 5 µV RMS g =100
d) Cross talk	-75 dB for adjacent channels, ≤ -90 dB others.	-75 DB for adjacent channels, -90 dB for others.	-75 DB for adjacent channels, -90 dB for others.	-75 DB for adjacent channels, -90 dB for others.	All 3 the same.	NA

[12] Specifications from NI include errors before calibration, which are large. It is assumed that the DAQ system has been calibrated before use so the “after calibration” specifications apply.
[13] THD = total harmonic distortion
[14] RMS = root mean square

Uncertainty Source	NI-6036E DAQ (Laptop @ RHF)	NI-6052E DAQ (LCBS)	NI-6062E DAQ (Laptop @ RHF)	NI-6070E DAQ RH	Comments	SCXI-1102 Signal Conditioning Card
4) Stability						
a) Warm-up time	15 min	15 min	15 min	30 min	Similar	20 min
b) Offset temperature coefficient	Pre-gain: ±20 µV/°C; Post-gain: ±175 µV/°C	Pre-gain: ±4µV/°C Post-gain: ±120µV/°C bipolar ±30µV/°C unipolar	Pre-gain: ±5 µV/°C Post-gain: ±240 µV/°C	Pre-gain: ±5 µV/°C Post-gain: ±240 µV/°C	Similar	G = 1: 20µV/°C G = 100: 1µV/°C
c) Gain temp. coefficient[15]	±20 ppm/°C[16] (±.002%/°C)	±17 ppm/°C (±.0017%/°C)	±20 ppm/°C (±.002%/°C)	±20 ppm/°C (±.002%/°C)		10 ppm/°C
Timing I/O						
a) Base clock accuracy	0.01%	0.01%	0.01%	0.01%	Same	NA
b) Maximum source frequency	20 MHz	20 MHz	20 MHz	20 MHz	Same	NA
Environment						
a) Storage temperature	-20-70°C	-20-70°C	-20-70°C	-20-70°C	Same	-55 to +150°C
b) Operating temperature	0-55°C	0-55°C	0-50°C	0-50°C	Almost the same	0-50°C
c) Humidity	10-90%, non-condensing	5-90%, non-condensing	5-90%, non-condensing	5-90%, non-condensing	Almost the same	5-90%, non-condensing

[15] See Section 6.4.4.4
[16] 20 ppm = 20 E-06

6.4 Example

6.4.1 Data Acquisition System (DAS) and Thermocouples

A National Instruments (NI) data acquisition system (DAS) was used to gather data from the thermocouples (TCs) on several component tests. This system was comprised of two (2) SCXI –1102 thermocouple amplifier modules (Signal Conditioning eXtensions for Instrumentation), TC-2095 terminal blocks (2), and a DAQCard 6062E (data acquisition card in a Dell laptop computer). Data were sampled sequentially for all thermocouple channels at a rate of once per second, starting at least 30-45 seconds prior to applying power to the battery igniter, and continuing until the test was complete (usually 90-100 minutes). All data were backed up to the disc after each scan to ensure no loss.

All thermocouples (TCs) used were either 30 or 24-gage fiberglass insulated wire, which consists of both the chromel and alumel wires individually insulated then a fiberglass wrap covering both wires. No mineral-insulated, metal-sheathed (MIMS) TCs were used on these experiments.

6.4.2 Data Validation

A data validation process was instituted to confirm the validity of TCs and the DAS both before tests were performed and after data was gathered. A number of checks were made on the TCs. Tasks such as checking for thermocouple connector problems (e.g., loose wires) were performed before the tests. Other obvious failures were checked on all channels (e.g., shorted wires inside connectors). The most prevalent problem was poor connector wiring (due to the small TC wire used). Obviously bad channels were eliminated from use in data analysis and reduction. An example of an "obviously" bad channel is one that has intermittent shorts where the temperature rapidly rises and falls in a physically unrealistic manner. Following the tests all thermocouples were checked to see if they remained securely bonded to a layer of foam (all did). Measurements of TC resistance also aided in checking TC integrity; this helped to identify shorted wiring.

The integrity of all DAS channels was evaluated before the first three tests, after the first three tests, and again before the last three tests. This was accomplished by an "end-to-end" calibration of each channel from the TC-2095 terminal block to the laptop output. Details of the calibration procedure are provided in Section 6.4.4.3.

Another benefit of the data validation process is to eliminate measurements from further consideration that were not made as desired. An example was several TCs attached to aluminum tabs on a support ring. Adhesive tape was used to hold them in place, but as the tabs reached their maximum temperatures (e.g., 70-80°C), the adhesive loosened and the TC junctions came off the surface. Temperatures "looked" good but careful post test inspection showed the TC junctions were not located on the surface. The TCs read only about 60°C, lower than the actual temperature (70-80°C). This error was discovered before the last experiment so the mounting procedure was modified to ensure the TC junctions were firmly attached to the surface (via twisted wire). Data from the first two experiments were eliminated from further consideration even though the data "looked" good.

Other tasks related to data quality and validation are described in Appendix A of the TT-1 Test Plan [30].

6.4.3 Uncertainty of Overall System

The uncertainty of the overall system is estimated by looking at the individual uncertainties of each component, then combining them using the method from reference [3]. As with the HP analysis, the uncertainties are assumed to be uncorrelated. Figure 6-2 shows a schematic of the DAS used.

As can be seen in Figure 6-1, the TC and DAS can be separated into the following components:

1) Thermocouple (TC)
2) TC connectors
3) TC-2095 terminal block
4) National Instruments DAS including SCXI-1102 (Signal Conditioning eXtensions for Instrumentation), and,
5) DAQCard 6062E (data acquisition card) inside Dell laptop computer.

An end-to-end calibration was performed between the TC-2095 terminal block and the laptop.

6.4.4 Uncertainty Sources

Table 6-2 provides a brief listing of the uncertainty sources present in this example where an end-to-end calibration is performed. Table 6-9 provides a more detailed discussion of the same uncertainty sources. Each source of uncertainty is discussed individually below.

6.4.4.1 Type K, chromel-alumel TC

All TCs used were Type K, chromel-alumel, made of either 30 or 24-gage[17] fiberglass sheathed TC wire. TC wire (rather than mineral-insulated, metal sheathed TCs) was used to reduce the cost of calibration and to provide more mechanical robustness during transportation to and from the assembly site. 24-gage wire was used on the component metal case, and 30-gage wire used on the foam. The smaller diameter wire (30-gage) was used on the foam to provide better thermal response. A polyimide tape was used to attach the TC to the foam.

For uncalibrated TCs, uncertainty is ±2.2°C (or K) or ±0.75% of the reading in °C, which ever is greater. This is the standard specification from ASTM [ref. 11]. Five (5) of the 30-gage intrinsic TCs, and ten (10) of the 24-gage TCs were calibrated by Sandia's Primary Standards Laboratory to see if the TCs had better accuracy than the standard value (often the case). All of the 5 of the 30-gage TCs had an uncertainty of ±1.2°C (±2.2°F) or 0.75% of reading (in °F) for the range 23-260°C (74-500°F). The 10, 24-gage TCs had a maximum accuracy of ±2.2°C for the same range. As can be seen, the 30-gage TC uncertainties (±1.2°C) are about ½ of the standard uncertainties (±2.2°C), but the 24-gage wire uncertainty was no better than the standard value.

[17] 30-gage TC wire nominal overall dimensions are: 1.09mm x 1.63mm (0.043 x 0.064 in), nominal conductor size is 0.254 mm (0.010 in). 24-gage wire nominal overall dimensions are 1.14 mm x 1.83mm (0.045 in x 0.072 in), nominal conductor size is 0.508mm (0.020 in).

Table 6- 2. Thermocouple & Data Acquisition System Uncertainty Sources

Source	Comments
Thermocouple (TC) wire calibration	"Standard" calibration specified by ASTM. "Special" calibration can be purchased for additional cost.
TC connectors	Due to temperature difference across TC connectors. TC connector materials not of equal quality as wire.
TC terminal block to laptop computer includes data acquisition card, mV to temperature conversion, and all components enveloped by end-to-end static calibration.	Uncertainty sources include non-linearity, offset, gain error, 50-60 Hz CMRR, system noise, normal mode rejection (60 Hz).
TC terminal block to laptop computer, all uncertainty sources **not** enveloped by end-to-end static calibration.	Filter cut-off and filter step response, CMRR, long-term stability, gain temperature coefficient, and cross-talk are not covered by end-to-end Fluke calibration.
Intrinsic TC mounting error	Error due to finite size of TC and fact that TC temperature never exactly the same as the surface you are trying to measure.

6.4.4.2 TC Connectors

For isothermal conditions (no temperature difference along the TC pins), there is no uncertainty from this source. Because the connector pins are made of lesser quality material than the TC wire, and if there is a temperature difference on the pins, there can be a small uncertainty due to that temperature difference because the Seebeck coefficient for the connector material is different than that from the TC wire. An analysis was performed in Appendix A and for every ±2°F ΔT across the connector pins, there is an associated uncertainty of about the same value ±2°F. This can be a concern in outdoor operations (e.g., at the LCBS), but is not considered a significant source for these tests because they were performed inside a laboratory with a controlled environment. In addition, miniature connectors were used so any temperature difference across the connector would be small. For these reasons, this uncertainty source will be assumed to be negligible.

6.4.4.3 End-to-End Calibration of TC-2095 Terminal Block, SCXI-1102 TC Amplifier Modules, and NI DAQCard 6062E

The three NI devices, (TC-2095, SCXI-1102, and DAQCard 6062E) were calibrated as a unit using an end-to-end calibration system. Prior to the first experiment, a check of the system was performed to ensure all channels worked properly. After the third and sixth tests a calibration was also performed. A known signal was applied to the terminal block and output was recorded on the laptop. This calibration was performed at 10°C increments from 0 to 150°C, which spanned the range of temperatures expected in the tests. Calibrations were performed by use of a thermocouple simulator (Fluke Model 5520A SN 8160014) that provides a known value into the TC terminal block plug board. A minimum of about 600 and maximum of about 1200 readings (600 readings per second for 1-2 seconds) were taken to provide a mean temperature, a standard deviation, and an error ("true" temperature – mean temperature) at each 10°C increment. Output is provided in a spreadsheet format. This device (Fluke) simulates Type K output to within about ± 0.16°C in the –25 to 120°C range [31]. For the 120 to 1000°C range, the absolute uncertainty is ±0.26°C. Because all of the temperatures measured were below 120°C, the Fluke uncertainty will be assumed to be ±0.16°C.

Input was provided on each channel individually, allowed to stabilize, then automatically recorded. This was performed on all channels used in the six tests. There were two TC-2095 TC terminal blocks used ("Slot #1" or "Terminal Block #1", and "Slot #2" or "Terminal Block #2"), each containing 32 channels. Because we only used the first 12 channels of TB #2, only the first 12 channels were calibrated. A partial example of the output can be viewed in Table 6-3 for channels 0, 1, and 2. A summary of the results is shown in Tables 6-4 through 6-8 for both terminal blocks.

There are enough results to provide calibration data for each channel at 10°C increments throughout the temperature range. This would comprise a large amount of data and make presentation of the results more difficult. Therefore, a different method was chosen to present the results. It was desired to provide a single value of total uncertainty that could be used to provide uncertainty limits and facilitate ease of comparison with computational predictions. Therefore, data were averaged to obtain mean values and the standard deviation of those means. Also, the standard deviation of the 600-1200 readings was used to provide an average bias or systematic error for all channels, and a standard deviation for all channels. This bias and standard deviation was used to compute total TC uncertainty.

Table 6-3 provides data for each channel at temperatures ranging from 0-150°C in 10°C increments. The mean value is provided, the standard deviation of the readings (1200 in this case), and the error (Mean value – set point). For example, for Channel 0 at 50°C, the mean value was 50.123°C, the standard deviation was 0.591°C, and the error was therefore 0.123°C. Channel 0 errors ranged from a maximum of 0.418°C to a low of -.143°C with a mean of about 0.075°C. The standard deviation of the 1200 readings at 50°C was 0.591°C. The maximum standard deviation from all temperature set points was about 0.763°C. To obtain a single value of uncertainty good to about 95% confidence, one should not use the maximum error seen (e.g., 0.418°C), but a value that encompasses about 95% of the errors. That can be estimated by taking the standard deviation of the sample of 16 errors. The result is 0.148°C. Therefore, for Channel 0, one can say that the bias with 95% confidence is the mean error (0.075°C) $\pm 2\sigma$, where $\sigma = 0.148$°C.

Maximum, minimum, and mean errors are provided in right side of Table 6-3 for each channel over the entire temperature range (0-150°C). Also provided are the maximum standard deviation for each channel, and the standard deviation of the errors (over the whole range). These values will be averaged again to estimate a single overall value of bias and random uncertainty sufficiently large to represent about 95% of all channels at all temperatures.

Tables 6-4 through 6-8 provide summary data for the two terminal blocks by channel for calibrations performed after the tests in November 2002, and again in February 2003. As can be seen in Tables 6-4 and 6-5, values of "mean errors" (i.e., biases) for terminal block #1 were all positive, while "mean errors" for terminal block #2 were mostly negative. Overall, for the November calibration, terminal block #1 had an average mean error of about 0.40°C, while terminal block #2 had an average mean error of about -0.39°C (channels 0-11). For TB #1, the standard deviations of the mean errors was generally very consistent from channel to channel, with an average standard deviation of about 0.15°C. For TB #2, the standard deviations were also very consistent from channel to channel, with an average standard deviation of about 0.17°C for the first 12 channels.

Similarly, for the February 2003 calibration, terminal block #1 had an average mean error of about 0.33°C, while terminal block #2 had an average mean error of about -0.44°C (channels 0-11). For TB #1, the standard deviations of the mean errors was generally very consistent from channel to channel, with an average standard deviation of about 0.17°C. For TB #2, the standard deviations were also very consistent from channel to channel, with an average standard deviation of about 0.19°C for the first 12 channels.

Table 6-8 provides a single value of bias and random uncertainty that can be used for all channels. Although these values will overstate the uncertainty for some channels, the use of a single value is particularly attractive to conservatively capture the total uncertainty. As Table 6-8 shows, the recommended values for the end-to-end calibration are a bias of ±0.80°C and a random uncertainty (1σ) of ±0.83°C. These values are used in Table 6-9 to estimate the total uncertainty for all channels at all temperatures.

This type of "end-to-end" calibration is particularly useful because it takes into account almost all of the uncertainty sources present in the DAS that would otherwise have to be specified individually then combined. Because uncertainties provided by the manufacturer are often maximum possible values, this individual summing can result in a calculated uncertainty larger than that afforded by the end-to-end calibration. Some of the uncertainty and error sources captured by the end-to-end calibration are noise, 50-60 Hz rejection, non-linearity, MV to temperature conversion, and gain error. Uncertainties not accounted for in the calibration are filter cut-off, filter step response, long-term stability, gain temperature coefficient, channel-to-channel cross talk, noise from the RHF AC power system, and from common mode rejection ratio (CMRR). Uncertainty sources not covered by the Fluke calibration are discussed below.

Table 6- 3. Calibration of NI DAQPad 6062E and SCXI-1102 TC Modules, Channels 0 and 1.

Post-test calibration of NI SCXI DAQ system 11/15/02. Used Fluke calibrator
1200 readings for each temp - used to calc mean

Channel	Set Point, C	Average, C	Std dev of readings, C	Bias Error, C
0	0	0.046352	0.762935	0.046352
	10	10.060503	0.756614	0.060503
	20	20.120594	0.651953	0.120594
	30	29.856539	0.608247	-0.143461
	40	39.975579	0.723074	-0.024421
	50	50.123189	0.59147	0.123189
	60	60.266712	0.746229	0.266712
	70	70.078433	0.632119	0.078433
	80	80.09503	0.693445	0.09503
	90	90.201045	0.593116	0.201045
	100	100.418051	0.718274	0.418051
	110	109.862051	0.73684	-0.137949
	120	119.904906	0.598337	-0.095094
	130	130.064031	0.722407	0.064031
	140	140.162796	0.600197	0.162796
	150	149.970961	0.609263	-0.029039
1	0	0.105743	0.737442	0.105743
	10	9.994289	0.733668	-0.005711
	20	20.129443	0.747201	0.129443
	30	29.935202	0.681769	-0.064798
	40	39.920628	0.637778	-0.079372
	50	50.148864	0.703723	0.148864
	60	60.152269	0.646616	0.152269
	70	69.973369	0.619484	-0.026631
	80	80.049936	0.630762	0.049936
	90	90.229526	0.674166	0.229526
	100	100.272612	0.688901	0.272612
	110	109.789303	0.716647	-0.210697
	120	119.975554	0.630911	-0.024446
	130	129.961269	0.681517	-0.038731
	140	140.209907	0.67653	0.209907
	150	150.081708	0.628988	0.081708

Channel 0:
0.418051 max bias error
-0.143461 min bias error
0.762935 max std dev
0.075423 Average bias error
0.147582 Std dev of bias errors

Channel 1:
0.272612 max bias error
-0.210697 min bias error
0.747201 max std dev
0.058101 Average bias error
0.130954 Std dev of bias errors

Table 6- 4. Summary Data for Terminal Block (TB) #1 (Slot #1), November 2002 Calibration

NI SCXI Model 6062E DAQCard Data Acquisition System, Slot #1 Calibration 11/15/02

Channel	Maximum Error, C	Minimum Error, C	Mean Error, C	Standard Deviation of Error, C	Maximum Standard Deviation of Readings, C
0	0.42	-0.14	0.08	0.15	0.76
1	0.27	-0.21	0.06	0.13	0.75
2	0.52	0.02	0.25	0.15	0.70
3	0.69	0.18	0.47	0.13	0.74
4	0.59	-0.03	0.26	0.19	0.70
5	0.50	-0.15	0.13	0.17	0.70
6	0.85	-0.24	0.51	0.16	0.71
7	0.42	-0.40	0.02	0.20	0.73
8	0.69	0.07	0.32	0.17	0.73
9	0.84	0.28	0.50	0.15	0.70
10	0.78	0.15	0.41	0.16	0.72
11	0.74	0.25	0.48	0.14	0.73
12	0.82	0.25	0.48	0.16	0.72
13	0.92	0.26	0.51	0.17	0.69
14	0.69	0.22	0.43	0.13	0.74
15	0.78	0.13	0.44	0.16	0.71
16	0.56	0.08	0.32	0.13	0.71
17	0.74	0.15	0.40	0.16	0.73
18	0.91	0.30	0.56	0.16	0.70
19	0.74	0.21	0.44	0.15	0.72
20	0.72	0.16	0.43	0.14	0.76
21	0.56	0.15	0.35	0.12	0.79
22	0.93	0.26	0.51	0.17	0.72
23	0.67	0.12	0.36	0.15	0.71
24	0.78	0.11	0.38	0.16	0.69
25	0.82	0.33	0.56	0.14	0.71
26	0.75	0.19	0.42	0.15	0.69
27	0.93	0.29	0.58	0.14	0.73
28	0.91	0.32	0.56	0.15	0.70
29	0.94	0.34	0.60	0.16	0.69
30	0.85	0.26	0.50	0.15	0.70
31	0.73	0.18	0.41	0.15	0.72
			Avg std dev of readings ------->		**0.72**
		Avg bias -->	**0.40**	**0.15**	**<---- Avg std dev of biases**

Table 6- 5. Summary of Calibration of Terminal Block (TB) #2 (Slot #2), November 2002 Calibration

NI SCXI DAQ System, Slot #2 Calibration 11/15/02
NI SCXI Model 6062E DAQCard Data Acquisition System, Slot #2 Calibration 11/15/02

Channel	Maximum Error, C	Minimum Error, C	Mean Error, C	Standard Deviation of Error, C	Maximum Standard Deviation of Readings, C
0	0.12	-0.40	-0.16	0.15	0.95
1	-0.06	-0.73	-0.43	0.19	0.93
2	0.13	-0.30	-0.07	0.13	0.90
3	-0.25	-0.82	-0.46	0.17	0.93
4	0.04	-0.51	-0.20	0.15	0.91
5	-0.34	-0.97	-0.63	0.17	0.92
6	-0.46	-1.12	-0.81	0.19	0.89
7	-0.07	-0.56	-0.33	0.16	0.89
8	-0.20	-0.90	-0.55	0.19	0.91
9	0.06	-0.40	-0.15	0.16	0.88
10	-0.03	-0.86	-0.48	0.21	0.88
11	-0.02	-0.88	-0.42	0.23	0.86
12	-0.04	-0.57	-0.34	0.18	0.84
13	0.20	-0.24	0.01	0.13	0.86
14	0.28	-0.15	0.06	0.13	0.88
15	0.12	-0.49	-0.22	0.18	0.86
16	0.08	-0.57	-0.24	0.20	0.77
17	0.40	-0.18	0.14	0.15	0.85
18	0.17	-0.32	-0.08	0.16	0.79
19	0.28	-0.45	-0.05	0.20	0.77
20	0.38	-0.19	0.16	0.17	0.83
21	0.37	-0.13	0.19	0.14	0.77
22	0.16	-0.57	-0.23	0.20	0.81
23	0.29	-0.26	-0.01	0.16	0.75
24	0.10	-0.43	-0.19	0.17	0.77
25	0.35	-0.64	-0.09	0.26	0.75
26	0.44	-0.16	0.16	0.14	0.75
27	0.41	-0.17	0.11	0.16	0.76
28	0.46	-0.07	0.18	0.17	0.70
29	0.09	-0.77	-0.30	0.23	0.74
30	0.21	-0.63	-0.21	0.22	0.75
31	0.16	-0.55	-0.22	0.19	0.75
			Avg std dev of readings ---------->		**0.83**
	All channels:	**Avg bias -->**	**-0.18**	**0.18**	**<--- Avg std dev of biases**
	Ch 0-11:	**Avg bias -->**	**-0.39**	**0.17**	**<--- Avg std dev of biases**
	Ch 0-11:		**Avg std dev of readings -------------**		**0.90**

Table 6- 6. Summary Data for Terminal Block (TB) #1 (Slot #1), February 2003 Calibration

NI SCXI 6062E DAS, post-test calibration, 2/27/03.
Slot #1

Channel	Maximum Error, C	Minimum Error, C	Mean Error, C	Standard Deviation of Error, C	Maximum Standard Deviation of Readings, C
0	0.45	-0.29	0.19	0.20	0.80
1	0.30	-0.37	-0.06	0.19	0.84
2	0.53	-0.13	0.28	0.17	0.94
3	0.47	-0.30	0.21	0.20	0.78
4	0.45	-0.31	0.20	0.19	0.78
5	0.59	-0.14	0.28	0.18	0.77
6	0.83	0.05	0.51	0.20	0.76
7	0.44	-0.26	0.12	0.18	0.76
8	0.57	-0.24	0.23	0.20	0.75
9	0.71	0.07	0.41	0.16	0.79
10	0.19	-0.53	-0.08	0.19	0.79
11	0.56	-0.19	0.23	0.19	0.76
12	0.53	0.04	0.28	0.16	0.72
13	0.50	-0.08	0.28	0.16	0.79
14	0.49	0.06	0.28	0.14	0.75
15	0.62	0.08	0.40	0.15	0.84
16	0.73	0.16	0.41	0.15	0.82
17	0.65	0.06	0.34	0.18	0.82
18	0.73	0.27	0.52	0.14	0.77
19	0.68	0.17	0.46	0.13	0.85
20	0.67	-0.07	0.41	0.18	0.83
21	0.56	0.05	0.37	0.13	0.82
22	0.84	0.29	0.53	0.16	0.77
23	0.54	-0.52	0.09	0.25	0.78
24	0.50	-0.47	0.06	0.25	0.77
25	0.89	0.39	0.69	0.14	0.87
26	0.80	0.31	0.54	0.14	0.85
27	0.93	0.40	0.69	0.14	0.92
28	0.92	0.34	0.59	0.16	0.86
29	0.94	0.41	0.66	0.15	0.83
30	0.77	0.23	0.53	0.14	0.90
31	0.36	-0.45	0.02	0.23	0.87
			Avg std dev of readings --->		**0.81**
		Avg bias --->	**0.33**	**0.17**	**<--- Avg std dev of biases**

Table 6- 7. Summary Data for Terminal Block (TB) #2 (Slot #2), February 2003 Calibration

NI SCXI 6062E DAS, post-test calibration, 2/27/03.
Slot #2

Channel	Maximum Error, C	Minimum Error, C	Mean Error, C	Standard Deviation of Error, C	Maximum Standard Deviation of Readings, C	
0	0.03	-0.60	-0.33	0.17	0.83	
1	-0.18	-1.03	-0.54	0.23	0.79	
2	0.08	-0.44	-0.18	0.16	0.84	
3	-0.12	-1.02	-0.55	0.23	0.84	
4	0.03	-0.48	-0.24	0.14	0.79	
5	-0.32	-1.09	-0.61	0.22	0.83	
6	-0.48	-1.24	-0.84	0.21	0.81	
7	-0.12	-0.60	-0.34	0.13	0.77	
8	-0.25	-1.00	-0.58	0.21	0.78	
9	0.12	-0.42	-0.11	0.16	0.79	
10	-0.03	-0.94	-0.47	0.22	0.76	
11	-0.10	-0.82	-0.43	0.21	0.75	
			Avg std dev of readings -->		**0.80**	
		Avg bias --->	**-0.44**	**0.19**	**<--- Avg std dev of biases**	

Table 6- 8. Summary for All Channels, All Temperatures, both Terminal Blocks

Calibration Date	Terminal Block (Slot) #1			Terminal Block (Slot) #2		
	Average bias error	Average standard deviation of bias errors	Average standard deviation of readings	Average bias error	Average standard deviation of bias errors	Average standard deviation of readings
November 2002	+0.40°C	0.15°C	0.72°C	-0.39°C	0.17°C	0.83
February 2003	+0.33°C	0.17°C	0.81°C	-0.44°C	0.18°C	0.80°C
	95% confidence bias: +0.40 ± 2σ = +0.74, +0.06		Use larger value: 0.81°C	95% confidence bias: +0.44 ± 2σ = -0.08, -0.80		Use larger value: 0.83°C
Summary:	To cover all channels use: ±0.80 for bias, and ±0.83 for random uncertainties for NI DAS. See Table 6-9.					

6.4.4.4 Uncertainty Sources Not Covered by End-to-End Calibration[18]

1) Filter cutoff: -3dB at 2 Hz

   The NI SCXI-1102 TC amplifier module has a 2 Hz low-pass filter with a –3dB cutoff at 2 Hz. The –3 dB specification corresponds to about a 29% error. Therefore, if one were trying to measure a 2 Hz varying TC signal with the above system, assuming a perfectly responding TC, the error would be 29%. It is assumed that the response of the component is very slow, almost a DC signal, so frequency cut-off is a negligible error.

2) Filter step response: 1 sec to 0.1% of step value, 10 sec to 0.01%.

   Similar to the frequency response, if one attempted to measure a step response with the SCXI-1102 modules to 99.9% of peak, one would have to wait 1 sec. Because the sample rate used was 1/sec., an uncertainty of 0.1% will be used. If we were to sample less frequently, this error would be less. This value is assumed to be 0.1% of the reading in absolute temperature (K).

3) Long term stability = 1µV/°C for gain=100, 20µV/°C for gain=1

   For these experiments the gain was auto-selected, but because TC output at these temperatures was less than 50mV, a gain of 100 was likely used [19]. It will be assumed that the ambient temperature inside the laboratory where the tests were performed changed by no more than ±3°C during the experiments (a reasonable approximation of the building heating, ventilating, and air conditioning system control). As a result, the long-term stability was about ± 3 µV or about ± 0.08°C (assuming a 25°C change in temperature for every 1000µV change in electric potential). This source is negligible.

4) Gain temperature coefficient = 10ppm/°C.

   Again assuming the temperature changes by no more than ± 3°C, the gain temperature coefficient is about ± 30ppm (30E-06) or 0.0003%, which is negligible.

5) Settling time: 3µsec for 0.012% accuracy. Because the sample rate for the battery tests was 1 sample per second, any accuracy penalty from settling time is negligible.

f) CMRR (common mode rejection ratio) for gain = 100 is minimum of 100dB (from SCXI-1102 specifications)

   The CMRR is defined in equation {5-3{:

$$CMRR, dB = 20\log(CMRR) = 20\log(gain * e_{cmv} / e^{e}{}_{cmv})$$

{5-3}

$$e^{e}{}_{cmv} = (e_{cmv} * gain) / \log^{-1}(CMRR, dB / 20)$$

   Where e_{cmv} = common mode voltage and $e^{e}{}_{cmv}$ = common mode voltage error.

   During the first test the pin-to-case potential on the battery case was measured as 35 mV. Because this could be a CMV applied to the metal case TCs it will be used as the CMV for all TCs (for simplicity). Therefore, assuming that the maximum common mode voltage is about equal to the pin-to-

[18] All specifications were obtained from National Instruments users manuals for the SCXI-1102 modules, and DAQCard 6062E data acquisition card, references [25-29].

[19] Per Chuck Hanks, 2/6/02, SCXI card uses gain = 100 for TC measurements.

case potential measured during the first battery experiment (35 mV), an estimate of the common mode voltage error is:

$$e^{e}{}_{cmv} = e_{cmv} * gain / \log^{-1}(100/20) = 0.035 * 100 / \log^{-1}(5) = 35\mu V$$

This value (35μV) corresponds to an uncertainty of about 0.8°C. It is important to keep the common mode voltage levels as low as possible, and to use the smallest gain as possible, or the common mode error will be large compared with other error sources.

g) Crosstalk: this uncertainty source is due to one channel affecting an adjacent channel during scanning. Specifications for the NI-DAQCard 6062E are –75 dB for adjacent channels and –90dB for all other channels. This specification is converted to a ratio of variables via the following relation [9]:

Cross talk, dB = 20 $\log_{10}$ (ΔV/V) {5-1}

ΔV may be interpreted as the voltage induced on channel 2 as a result of the difference in voltage (V) between channel 1 and channel 2. Substituting into the above equation assuming the maximum difference between channels is 50mV, ΔV = 9μV or about 0.2°C.

According to Taylor [8], all of the sources in this section (6.4.4.4) should be categorized as systematic uncertainties.

6.4.4.5 Systematic (Bias) Error Due to Imperfect TC Mounting

This uncertainty source is often the most important, especially in abnormal thermal environments. There is always some difference between the temperature of the TC junction and the temperature of the surface being measured. This difference can be the largest source when measuring high temperatures (e.g., 1000°C) because the heat transfer from the TC and the surface being measured is so large. It is also an insidious type of error because one may have a small random error but a large unknown bias. A separate analysis will be performed for the TCs mounted on the foam and those mounted on the metal case because the heat fluxes and thermal contact resistances are different. An analysis for the TCs attached to the inside of the chamber was not performed because those measurements are of lesser interest.

Error from Contact Resistance, Foam TCs

There is thermal contact resistance between the TC bead and the foam or metal case. This contact resistance creates a temperature difference between the bead and the surface to which it attached, and the temperature we are trying to measure. This temperature difference is an error that should be added to the total uncertainty.

One can approximate the temperature difference generated via thermal contact resistance by use of equation {6-1}:

$\Delta T = q*R_{tc}$ {6-1}

where ΔT is the temperature difference between the surface and the TC bead, q is the heat flux, and R_{tc} is the thermal contact resistance [ref. 32].

From reference [32], metal-to-metal contact resistances range from 0.01 x10^{-4} to 0.9 x 10^{-4} m^2-K/W. The lowest value is for aluminum in contact with aluminum with metallic lead coating. The highest value is for a silicon chip in contact with aluminum with a 0.02 mm thick epoxy coating. These convert to contact conductance values ranging from 1,000,000 to 11,111 W/m^2-K. From another source, recommended values of contact conductance for stainless steel to stainless steel interfaces range from 500-2000 W/m^2-K.[20] Therefore, possible contact conductances range from 5 x 10^2 to 1 x 10^6, over three orders of magnitude difference. Using the maximum and minimum values will therefore result in vastly different estimates of the error due to contact resistance.

To apply equation (6-1) one needs an estimate of the heat flux, q. This can be obtained through an energy balance as follows. An energy balance is made by equating the energy leaving the surface of the foamed component and equating that to the energy that is transferred to the walls of the chamber:

$$q_{total} = q_{cond} + q_{conv} + q_{rad} \qquad \{6\text{-}2\}$$

where q_{total} is the total heat loss between the foam and the chamber, q_{cond} is the heat transfer via conduction through the air, q_{conv} is convection between the air and foam, and q_{rad} is the radiative transfer between the foam and the chamber walls (air assumed to be a transparent (i.e., non-absorbing) medium). The air temperature and chamber wall temperatures were measured during the experiments. Typical of the responses show that the wall and air temperatures rise slightly during the test but stay within the range 23-27°C. Therefore, an average wall and air temperature of 25°C will be assumed. The maximum foam temperatures were seen on the top of the component and were about 70°C.

Equation 6-2 can be re-written as follows:

$$q_{total} = k_{air} * (T_{foam} - T_{air}) / \Delta x + h_{air-foam} (T_{foam} - T_{air}) + \varepsilon_{foam} \sigma * (T_{foam}{}^4 - T_{wall}{}^4) \qquad \{6\text{-}3\}$$

where:

k_{air} = thermal conductivity of air = 27.8 E-03 W/m-K at 25°C,

T_{foam} = nominal foam temperature = 70°C,

T_{air} = nominal air temperature = 25°C,

Δx = thermal boundary layer thickness, average value of about 1.5 cm (calculation not shown here),

$h_{air-foam}$ = convective heat transfer coefficient, 6.2 W/m^2-K,

ε_{foam} = foam emissivity = 0.8[21]

σ = 5.67 x 10-8 W/m^2-K^4,

T_{wall} = nominal chamber wall temperature, 25°C.

Substituting values into equation {6-3} one obtains:

q_{total} = 83 (conduction) + 277 (convection) + 270 (radiation) = 630 W/m^2

In this case convection contributes 44%, radiation 43%, and conduction 13% of the total.

For foam mounted TCs, contact resistance values spanning the entire range will be used to see if the error is negligible. The appropriate level of heat flux is that estimated above, 630 W/m^2.

$\Delta T_{min} = q*R_{tc}$ = 630*0.01 x10^{-4} = 0.0006K (negligible),

$\Delta T_1 = q*R_{tc}$ = 630*0.9 x10^{-4} = 0.06K (negligible),

$\Delta T_2 = q*R_{tc}$ = 630*5 x10^{-4} = 0.32K (small but not negligible),

[20] Telecom with Victor Figueroa on 1/10/03. Mr. Figueroa's source was a memo from B.F. Blackwell.

[21] Personal communication with Dean Dobranich, 12/2/02. 0.8 for (white but rough) foam; 0.8-0.9 for charred foam.

ΔT_{max} = q*R_{tc} = 630*2 x10^{-3} = 1.26K (relatively large),

The minimum ΔT (0.006°K error) is clearly negligible, while the maximum error (1.26 K) is not negligible. Engineering judgment would say that the error due to contact resistance should be larger than the smallest error (0.006 K). The largest value (1.26 K) was estimated using the contact resistance from stainless steel (SS) to SS, and is likely not suitable for TCs mounted on foam using polyimide tape with adhesive. Assuming the maximum value from [32] (0.9 x 10^{-4} m^2-K/W) is appropriate for the foam TCs, the error is 0.06K. This error is negligible.[22]

Summary: For the foam TCs for the maximum range of thermal contact resistances believed to be applicable, the TC mounting error is negligible.

Error from Contact Resistance Intrinsic, Metal Case TCs

A similar analysis can be made for the TCs attached to the metal case. From reference [32], for SS to SS contact with Dow Corning grease the resistance value quoted is 0.04 x 10^{-4}, or a conductance of 250,000 W/m^2*K. The other values provided (500-2000 W/m^2*K) are much lower. The lower values (500-250,000 W/m^2*K) are more relevant because conductive grease was not used.

The level of heat flux is different for the metal case TCs. Because the metal case TCs are covered with foam insulation, one could say that they are well insulated and are not affected by the chamber. The TCs are in direct contact with the metal case so the heat flux from the case is most relevant. If one assumes the metal case is a lumped mass, a level of heat transfer can be estimated by estimating the temperature rise of the metal case TCs and adding the conduction through the foam. The highest temperature rise rate on the metal case TCs was about 6.5 C/minute. Using a lumped mass assumption, one can estimate the magnitude of the heat transfer as follows:

$$q = [\rho c_p t(\Delta T / \Delta t)]_{ss} + [\rho c_p t(\Delta T / \Delta t)]_{foam} + k_{foam}(T_{case} - T_{foam}) / \Delta x_{foam} \qquad \{6\text{-}4\}$$

where ρ is the density, c_p is the specific heat, and t is the material thickness. Because the case thickness is so thin (0.035”), the lumped mass assumption is valid. SS density is about 8000 kg/m^3, and specific heat is about 480 J/kg*°C. Assuming ΔT/Δt ~ 6.5°C/min, the flux is about 370 W/m^2 from the first term in equation {6-4}. For the foam, a value of 4°C/min was assumed for ΔT/Δt. Estimates were made of the flux through the foam at various thicknesses. An average value is about 300 W/m^2 (flux varies depending on foam thickness). An estimate was also made for the energy storage term in equation {6-4} (second term) and the results was about 140 W/m^2. Therefore, the total flux is about 810 W/m^2.

Using equation {6-1} with q = 810 W/m^2 and thermal resistances from 4 x 10^{-6} to 2 x 10^{-3} (contact resistance values suitable for TC bead to metal case interface) the error is:

ΔT_{min} = 4 x 10^{-6} * 810 = 0.003°C (negligible)

ΔT_{max} = 0.002 * 810 = 1.62°C (not negligible)

Based on a subjective assessment of the care taken when mounting the metal case TCs, and engineering judgement, it is assumed that the maximum error of 1.62°C is unrealistic. It will be (arbitrarily) assumed that a reasonable estimate of the error for the metal case TCs is about 0.1°C. This value is about 15% of

[22] Note that results of the contact resistance analysis are themselves “uncertain” due to the large range of values that can be used for the thermal contact resistance. However, judgments have to be made and arguments for changing the error estimates are welcome.

the maximum value (0.7°C), but 100 times larger than the minimum value (0.001°C). An error of 0.1°C adds only a very small amount to the total uncertainty.

Summary: For the metal case TCs (for the maximum range of thermal contact resistances believed to be applicable), the TC mounting error is negligible.

6.5 Summary for NI DAS Example

A total uncertainty value is estimated by first combining the systematic and random uncertainties separately, then combining the results using the method in reference [3]. Results are shown on the bottom of Table 6-9. The maximum total uncertainty is about ±2.4°C (or ±2.4 K) for the foam TCs, and ±3.0K for the metal case TCs, or about 1% of the reading in K.

6.6 Relative Contribution of Uncertainty Sources to Total

Table 6-10 shows the results of an analysis similar to the one generated for the HP-3852A example for the foam and metal case TCs. For the foam TCs the largest source is the end-to-end static calibration followed by sources not covered by the calibration (dominated by the CMRR), and last the TC wire uncertainty. For the metal case TCs, the largest source is the TC wire uncertainty, followed by the end-to-end static calibration, and finally the sources not covered by the end-to-end calibration (dominated by CMRR).

Of these sources, the end-to-end static calibration cannot be significantly reduced much because the sources are determined by hardware. One source that may help is the mV to temperature conversion, which may be tailored to the temperature range considered. However, in this case the conversion used was tailored to 0-300°C and little would be gained with effort on this source. The easiest reduction would be attained by purchasing specially calibrated thermocouple wire with a ±1.1°C tolerance from the factory. This would have helped the metal case TCs. Efforts to better quantify the common mode voltage might provide additional benefits. Another possibility is to use one of the NI systems with 16-bit accuracy.

6.7 Comparison with National Instruments Web Site Accuracy Calculator

The National Instruments web site (www.ni.com) has a uncertainty estimator where one inputs the DAS model and type of measurement and the web site estimates an accuracy value. For this system, the accuracy calculation includes five (5) sources, so does not include the entire DAS/TC system. Uncertainty sources considered were % of reading (overall accuracy of the voltmeter), offset, noise, quantization, and drift. For those five sources the “total system accuracy” was estimated to be ±0.054 mV (54.1µV). For the temperature range we are using (0-150°C) the nominal sensitivity is 41µV/1°C. So for 54.1 µV the total system accuracy is ±1.3°C. This is lower than the value estimated above, as expected, because the web site estimator does not include all the possible uncertainty sources.

Table 6- 9. Overall DAS TC Measurement Uncertainty Sources

Component	Systematic Error or Uncertainty	Random Uncertainty	Source/Comments
1) Type K, chromel-alumel TC	For uncalibrated TCs, uncertainty is ±2.2°C (or K) or ±0.75% of the reading in °C, which ever is greater. Five (5) of the 30-gage intrinsic TCs and 10 of the 24-gage TCs were calibrated by Sandia's Primary Standards Lab. All of the 30-gage TCs had an uncertainty of ±1.2°C (±2.2°F) or 0.75% of reading (in °F) for the range 23-260°C (74-500°F). All 24-gage TCs had an uncertainty no greater than ±2.2°C (±4.0°F) for the same temperature range.	NA	ASTM specifications (reference [11]) for standard grade TC wire is ±2.2°C or 0.75% of the reading in °C, which ever is greater. Specially calibrated wire can be obtained with accuracy of ±1.1°C, or 0.4%, which ever is greater, but was not purchased for these experiments.
2) TC connectors	Negligible assuming no ΔT across connector pins.	NA	Appendix A analyzes potential errors due to ΔT across connector pins.
3) TC-2095 terminal block to laptop computer: sources covered by Fluke calibration	Uncertainties assumed to have systematic (bias) and random components. See Tables 6-4 through 6-9. Table 6-9 has summary. Bias used is ±0.80°C.	See Tables 6-4 through 6-9. Table 6-9 has summary. Random uncertainty used is ±0.83°C. Add Fluke uncertainty: ±0.16°C.	Uncertainty sources include non-linearity, offset, gain error, 50-60 Hz CMRR, scan speed, system noise, normal mode rejection (60 Hz).
4) Sources not covered by Fluke calibration	a) Filter cutoff: -3dB at 2 Hz: negligible, see below.[23] b) Filter step response: 1 sec to 0.1% of peak, see below. At 100°C (373K) this is a 0.37K uncertainty. c) Long term stability = 1μV/°C for gain=100, 20μV/°C for gain=1. For gain = 100, and ±3°C		Filter cut-off and filter step response, CMRR, long-term stability, gain temperature coefficient, and cross-talk are not covered by end-to-end Fluke calibration.

[23] See references [25] - [29] for uncertainty specifications.

Component	Systematic Error or Uncertainty	Random Uncertainty	Source/Comments
	temperature variation, error is ±0.08°C, which is negligible (see below). d) Gain temperature coefficient = 10ppm/°C: 0.001% - negligible, see below. e) Settling time: for smallest error need 3µsec for 0.012% accuracy, negligible, see below. f) CMRR for gain = 100 is minimum of 100dB, which equals 35 µV, or 0.8°C, see below. g) Cross talk: -75dB for adjacent channels; -90 dB for all other channels. Maximum error is 0.2°C.		
5) Intrinsic TC mounting error	TC reads lower than foam surface temperature due to heat loss, imperfect contact, and finite size of TC bead. ΔT across bead is negligible (0.02°C). Error due to contact resistance is assumed to be 0.01°C for metal case TCs; and 0.06°C for foam TCs.		See discussion below. This is a difficult uncertainty source to quantify.
Overall TC measurement uncertainty	$U_{95} = \pm 2 * [\sum (B_R / 2)^2 + \sum S_R{}^2]^{1/2}$ = ±2.4°C (foam TCs), = ±3.0°C (metal case TCs). Overall: about ±1% of reading (in K)		Combine using RSS.

Table 6- 10. Relative Contribution of Uncertainty Sources to Total

Uncertainty Source	Foam TCs: Relative Contributions, %	Metal Case TCs: Relative Contributions, %
Thermocouple (TC) wire calibration	17	41
TC connectors	NA	NA
Terminal block to laptop computer, includes data acquisition card, mV to temperature conversion, i.e., all components enveloped by end-to-end static calibration	49	35
TC terminal block to laptop computer, includes data acquisition card, mV to temperature conversion, i.e., all components **not** enveloped by end-to-end static calibration	34	24
Intrinsic TC mounting error	<1%	<1%

6.8 Summary

From the example for abnormal thermal environments in Section 5.5 it was shown that the total uncertainty was dominated by the bias from the mounting method. Overall, the HP-3852A DAS uncertainty (not including the TC) was similar to that of the NI system. Therefore, if it is desired to reduce total uncertainty, the most resources should be spent on the TC mounting scheme for abnormal environments.

From the example in Section 6.4, for normal environments, the majority of the uncertainty was from the 12-bit (LSB) accuracy, from the TC wire uncertainty, and from common mode noise. See Tables 6-9 and 6-10. If it is desired to reduce the total uncertainty for normal environment experiments, one should concentrate on purchasing specially calibrated TC wire, not using extension cables, and using DASs with 16 bit resolution.

7 Conclusions

1) Typical uncertainty values of DAS systems used at the Radiant Heat Facility and Lurance Canyon Burn Site are ±1% of the reading in absolute temperature, e.g., ±3K at temperatures typical of normal environments (300 K). For abnormal environments (i.e., 1200-1300 K), TC mounting errors plays the major role in the total uncertainty. Uncertainties of ±2-3% are therefore more representative.
2) TC mounting errors can dominate the total uncertainty for abnormal environment experiments (primarily for MIMS TCs).
3) TC wire uncertainty and overall DAS accuracy dominate at low temperatures.
4) Don't use TC extender cables if they are not needed. They unnecessarily add to the total uncertainty.
5) Overall, a reasonable total uncertainty value to use for normal environments is ±1%, while for abnormal environments the total uncertainty value is about ±2-3%.
6) Because the 12 bit vs. 16 bit resolution accuracy makes such a large difference at low temperatures, 16 bit DAQ cards should be used.
7) TCs should be calibrated.

8 Future Work

Because the total uncertainty for TC measurements in abnormal environments (specifically using MIMS TCs) is dominated by the TC type and mounting method, an uncertainty quantification effort should continue to quantify those uncertainties for the most commonly used TC types and mounting methods in use at RHF and the LCBS.

9 Best Practices

Based on the results of this study, several best practices are recommended.

1) Don't use extension wire below 0°C unless calibrated.
2) Don't use extension wires unless required.
3) Keep TC connectors isothermal.
4) Be careful to quantify the "TC mounting error" for abnormal thermal environments.
5) Be aware that the selection of a specific junction type (e.g., ungrounded, grounded, or exposed/intrinsic) has an effect on the total uncertainty. Intrinsic/exposed junction TCs provide the least error.
6) Intrinsic or exposed junction TCs have the least error, but are not very reliable in abnormal thermal environments.
7) Often the TC limits of accuracy (±2.2°C or 0.75%) is the second largest source (after TC mounting errors).
8) Use 16-bit DASs whenever possible, especially for normal environment tests where the signals are low.

10 References

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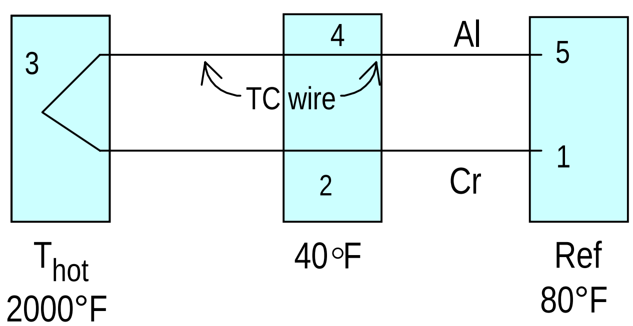
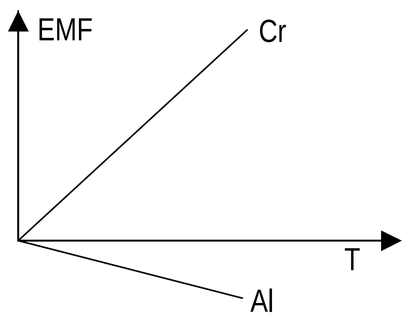
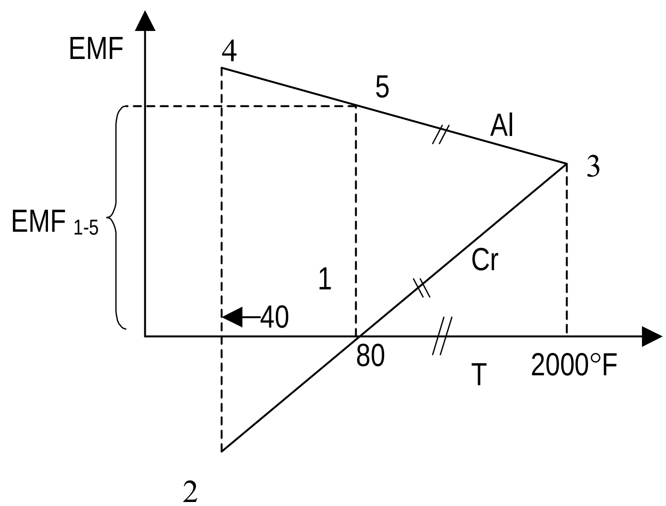
Appendix A: TC Connector and Extension Wire Errors

Several examples are provided below to help quantify TC connector and extension wire uncertainties.
Case 1 – No extension wire or connectors (Type K TC).

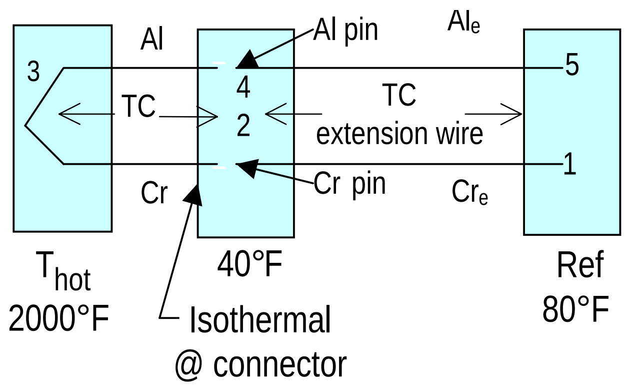






Result:
EMF $_{1\text{-}5}$ = that between points 1 and 5 going through 3 (as though 2 and 4 were not present); low temperature at 40°F has no effect. Similarly, if points 2 and 4 were at a higher temperature (e.g., 100°F), there would be no error.

Case 2 – Connector and extension cable present, connector isothermal, extension wire in temperature gradient. Al, Al_e, Cr, Cr_e curves arbitrarily assumed.

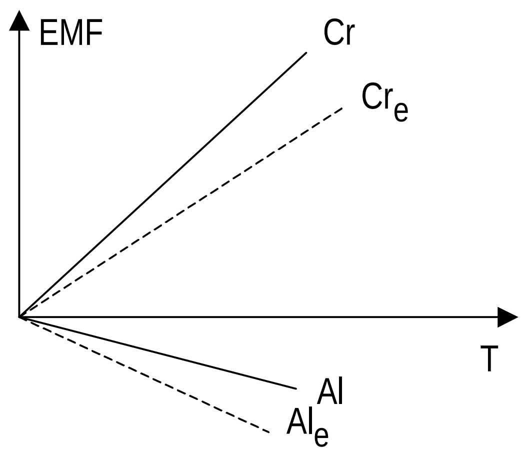


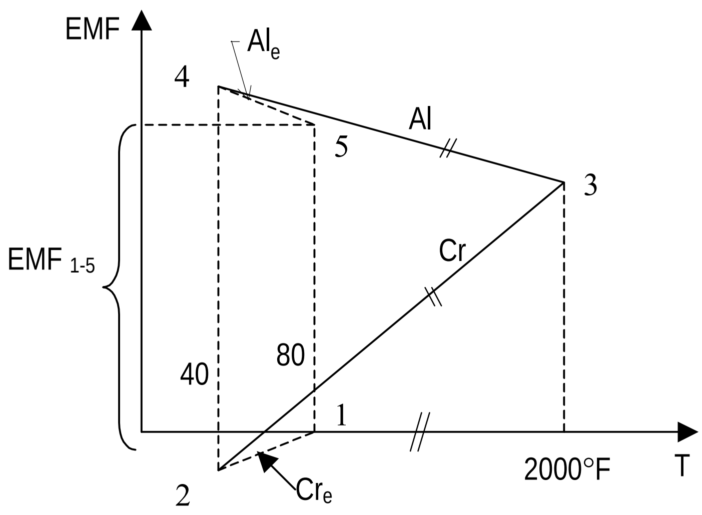
Cr = Seebeck coefficient, chromel wire

Cr_e = chromel extension wire – assume its Seebeck coeff. is *not* the same as Cr wire

Al = Seebeck coefficient, alumel wire

Al_e = alumel extension wire – assume its Seebeck coefficient is *not* the same as Al wire





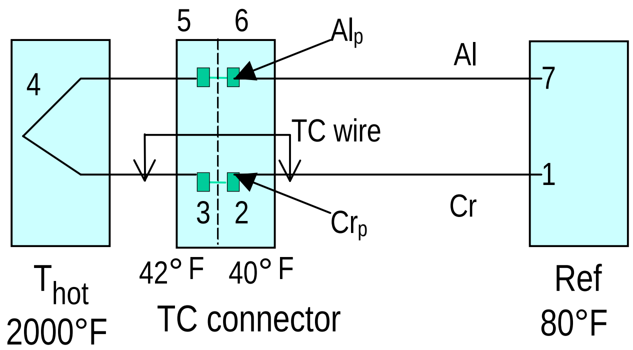
Result:
If the extension wire has a different EMF versus temperature curve than the TC wire, then there will be an additional uncertainty when using extension wire. Therefore, it is especially important to use TC extension wire in the temperature range for which it was specified. For example, the <u>Manual on the Use of</u>

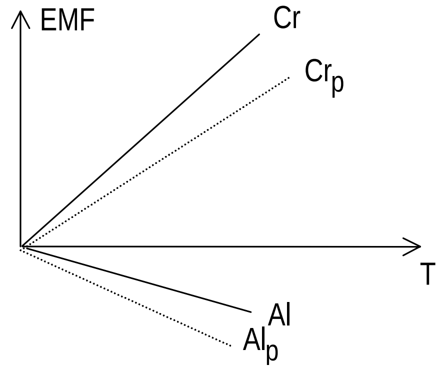
Appendix A. TC Connector and Extension Wire Errors

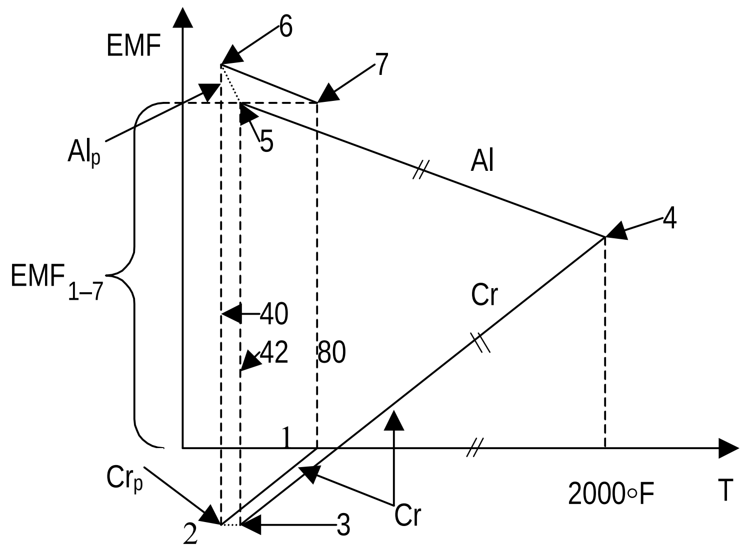
Thermocouples [Ref. 11], pages 36 and 37, shows TC extension wire properties, and the limits of error allowed are ±2.2°C (±4.0°F) from 32°– 400°F, the same as for normal TC wire. During winter testing at the Burn Site, temperatures routinely are below 32°F. An unknown uncertainty may result if the extension wire is used but not calibrated below 32°F.

TC extension wire has the same accuracy as TC wire but in a smaller temperature range. If the extension wire is used in its temperature range, then the uncertainty of the circuit can be as high as the RSS of TC plus extension wire uncertainties. But, for example, if the TC wire was calibrated, but the extension wire was not, then the overall accuracy is unknown.

Case 3a – Connector present but no extension wire, all TC wire, 2°F ΔT along length of pins on connector. Pins are not the same material as Cr or Al wire. Note: Al_p and Cr_p curves are arbitrarily assumed.



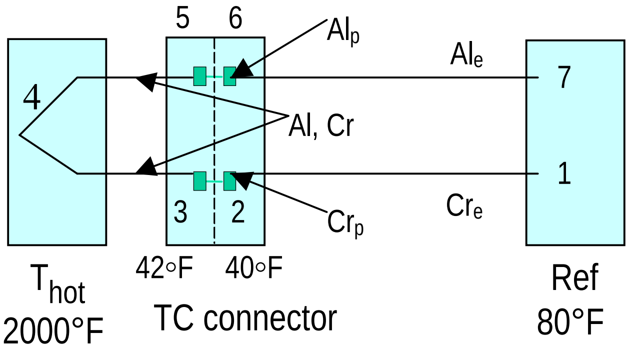


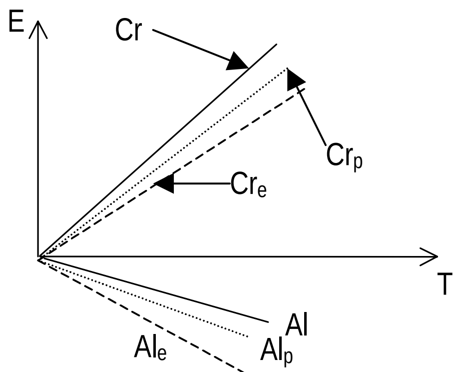


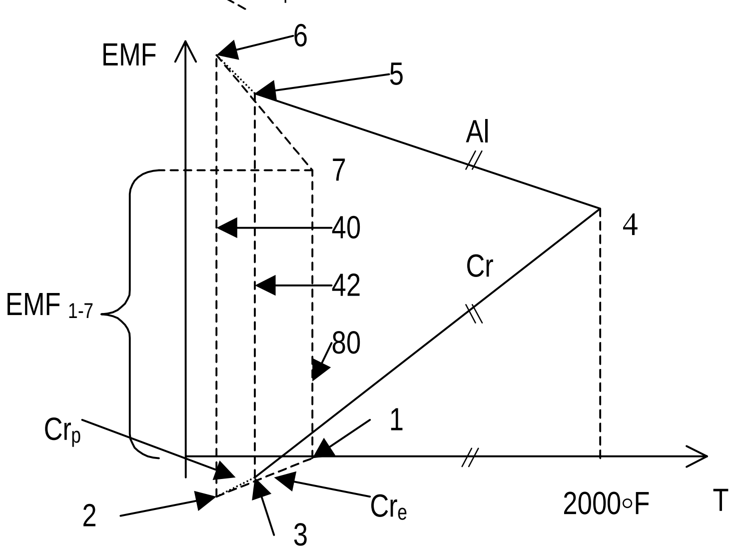
Result:

If Al_p = Al, Cr_p = Cr, then the total EMF is as though the connectors were not there. Otherwise an additional uncertainty is present. From page 35 in reference [11], every 1°F ΔT on the pins generates about a 1°F error, so uncertainty is about 2°F (42 – 40).

Case 3b – Connector and extension wire present, 2°F ΔT along length of connector pins. Pins are not the same material as TC wire or extension cable.



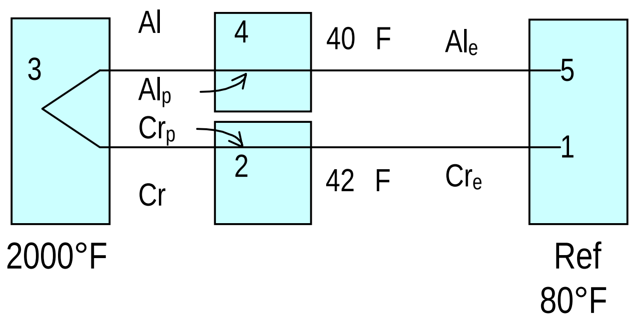


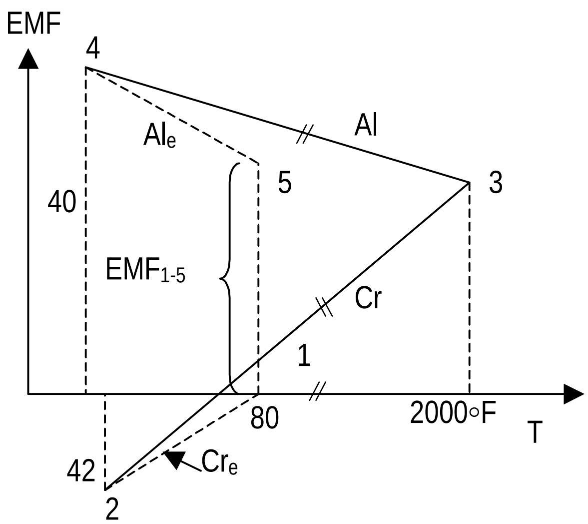


Result:

EMF$_{1-7}$ is modified due to ΔT along the pins and extension wire. In this case, total uncertainty is RSS of ±4°F or ±3/4% for TC, ±4°F for extension wire, and ±2°F for TC connector. It is important to realize that connector pins and extension wire are thermoelectric elements of unknown Seebeck coefficients. Therefore, connectors need to be kept isothermal and extension wires within their temperature limits (32-400°F).

Case 3c – Connector and extension wire present, 2°F ΔT perpendicular to connector pins. Pins are not the same material as TC wire or extension cable.





Result:

If the temperature gradient is perpendicular to the wire, not along its length, it does not matter what the connector pins are made of because there is no ΔT, and no EMF will be generated. As long as the extension wires are used within their specified range (i.e., 32–400°F), the total uncertainty is the RSS of the TC wire and extension cable uncertainties, same as in Case 2.

Appendix A. TC Connector and Extension Wire Errors

Summary:

Case 1 – No extension cable or connectors; going through cold length or hot length has no effect.

Case 2 – Extension wire and connector present, connector isothermal, extension cable in temperature gradient. Total uncertainty is the RSS of the extension wire and TC wire uncertainties; connector contributes nothing.

Case 3a – Connector present but no extension wire, 2°F ΔT along axis of pins in connector. If there are different EMF versus temperature curves for connector pins and TC wire, there is an additional uncertainty. From reference [11], a 1°F ΔT on the connector creates an error of about 1°F. Total uncertainty is the RSS of the connector and TC wire uncertainties.

Case 3b – Connector and extension wire present, 2°F ΔT along axis of pins in connector. In this case, total uncertainty is RSS of ±4°F or ±3/4% for TC, ±4°F for extension wire, and ±2°F for TC connector.

Case 3c – Connector and extension wire present, 2°F ΔT perpendicular to pins in connector. If the temperature gradient is perpendicular to the wire, not along its length, it does not matter what the connector pins are made of because there is no ΔT in a direction that will generate an EMF. As long as the extension wires are used within their specified range (i.e., 32–400°F), the total uncertainty is the RSS of the TC wire and extension cable uncertainties.

Appendix B: Select Plots from Reference [10] and data gathered for this report

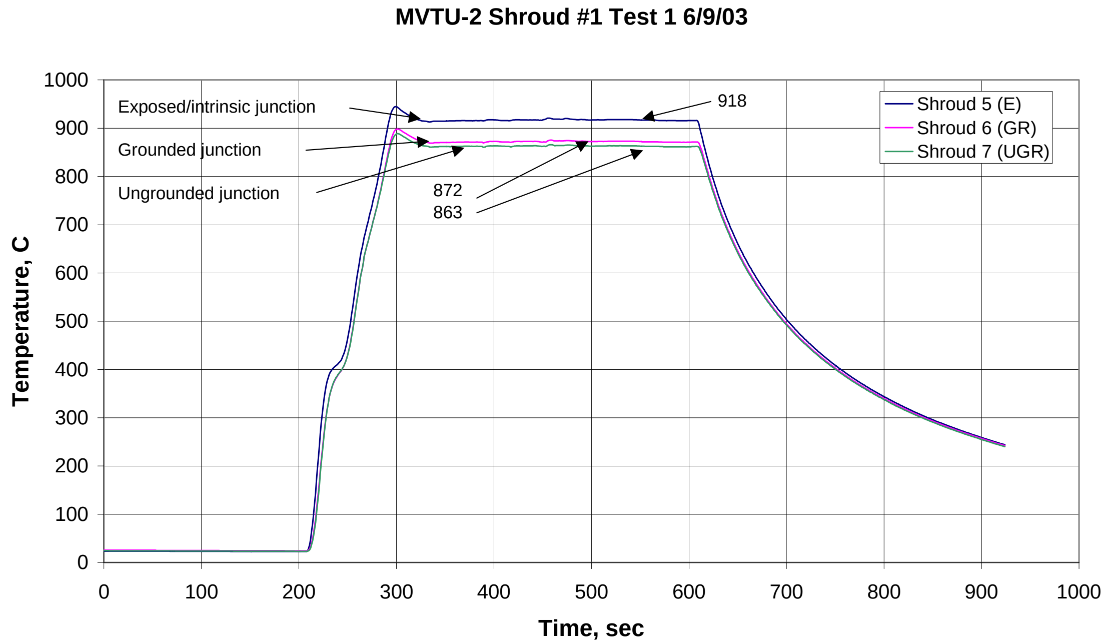


Figure B- 1. Comparison of Responses of Exposed, Grounded, and Ungrounded Junction Sheathed TCs on a Flat Shroud – TCs on Side Facing Away from Lamps

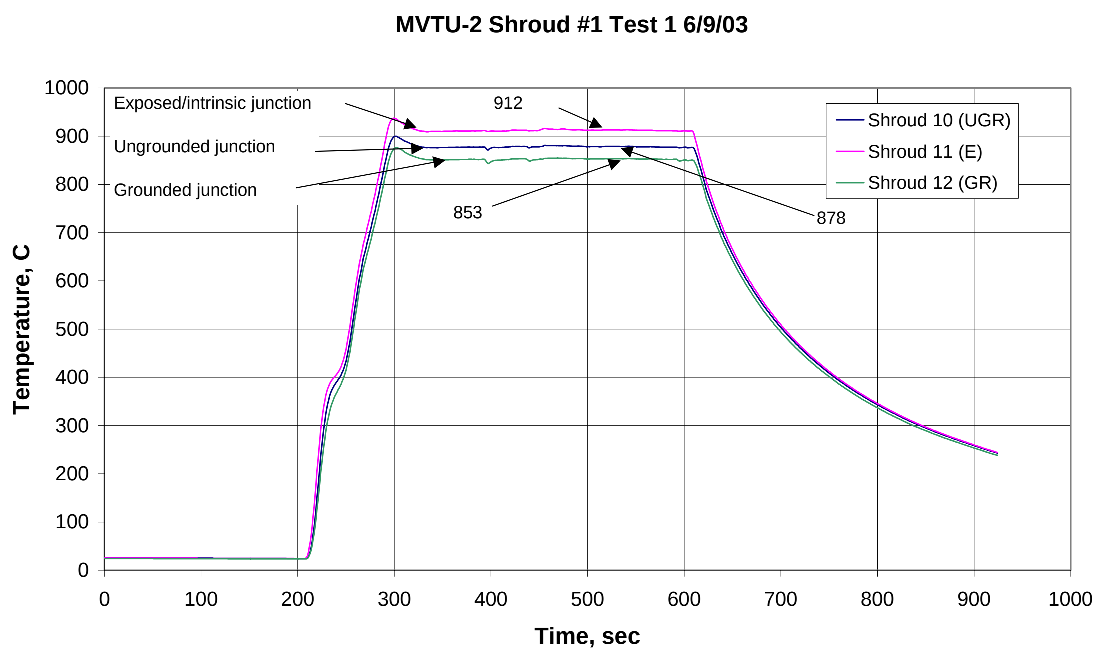


Figure B- 2. Comparison of Responses of 63 mil Diameter Exposed, Grounded and Ungrounded Junction Sheathed TCs on a Flat Shroud – TCs on Side Facing Away from Lamps

Appendix B. TC Junction Type and Diameter Errors

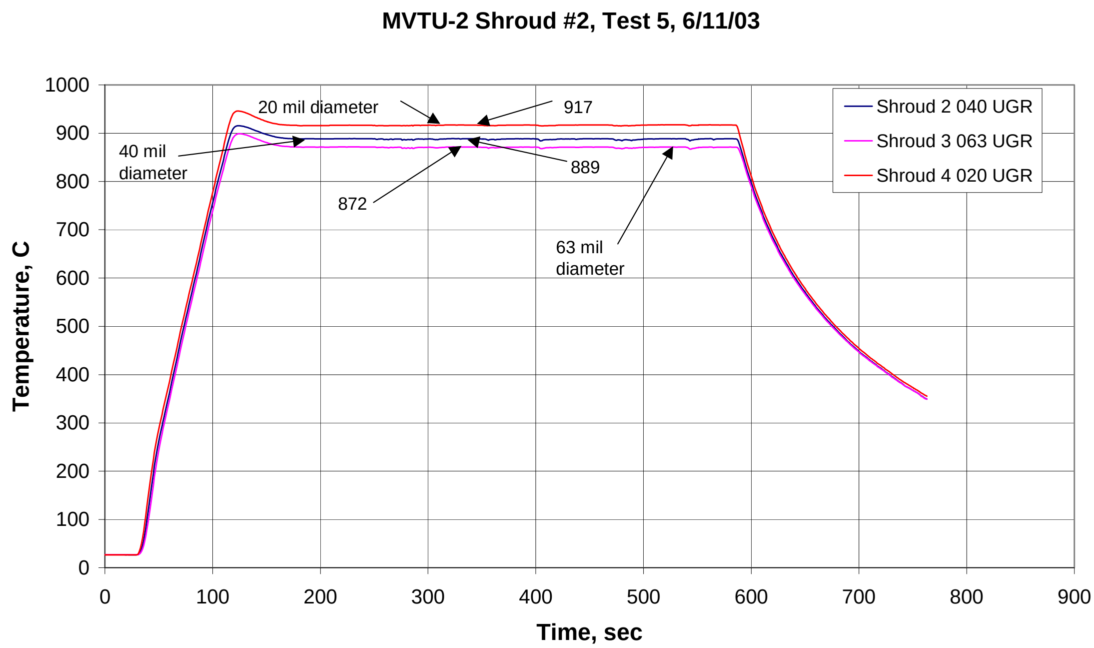


Figure B- 3. Comparison of Responses of 20, 40, and 63 mil Diameter Ungrounded Junction Sheathed TCs Mounted on a Flat Inconel Shroud – TCs on Side Facing Away from Lamps (TCs 2,3,4)

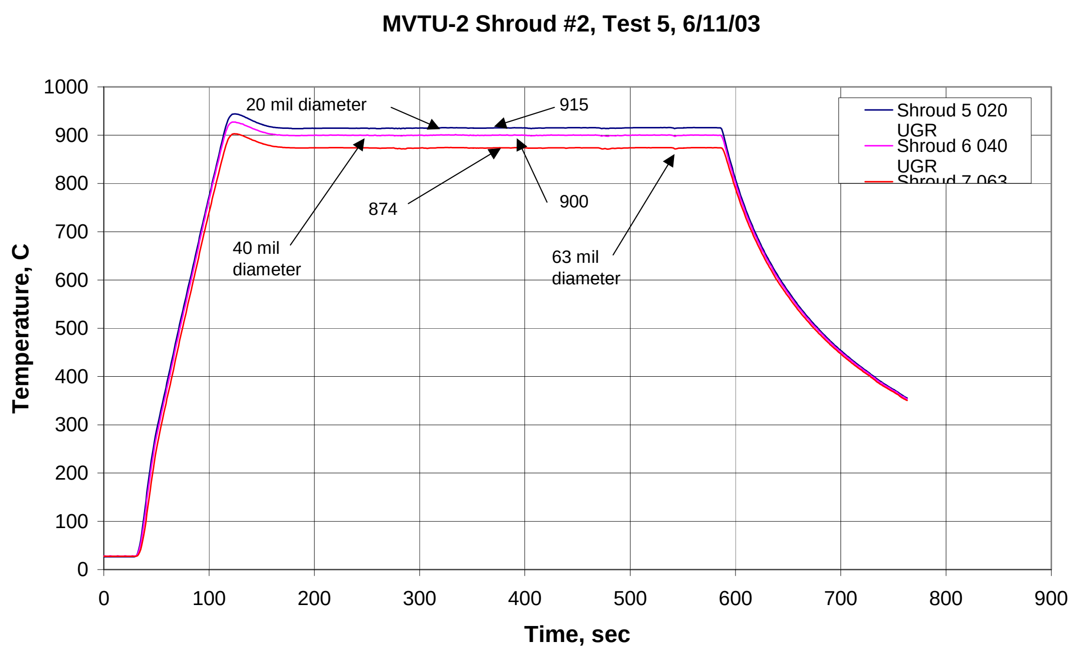


Figure B- 4. Comparison of Responses of 20, 40, and 63 mil diameter Ungrounded Junction Sheathed TCs Mounted on a Flat Inconel Shroud – TCs on Side Facing Away from Lamps (TCs 5,6,7)

Appendix B. TC Junction Type and Diameter Errors

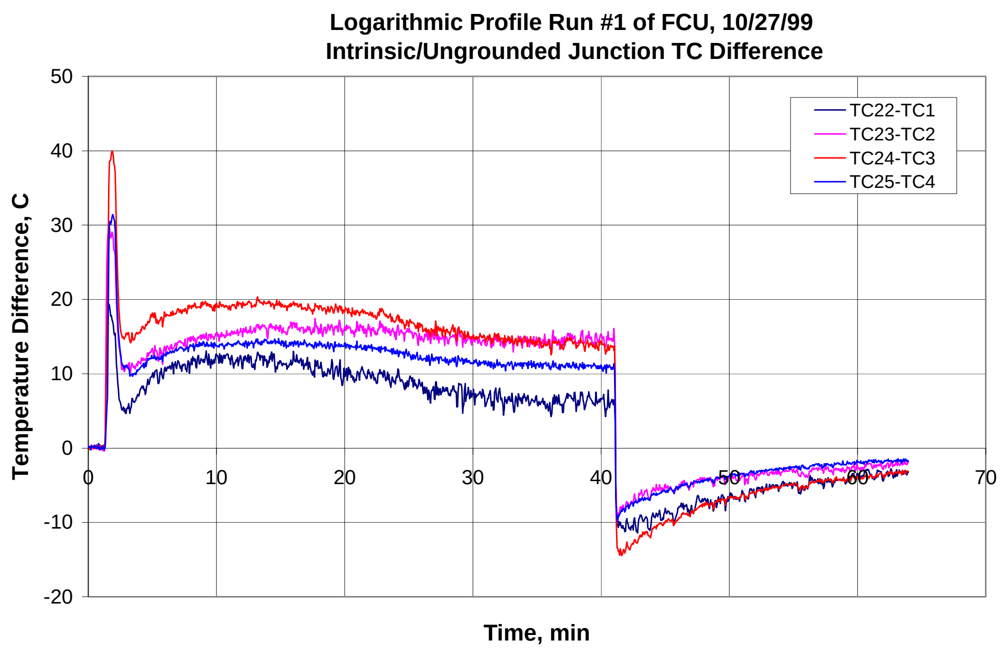


Figure B- 5. Error between Intrinsic and Ungrounded Junction TCs on a Radiatively Heated Flat Plate [10] (TCs 1-4 and 22-25)

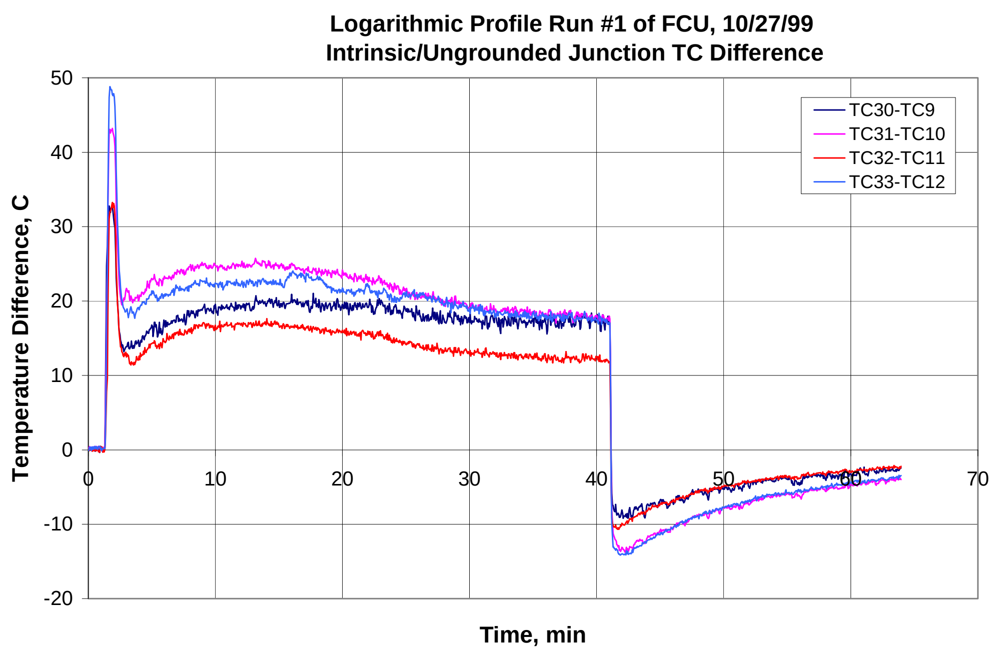


Figure B- 6. Error between Intrinsic and Ungrounded Junction TCs on a Radiatively Heated Flat Plate [10] (TCs 9-12 and 30-33)

Appendix B. TC Junction Type and Diameter Errors

Table B- 1. Comparison of Temperature Difference Between Intrinsic and Ungrounded Junction TCs – Logarithmic Profile Run 1, 10/27/99

TC numbers	Arithmetic Average of Temperature Difference (systematic error) between 5 and 41 minutes, °C	Comments
TC22-TC1	9.2	Errors are almost constant from 5-41 minutes.
TC23-TC2	15.1	
TC24-TC3	17.0	
TC25-TC4	12.7	
TC26-TC5	24.0	
TC27-TC6	19.8	
TC28-TC7	NA	TC28 is suspect
TC29-TC8	12.1	
TC30-TC9	18.3	
TC31-TC10	21.8	
TC32-TC11	14.7	
TC33-TC12	20.6	
TC34-TC13	17.4	
TC35-TC14	NA	TC35 is suspect
TC36-TC15	NA	TC36 is suspect
TC37-TC16	11.0	
TC38-TC17	18.1	
TC39-TC18	11.1	
TC40-TC19	18.4	
TC41-TC20	23.0	
Average	16.7	At 5 minutes, nominal shroud temperature is about 530°C, so error is 2.1% (16.7/530+273). At 41 minutes, nominal shroud temperature is 885°C so error is 1.4%.

Mean error: 16.7°C
Standard deviation of errors: 4.4°C
95% confidence error: 25.6°C
At 530°C (803K) error = 3.2%
At 885°C (1158K) error = 2.2%

Appendix C: Cross Talk Data on HP-3852A DAS

The channel-to-channel cross talk for the HP-3852A DAS is stated as "channel-to-channel, 50 Ω source, 1 MΩ termination, –35 dB (100 kHz)." Fortunately, we do not normally sample thermocouple signals of 100 kHz frequency because the –35 dB specification has a relatively large uncertainty:

$dB = 20 \log(\Delta V/V)$, so $\Delta V/V = \log^{-1}(-35/20) \approx 0.0178 \approx \pm 1.78\%$

ΔV may be interpreted as the voltage induced on channel 2 as a result of the difference in voltage (V) between channel 1 and channel 2. Substituting into the above equation and assuming the maximum difference between channels (V) is 50 mV, the crosstalk error ΔV would be:

$\Delta V = 0.0178*50 = 0.89mV$.

Assuming a sensitivity of about 40µV/°C can be seen this is an error of about 22.3°C.

To check the crosstalk on the HP-3852A system, two "shorted" TC connectors were placed between adjacent channels, which read temperatures up to about 350°C. For type K TCs 350°C is about a 14.3 mV signal. Four experiments were performed wherein the shorted connectors were placed between two channels with higher voltage to see if there was any measurable crosstalk generated between in the shorted channel. In this case "shorted" means a wire was placed on each of the connector pins so they were connected or "shorted." Data from four experiments performed in April 2003 showed no measurable crosstalk but some electrical noise due to the high power levels seen (10-35 kW).

Figures C-1 through C-4 show data from Foam Test 15, which began at 10:20am, when the ambient temperature was still rising. This is important because the shorted TCs show fluctuations. Figure C-1 shows data from crosstalk TC1 and adjacent TCs 10 and 11. Figure C-2 just shows crosstalk TC 1 and there is some temperature change but it is not correlated with the adjacent channels. Similar results can be seen in Figures C-3 and C-4. Figures C-2 and C-4 are almost identical indicating the ambient temperature near the DAS plug board is relatively uniform. Figure C-2 shows some noise that could be due to crosstalk, but is more likely due to the electrical power system.

Similar data can be seen in Figures C-5 through C-8, which began at about 4:26 pm. At that time the ambient temperature was decreasing, so Figures C-6 and C-8 show the shorted "crosstalk" TCs dropping as the adjacent TCs were rising. If crosstalk were present, the crosstalk TCs would have induced voltage and would show an apparent increase in temperature.

Based on these data and several more tests, it is assumed that crosstalk for thermocouple data on the HP-3852A DAS is negligible.

Appendix C. Cross Talk Data on HP-3852A DAS

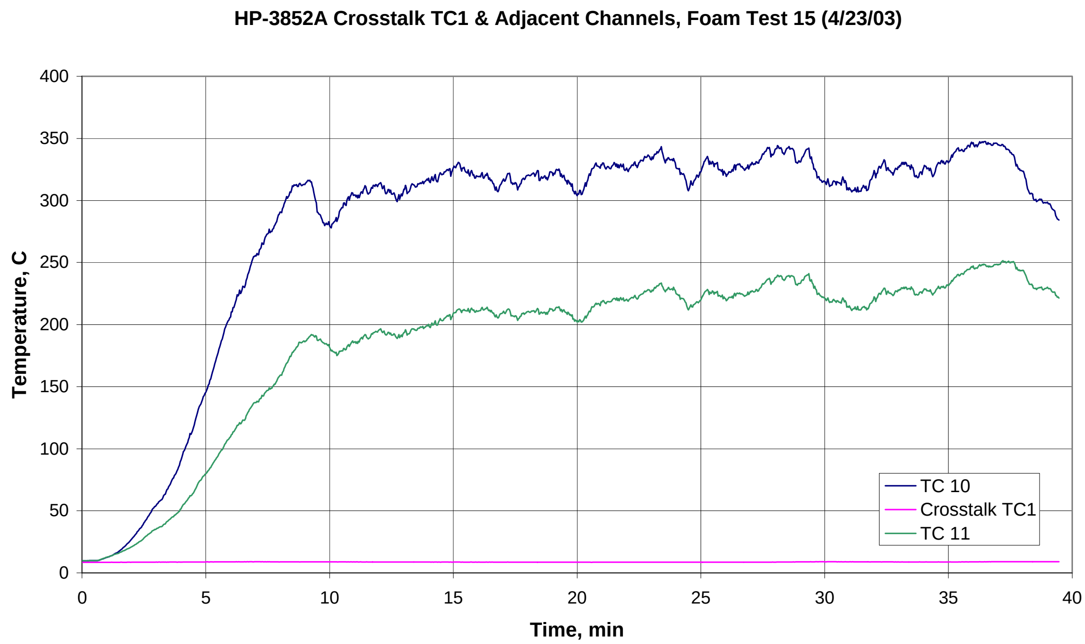


Figure C- 1. Foam Test 15 Crosstalk TC 1 and Adjacent TCs 10 & 11

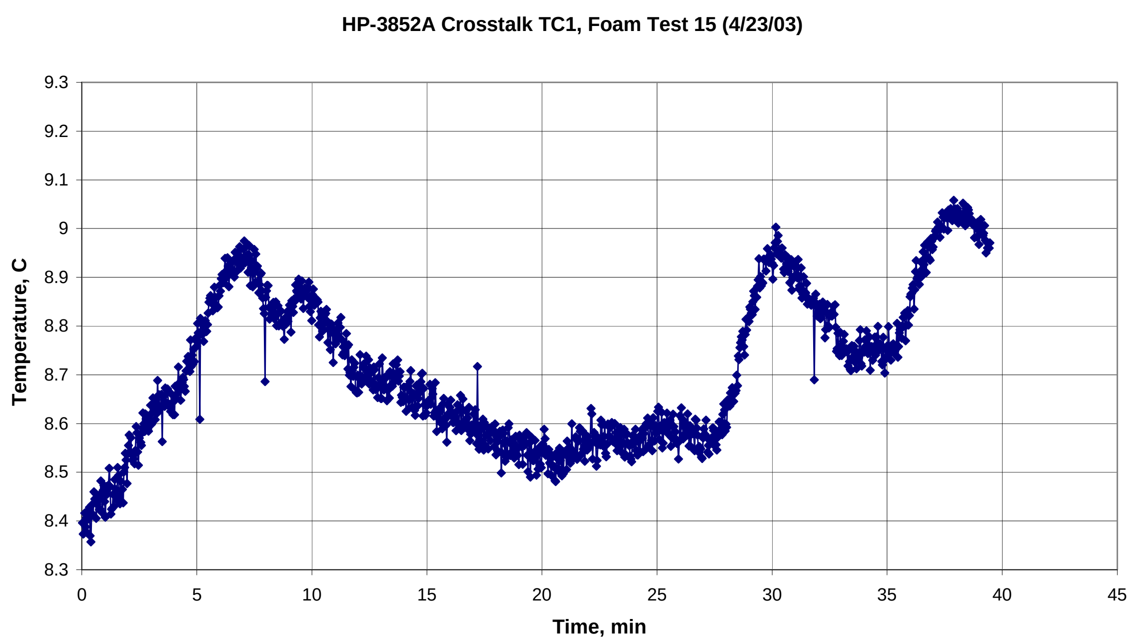


Figure C- 2. Foam Test Crosstalk TC 1

Appendix C. Cross Talk Data on HP-3852A DAS

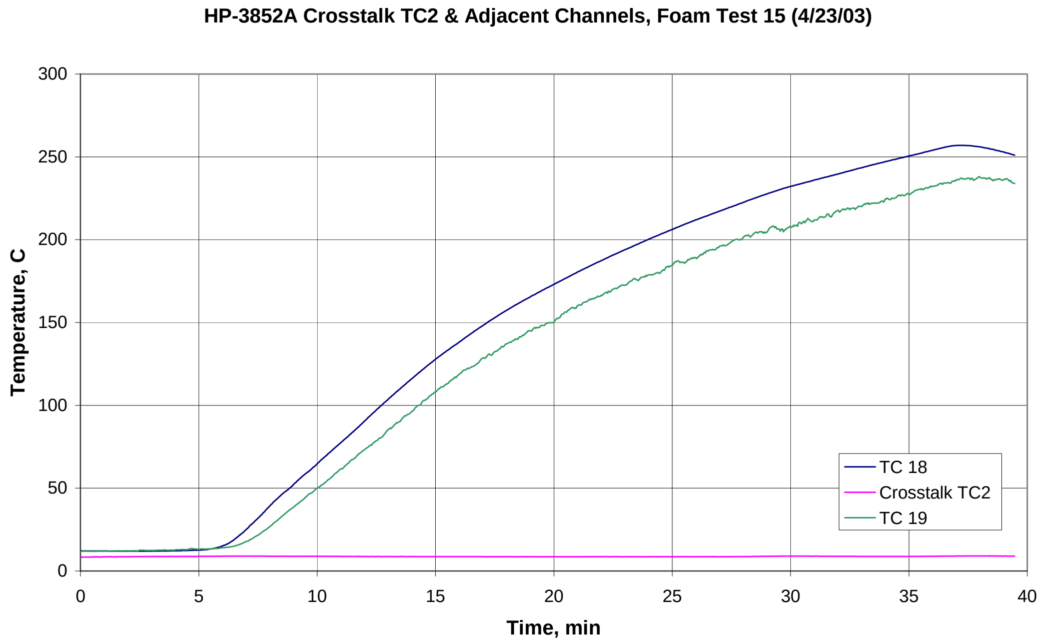


Figure C- 3. Foam Test 15 Crosstalk TC 2 and Adjacent TCs 18 & 19

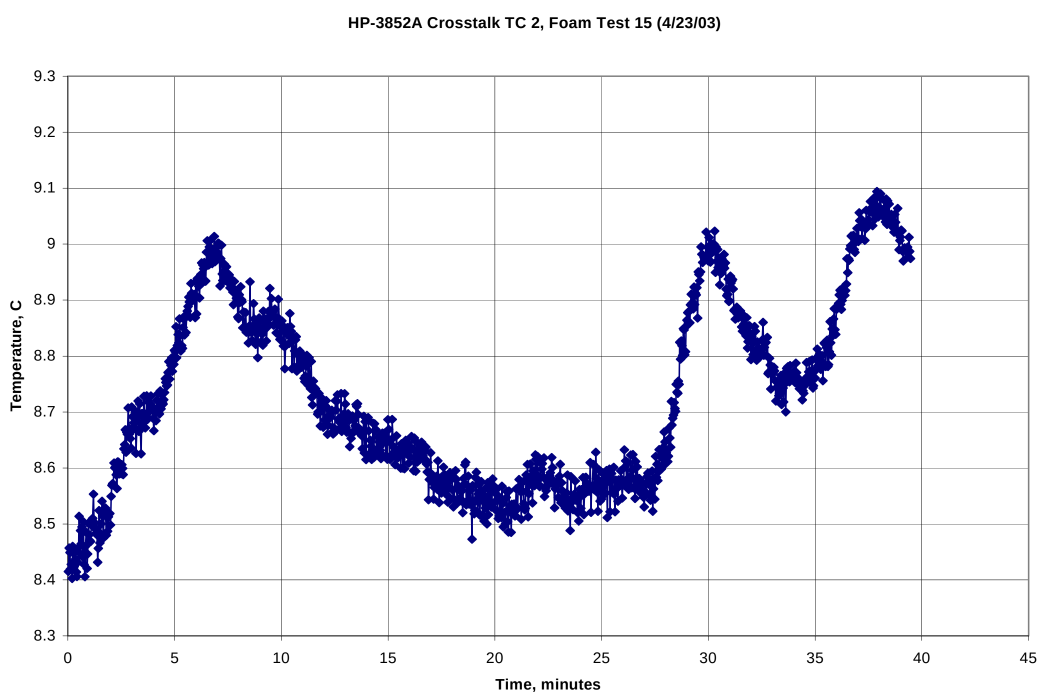


Figure C- 4. Foam Test 15 Crosstalk TC 2

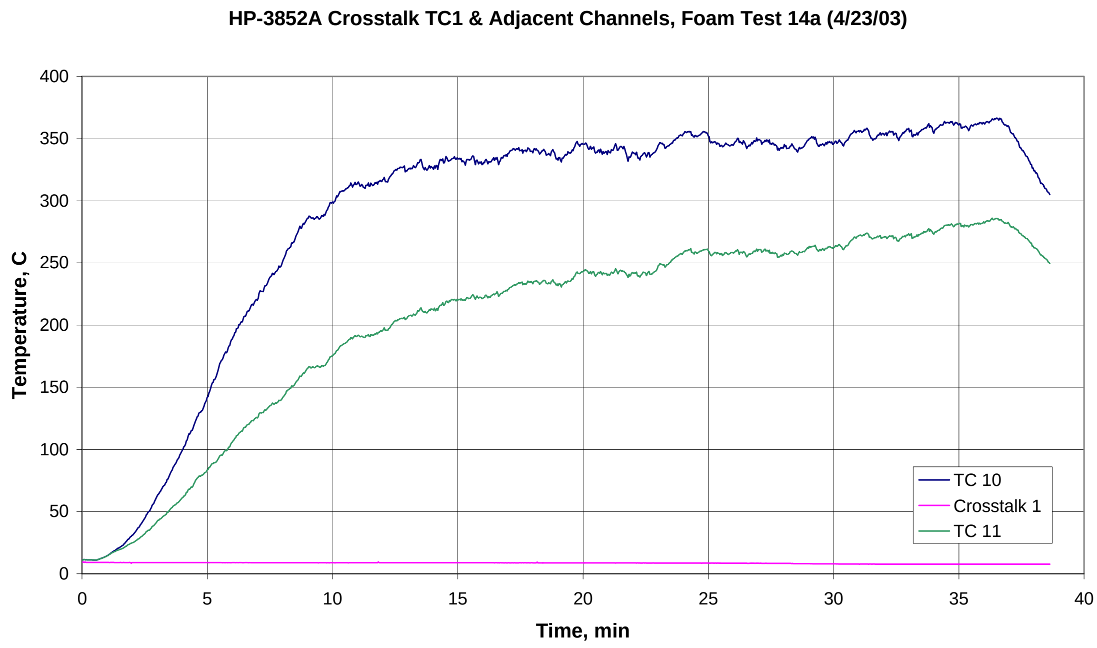


Figure C- 5. Foam Test 14a Crosstalk TC 1 and Adjacent TCs 10 & 11

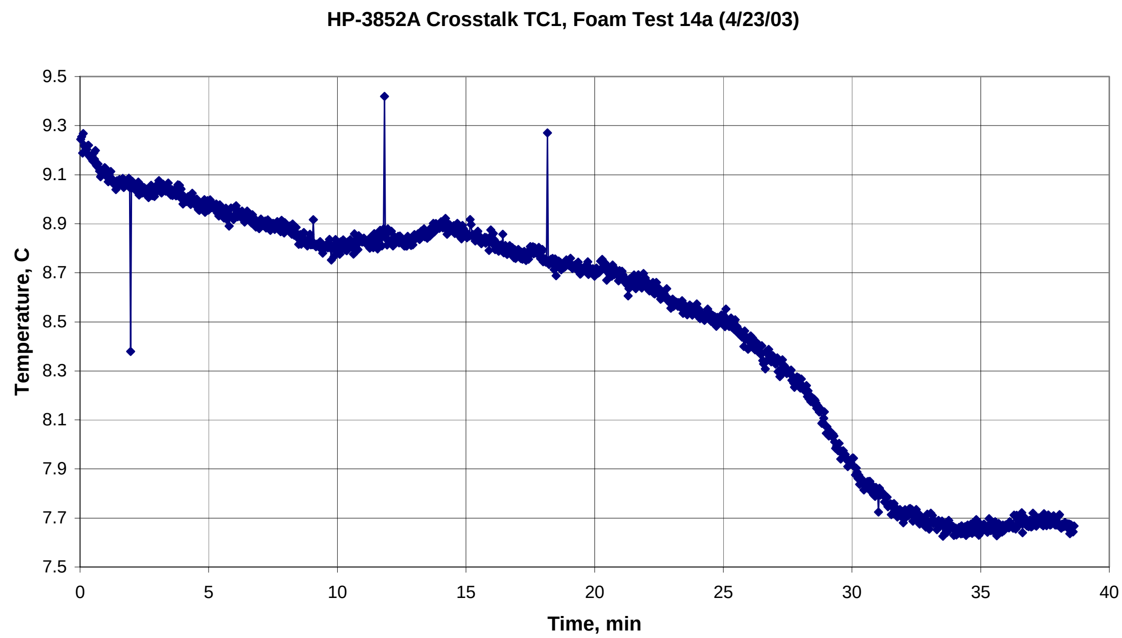


Figure C- 6. Foam Test 14a Crosstalk TC 1

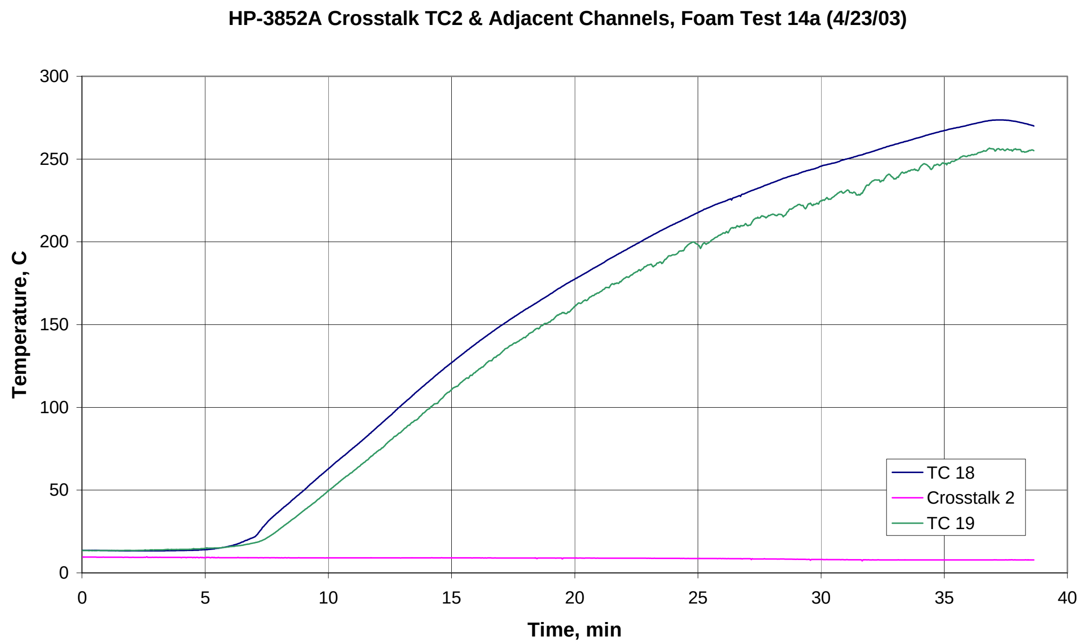


Figure C- 7. Foam Test 14a Crosstalk TC 2 and Adjacent TCs 18 & 19

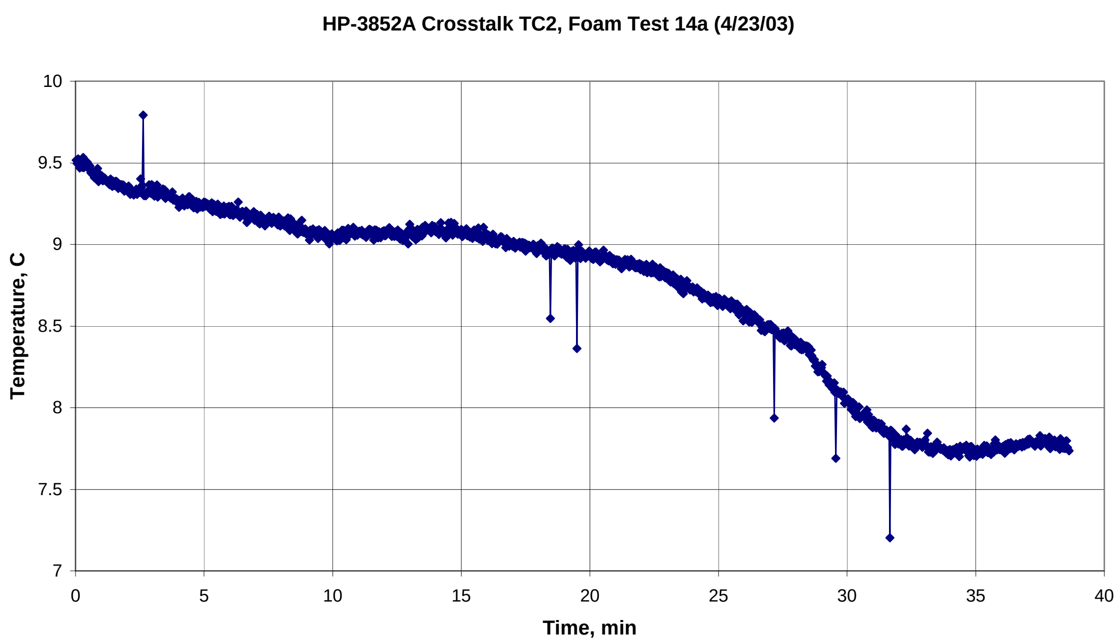


Figure C- 8. Foam Test 14a Crosstalk TC 2

Appendix D: Electrically Induced Noise from RHF Power System.

Energy used to power lamps at the RHF can induce noise in TCs. To obtain data on the noise levels present in typical RHF experiments, two, 1/16" diameter, inconel sheathed, ungrounded junction, MIMS TCs were installed inside a 4" x 4" x 1" thick copper block. The block was placed near a test setup but not in the direct line of sight of the lamp array, so it would stay almost isothermal. The copper block was insulated on all sides with 1" of "Duraboard" ceramic-fiber insulation. The two TCs were installed in holes drilled into the center of the copper block. In this way the copper block would not change temperature very much during the experiment, but noise induced into the long MIMS TC leads might show up on the data.

Figures D-1 though D-8 show select data from several experiments made during the Campaign 6 foam characterization experiments in April 2003. Figures D-1 and D-2 show data from foam test MFER 1. The first figure shows the power level in kW and noise TCs 1 & 2 (same scale). During this experiment, there is a clear indication of noise generated in TC 2 during the time when power was applied to the experiment. The power spiked beginning at about 1 minute to about 20 kW, then rose again to a peak of about 32 kW, and then dropped sharply to about 12 kW when the desired shroud temperature was reached. During the time when power was on, there were "spikes" in the data that indicate noise induced into the TCs. After power was turned off at about 36.5 minutes the TC signals do not exhibit the same spiked behavior. This is a strong indication of noise caused by the power system generated into the TC data. Due to the nature of the "spikes" (an excursion from an average value for one sample, then back to an average) it is likely that the larger of the spikes are caused by power system noise rather than by real temperature excursions. Note also on TC 1 at about 6.7 minutes an offset that lasts to about 12.5 minutes. It is not known what caused this offset. Even though the copper block had considerable thermal mass and was insulated, the block temperature rose about 4°C during the 48 minute long test. Similar data are seen in Figures D-3 and D-4 during test MFER 3, D-5 and D-6 for test MFER 13, and D-7 and D-8 for test MFER 14a. Additional data are available but plots are not shown.

Table D-1 provides a summary of noise-induced spikes during a number of foam experiments. In Table D-1 the magnitude of the noise spikes was estimated graphically from the plots and is an estimate based on the average value of the temperature at that time.

Table D- 1: Average Values of Electrical Noise

Test ID	Number of Noise Spikes	Maximum Noise Spike, °C	Average of Noise Spikes, °C	Standard Deviation of Spikes, °C	Max Power/ Constant Power, kW
MFER 1	15	0.48	0.29	0.09	32, 12
MFER 2	9	0.28	0.19	0.04	32, 12
MFER 3	13	0.50	0.29	0.11	41, 20
MFER 4	None	NA	NA	NA	41, 19
MFER13	21	0.30	0.17	0.16	37, 13
MFER14a	20	0.25	0.10	0.05	32, 13
MFER 15	1	0.10	0.10	NA	NA
MFER 16	None	NA	NA	NA	29, 11
Summary:		Max: 0.5°C	Avg: 0.2°C	Std dev=0.1°C	

Appendix D: Electrically Induced Noise from RHF Power System

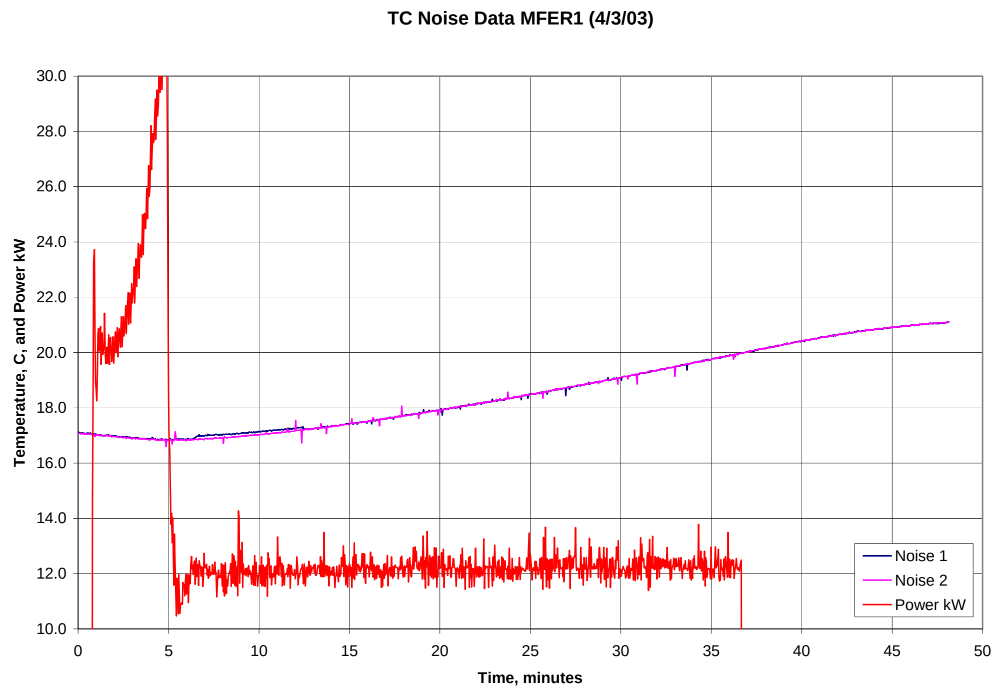


Figure D- 1. HP-3852A Noise Data, Foam Test MFER 1, Power and TCs 1 & 2

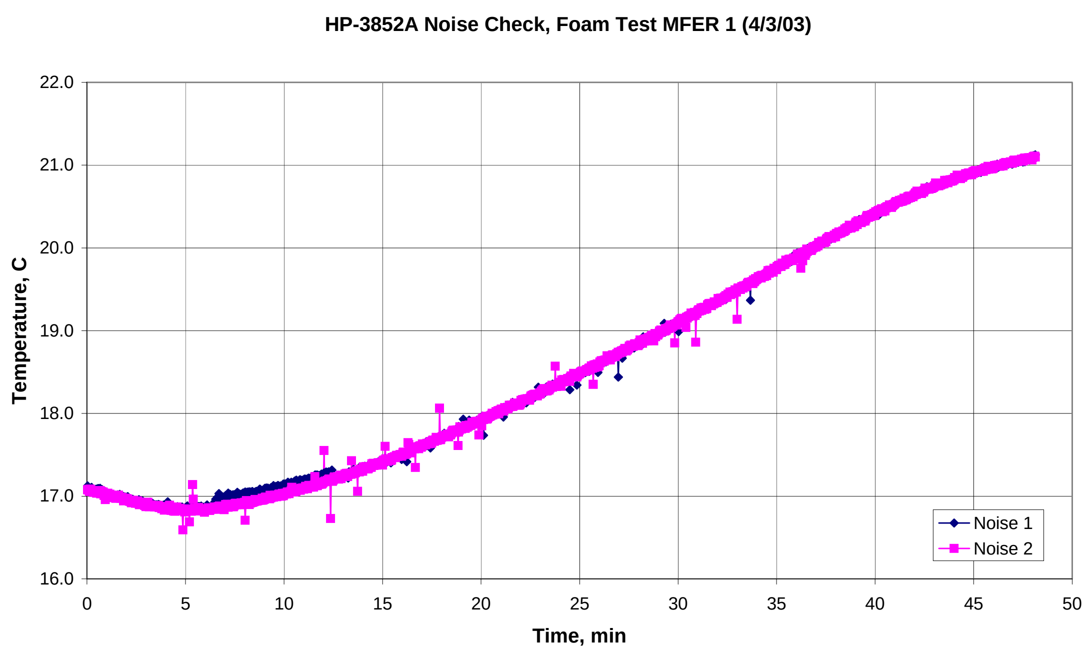


Figure D- 2. HP-3852A Noise Data, Foam Test MFER 1, TCs 1 & 2

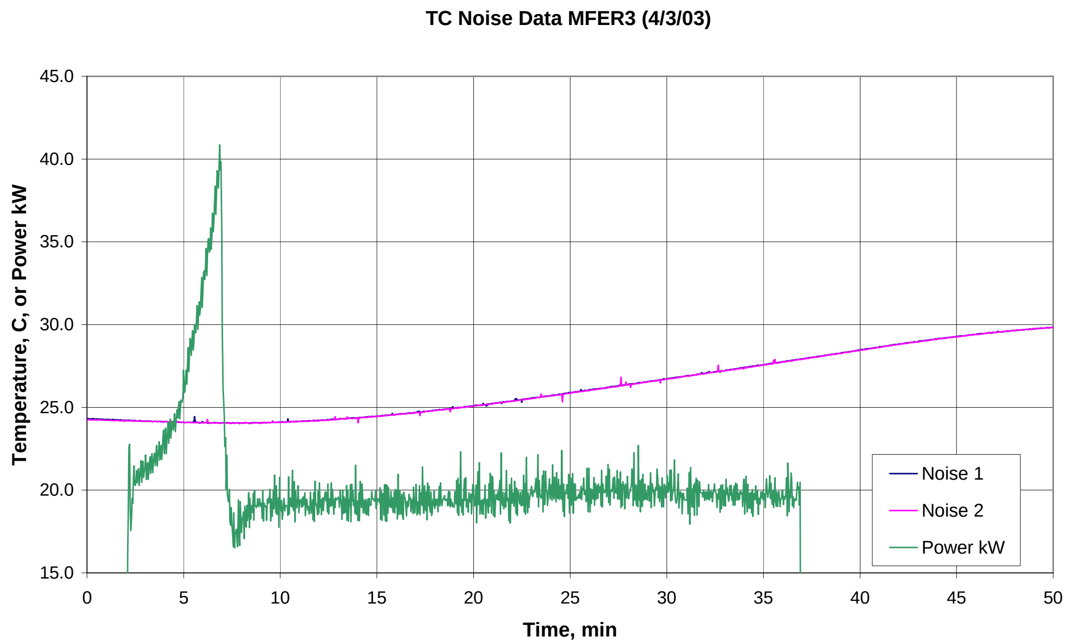


Figure D- 3. HP-3852A Noise Data, Foam Test MFER 3, Power and TCs 1 & 2

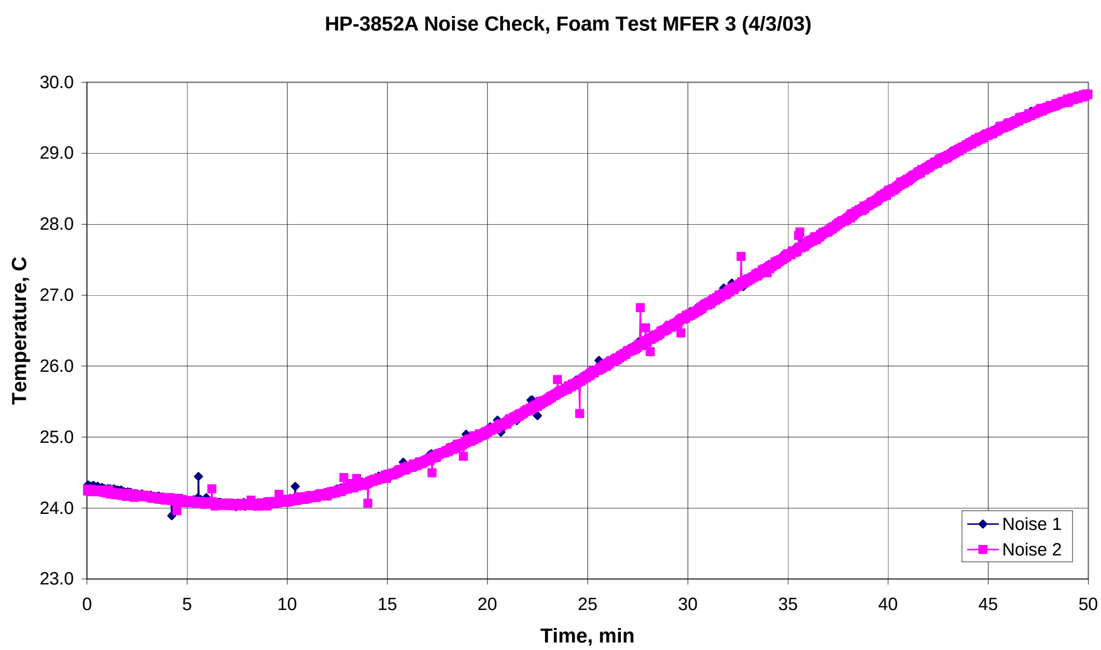


Figure D- 4. HP-3852A Noise Data, Foam Test MFER 3, TCs 1 & 2

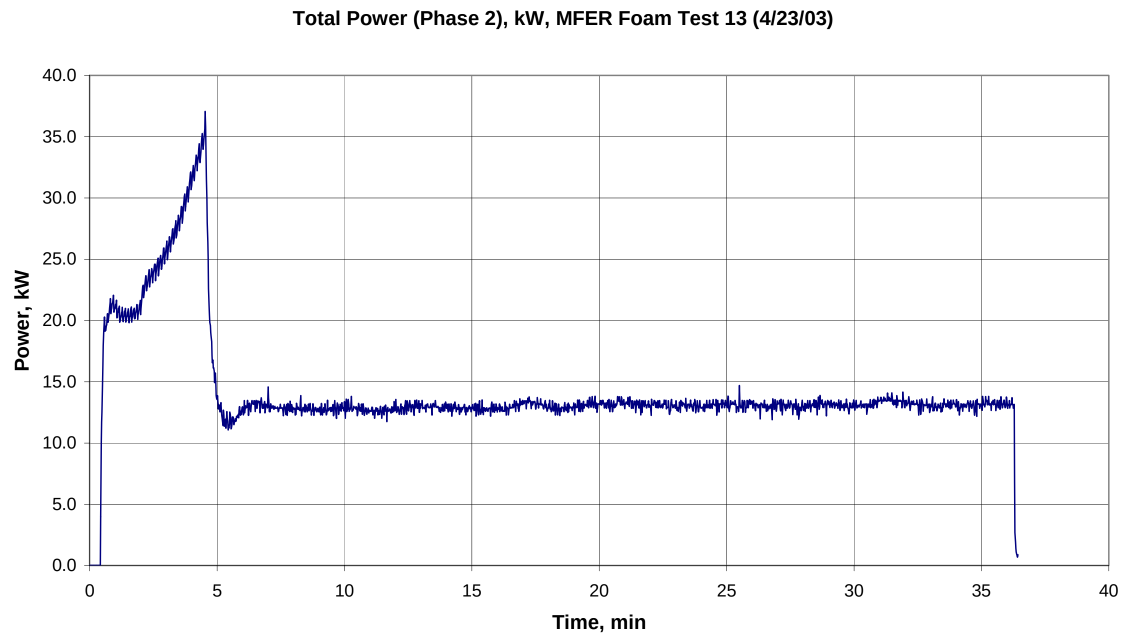


Figure D- 5. HP-3852A Noise Check, Foam Test MFER 13, Total Power

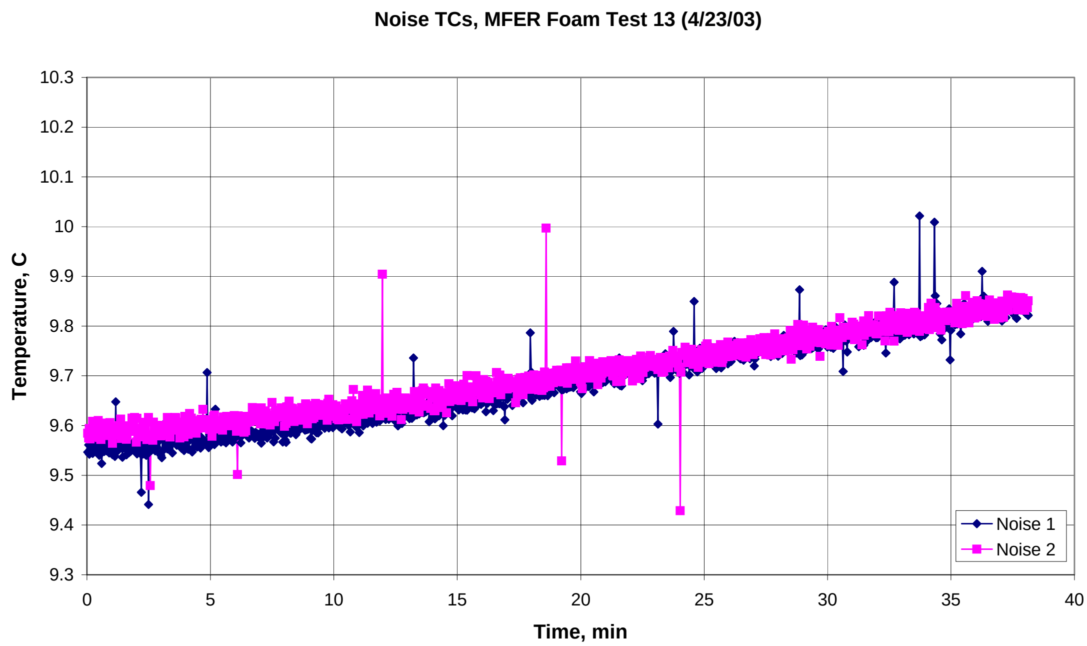


Figure D- 6. HP-3852A Foam Test MFER 14a, Noise TCs 1 & 2

Appendix D: Electrically Induced Noise from RHF Power System

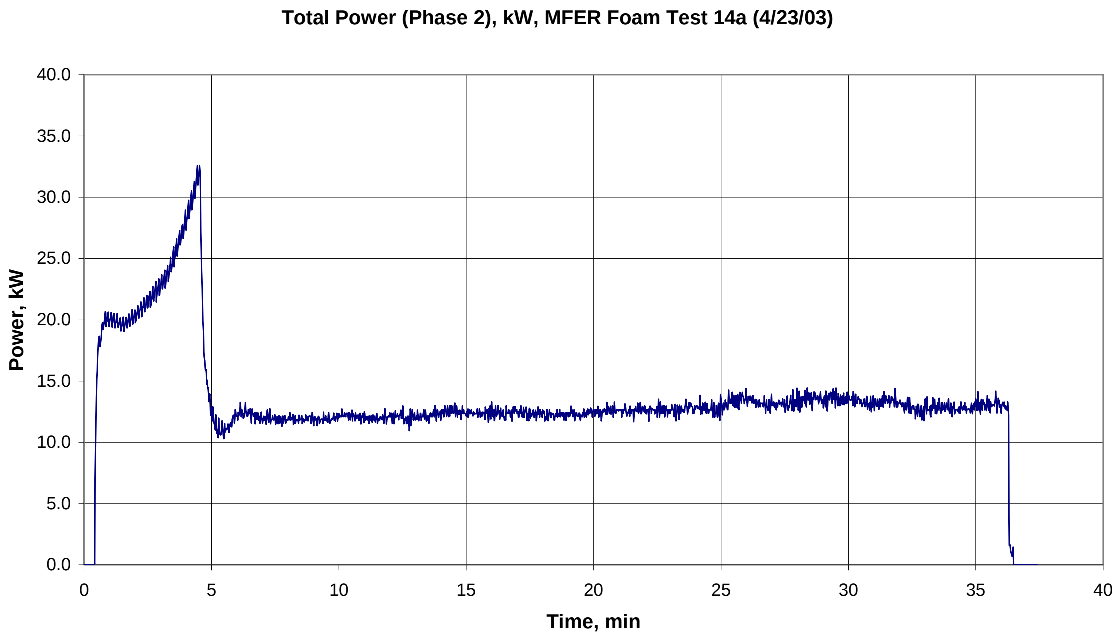


Figure D- 7. HP-3852A Foam Test MFER 14a, Total Power

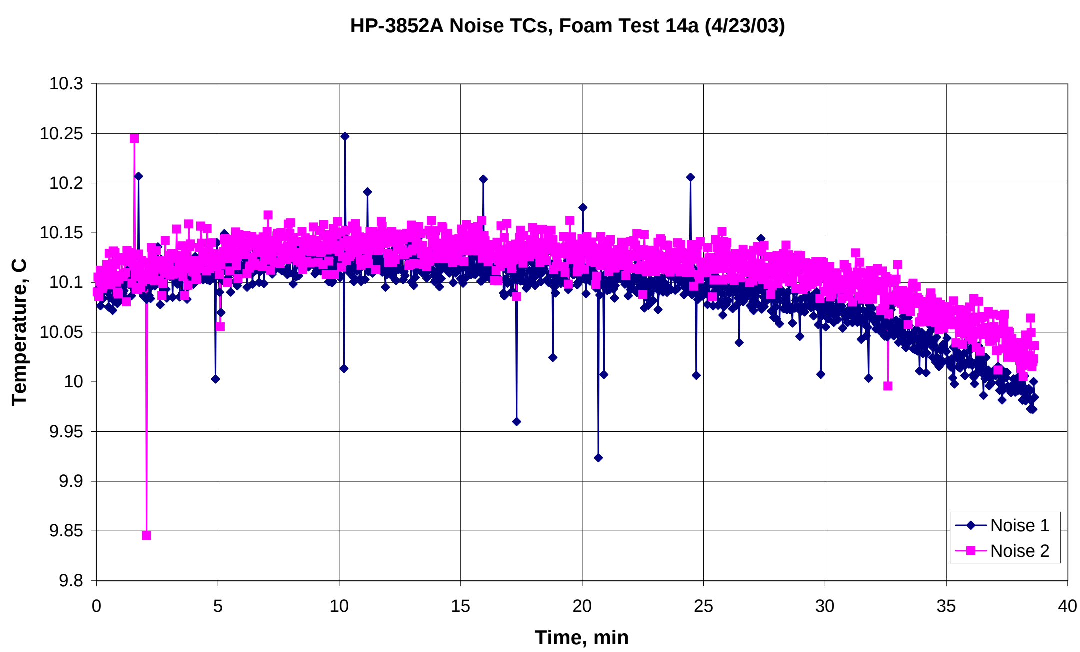


Figure D- 8. HP-3852A Foam Test MFER 14a, Noise TCs 1 & 2

Appendix E: HP-3852A End-to-End Calibration

Table E- 1. Data for Channels 100-106

HP-3852A post-test cal, April 2003, NPLC = 1.0, 25 samples for averages
Using Fluke calibrator, calibrated at 25, 250, 500, 750, and 1000C

Channel	Set Point, C	Mean	Std. Dev.	Error %	Error, C	For each channel:	
100	25	25.17	0.01593	0.69	0.17	Max error=	0.320
	250	250.19	0.01206	0.074	0.19	Min error =	0.130
	500	500.21	0.01222	0.042	0.21	Max std dev=	0.016
	750	750.13	0.01285	0.017	0.13	Mean error=	0.204
	1000	1000.32	0.01237	0.032	0.32	std dev of errors=	0.071
101	25	25.43	0.05011	1.732	0.43	Max error=	0.430
	250	250.31	0.01312	0.125	0.31	Min error =	0.190
	500	500.29	0.01053	0.058	0.29	Max std dev=	0.050
	750	750.19	0.01266	0.025	0.19	Mean error=	0.318
	1000	1000.37	0.01482	0.037	0.37	std dev of errors=	0.090
102	25	25.12	0.01214	0.487	0.12	Max error=	0.280
	250	250.13	0.02558	0.052	0.13	Min error =	0.080
	500	500.16	0.01081	0.032	0.16	Max std dev=	0.026
	750	750.08	0.01184	0.011	0.08	Mean error=	0.154
	1000	1000.28	0.01256	0.028	0.28	std dev of errors=	0.076
103	25	25.14	0.01419	0.558	0.14	Max error=	0.280
	250	250.14	0.00917	0.055	0.14	Min error =	0.080
	500	500.17	0.00812	0.034	0.17	Max std dev=	0.014
	750	750.08	0.01002	0.011	0.08	Mean error=	0.162
	1000	1000.28	0.01399	0.028	0.28	std dev of errors=	0.074
104	25	25.11	0.01073	0.426	0.11	Max error=	0.260
	250	250.12	0.01025	0.046	0.12	Min error =	0.060
	500	500.14	0.01374	0.029	0.14	Max std dev=	0.014
	750	750.06	0.01242	0.008	0.06	Mean error=	0.138
	1000	1000.26	0.01269	0.026	0.26	std dev of errors=	0.074
105	25	25.10	0.01375	0.389	0.10	Max error=	0.240
	250	250.10	0.01049	0.042	0.10	Min error =	0.050
	500	500.14	0.01282	0.028	0.14	Max std dev=	0.014
	750	750.05	0.01149	0.007	0.05	Mean error=	0.126
	1000	1000.24	0.01017	0.024	0.24	std dev of errors=	0.071
106	25	25.09	0.01576	0.344	0.09	Max error=	0.230
	250	250.09	0.01403	0.037	0.09	Min error =	0.040
	500	500.12	0.01265	0.024	0.12	Max std dev=	0.016
	750	750.04	0.01178	0.005	0.04	Mean error=	0.114
	1000	1000.23	0.01073	0.023	0.23	std dev of errors=	0.071

Table E- 2. Summary Data for all Channels

HP-3852A DAS Calibration 4/03, post-test for foam cans

Channel	Maximum Error, C	Minimum Error, C	Maximum Standard Deviation of Readings, C	Mean Error, C	Standard Deviation of Error, C	Average error, channels 100-119	Average error, channels 200-218
100	0.32	0.13	0.016	0.204	0.071	0.101	0.490
101	0.43	0.19	0.05	0.318	0.09		
102	0.28	0.08	0.026	0.154	0.076		
103	0.28	0.08	0.014	0.162	0.074		
104	0.26	0.06	0.014	0.138	0.074		
105	0.24	0.05	0.014	0.126	0.071		
106	0.23	0.04	0.016	0.114	0.071		
107	0.2	0.01	0.016	0.088	0.07		
108	0.2	0	0.015	0.078	0.075		
109	0.19	-0.01	0.013	0.066	0.075		
110	0.14	-0.05	0.015	0.022	0.072		
111	0.14	-0.05	0.015	0.02	0.074		
112	0.17	-0.02	0.014	0.052	0.072		
113	0.03	-0.17	0.013	-0.106	0.082		
114	0.19	0	0.014	0.07	0.072		
115	0.23	0.03	0.013	0.104	0.076		
116	0.23	0.04	0.013	0.114	0.073		
117	0.23	0.04	0.015	0.114	0.071		
118	0.23	0.03	0.013	0.106	0.075		
119	0.2	0	0.014	0.074	0.076		
200	0.66	0.44	0.016	0.516	0.084		
201	0.65	0.42	0.014	0.502	0.087		
202	0.67	0.44	0.014	0.522	0.087		
203	0.68	0.44	0.015	0.528	0.09		
204	0.63	0.4	0.014	0.466	0.094		
205	0.66	0.44	0.013	0.512	0.086		
206	0.64	0.42	0.017	0.496	0.084		
207	0.68	0.46	0.015	0.54	0.083		
208	0.67	0.45	0.013	0.524	0.085		
209	0.67	0.44	0.016	0.522	0.087		
210	0.68	0.45	0.018	0.534	0.086		
211	0.67	0.45	0.017	0.532	0.082		
212	0.64	0.42	0.014	0.49	0.087		
213	0.61	0.39	0.013	0.466	0.084		
214	0.62	0.4	0.016	0.48	0.083		
215	0.62	0.4	0.018	0.48	0.083		
216	0.58	0.36	0.016	0.444	0.081		
217	0.57	0.35	0.014	0.43	0.083		
218	0.37	0.2	0.012	0.318	0.069		

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