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Transient Adjustments for Metal-Sheathed Thermocouples on Metal Plates (Shrouds)

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ABSTRACT

This report provides guidance on how to adjust temperature measurements from mineral-insulated, metal-sheathed (MIMS) thermocouples (TCs) mounted on metal plates to correct for slow transient response. This information is needed so that more accurate transient temperature measurements can be made. These more accurate temperature measurements are of benefit for both qualification of hardware and as data sets for model validation. The approach was to use a relatively simple first order adjustment to the MIMS TC reading, as compared to a more accurate metal plate temperature measurement. MIMS TCs are used to improve reliability. Results from four data sets were analyzed to determine the time constraint; an overall average of 5.0 s was obtained.

ACKNOWLEDGEMENTS

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
E_{in}	Energy into TC
E_{out}	Energy out of TC
E_{store}	Energy stored in TC
IJTC	intrinsic junction thermocouple
MIMS	mineral-insulated, metal-sheathed
Tau	time constant
TC	thermocouple
TTC	Thermal Test Complex
UJTC	ungrounded junction thermocouple

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1. INTRODUCTION

This report provides information related to transient adjustments for mineral-insulated, metal-sheathed (MIMS) thermocouples (TCs) when compared to intrinsic TCs mounted on metal plates. This is based on the assumption that MIMS TCs can be adjusted using a first order correction. Because the errors are small and occur early in a test when the temperatures are low, transient adjustments may be appropriate in some cases but not others.

A first order correction was used on four data sets, which included multiple pairs of MIMS and intrinsic TCs mounted together. The intrinsic TCs were assumed to be the true temperature of the plate being measured, and the MIMS TCs were adjusted to agree as close as possible with the intrinsic TCs. The MIMS TCs were all 0.062-in diameter, Type-K (chromel-alumel), ungrounded junction (UJTC) commonly used at Sandia's Thermal Test Complex (TTC).

The error (T_{MIMS}-T_{int}) [1] is larger (in absolute value) early in a test when the temperature ramp rate is highest, and drops to an almost steady value as time progresses and the plate temperature variation is much less. Average time constants (τ or tau) from this study ranged from 4.6-5.4 s. Data is used from four tests each with multiple TC pairs (10 pairs for three data sets, and 6 pairs for the last data set). The values from this study are consistent with the value from Blanchat et al. [1], 5.4 s. The value from Blanchat was obtained from a single 62-mil diameter MIMS-intrinsic TC pair and data from a single step profile. The plate thickness was 0.010 in. The methodology used is different in that a single value was obtained for each pair in this study, while in Blanchat, multiple values were obtained for the single pair as a function of the time rate of change of temperature [1]. The user should analyze her application to see if this kind of adjustment is warranted.

As will be shown, the adjustment only needs to be applied early in the test when the time rate of change of the plate is largest. However, that is also the time when the nominal plate temperature is low, so any error may not have a significant effect on the results. In other cases, an adjustment is warranted [2].

[1] T_{int} = temperature indicated by the intrinsic TC; T_{MIMS} = temperature indicated by the ungrounded junction MIMS TC.

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2. BACKGROUND

Measurement of temperatures approaching 1000ºC can be difficult because the severe environment can degrade the TC to such an extent that it fails during a test. This is especially an issue with intrinsic TCs, which are fabricated by individually welding each wire to the plate being measured. In an intrinsic TC, the surface being measured is an "intrinsic" part of the measurement. Factors such as differential thermal expansion and degradation of the insulation between the wires can cause the intrinsic TC to fail. So, even though the intrinsic TCs are the most accurate of the two choices (intrinsic and UJTC MIMS TCs), the risk of failure during the test overrides desire for accuracy. We therefore almost always use UJTC MIMS TCs instead of intrinsic TCs in high-consequence testing. Type K (chromel-alumel) TCs are almost always used (there are few other choices). A cross-sectional view of a MIMS TC is shown in Figure 2-1 [3], and a photograph of an intrinsic and MIMS TC pair mounted on a plate is shown in Figure 2-2.

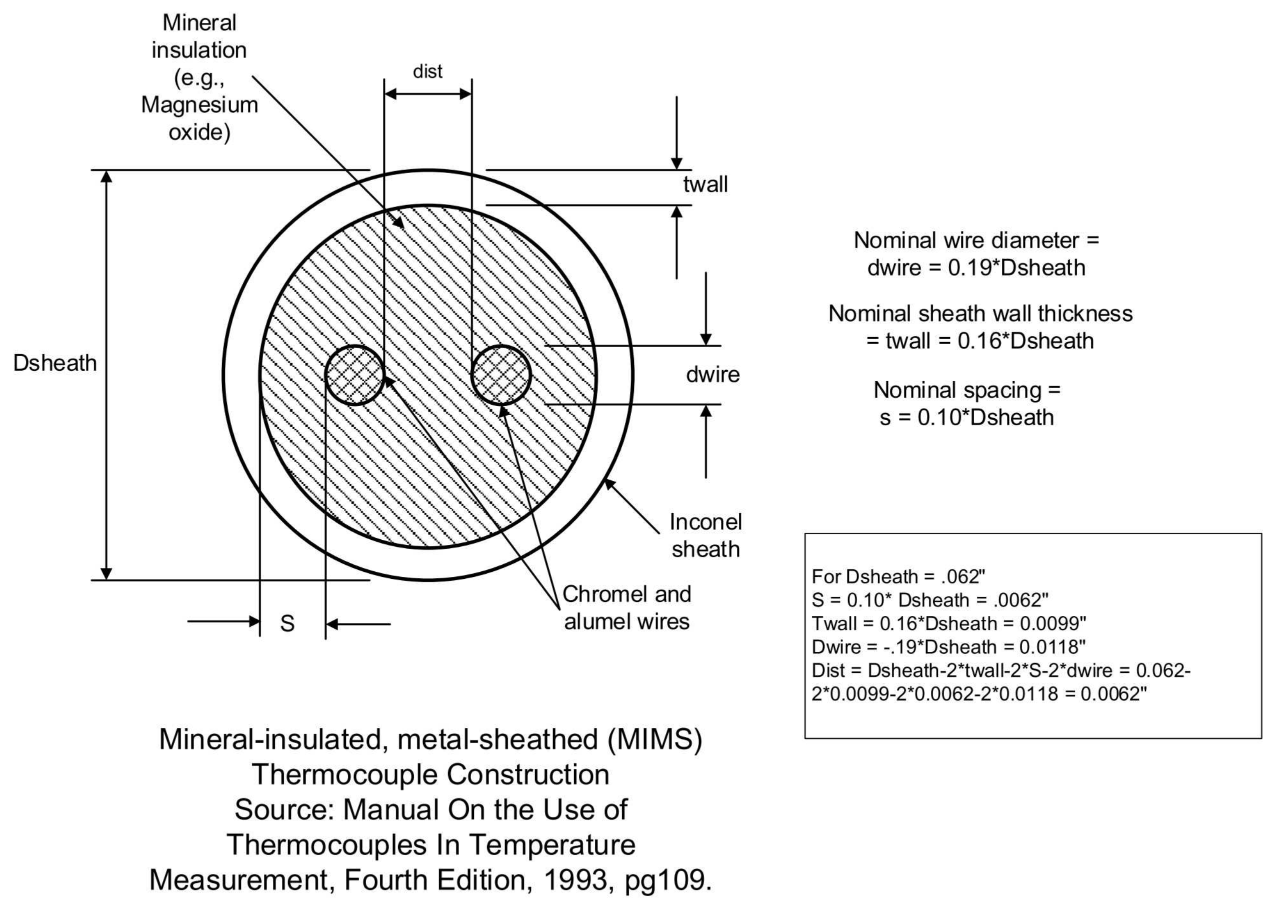

Figure 2-1: MIMS TC cross-section

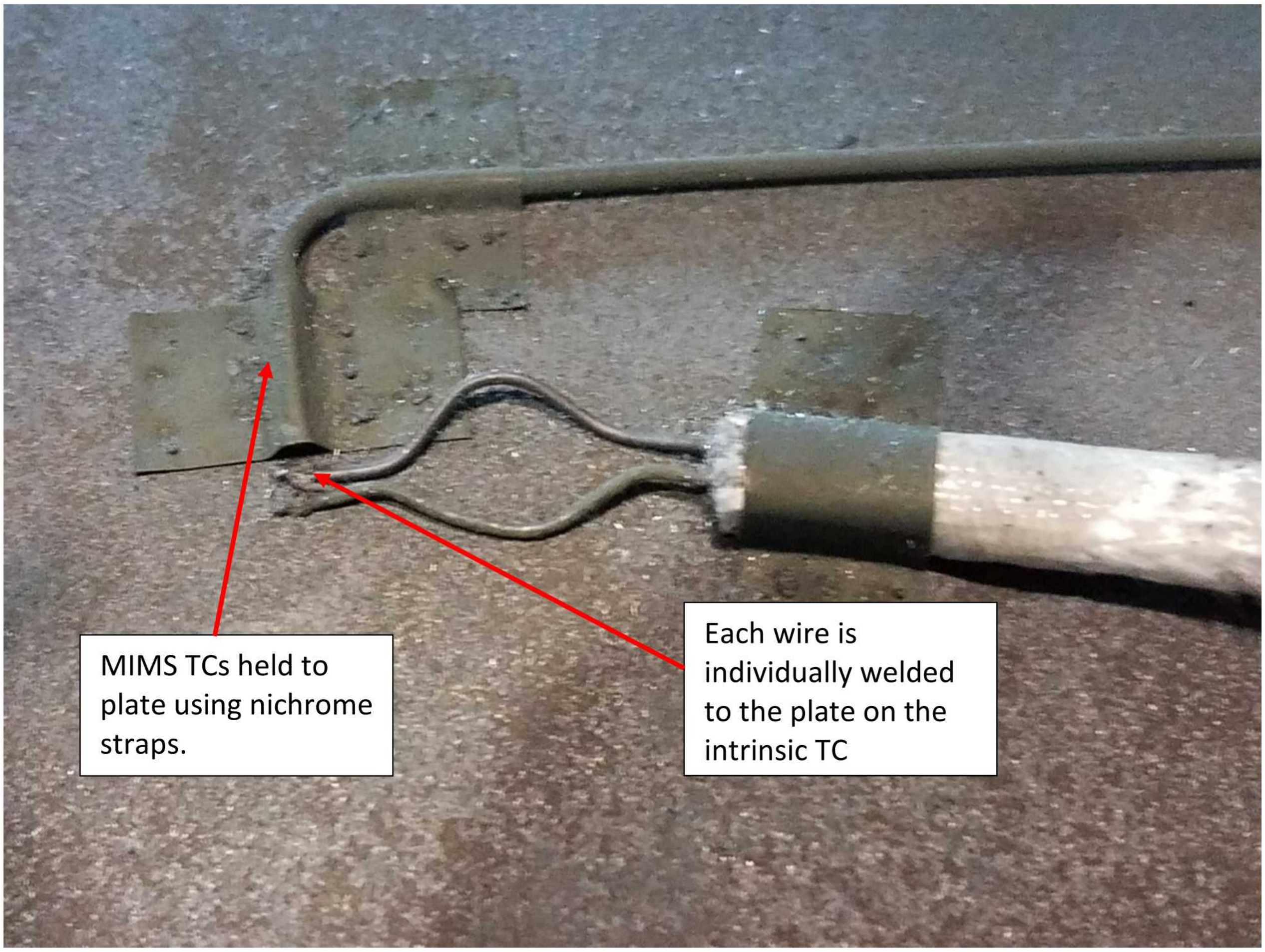

Figure 2-2: Photo of Intrinsic and MIMS TCs on a flat plate

A typical plot of the temperatures from an intrinsic and MIMS TC co-located on an Inconel plate is shown in Figure 2-3. The temperature is seen to rapidly rise from ambient and approaches about 825°C at the end of the test. This type of profile is typical of many of our radiant heat and fire tests.

In Figure 2-2 the "IJTC" is Type-K 24-gage insulated wire, but data in Figure 2-3 is from MIMS TCs with the sheath removed from the tip, exposing the chromel and alumel wires. The two types of intrinsic TCs (24-gage Nextel insulated wire and the MIMS TCs with the sheath tip removed) responded similarly.

In the data that follows for the log-profile and the long and short step profiles, the TCs were made from removing the sheath end of a MIMS TC. Data from the cylindrical shroud test were from intrinsic TCs made from 24-gage wire (Figure 2-2).

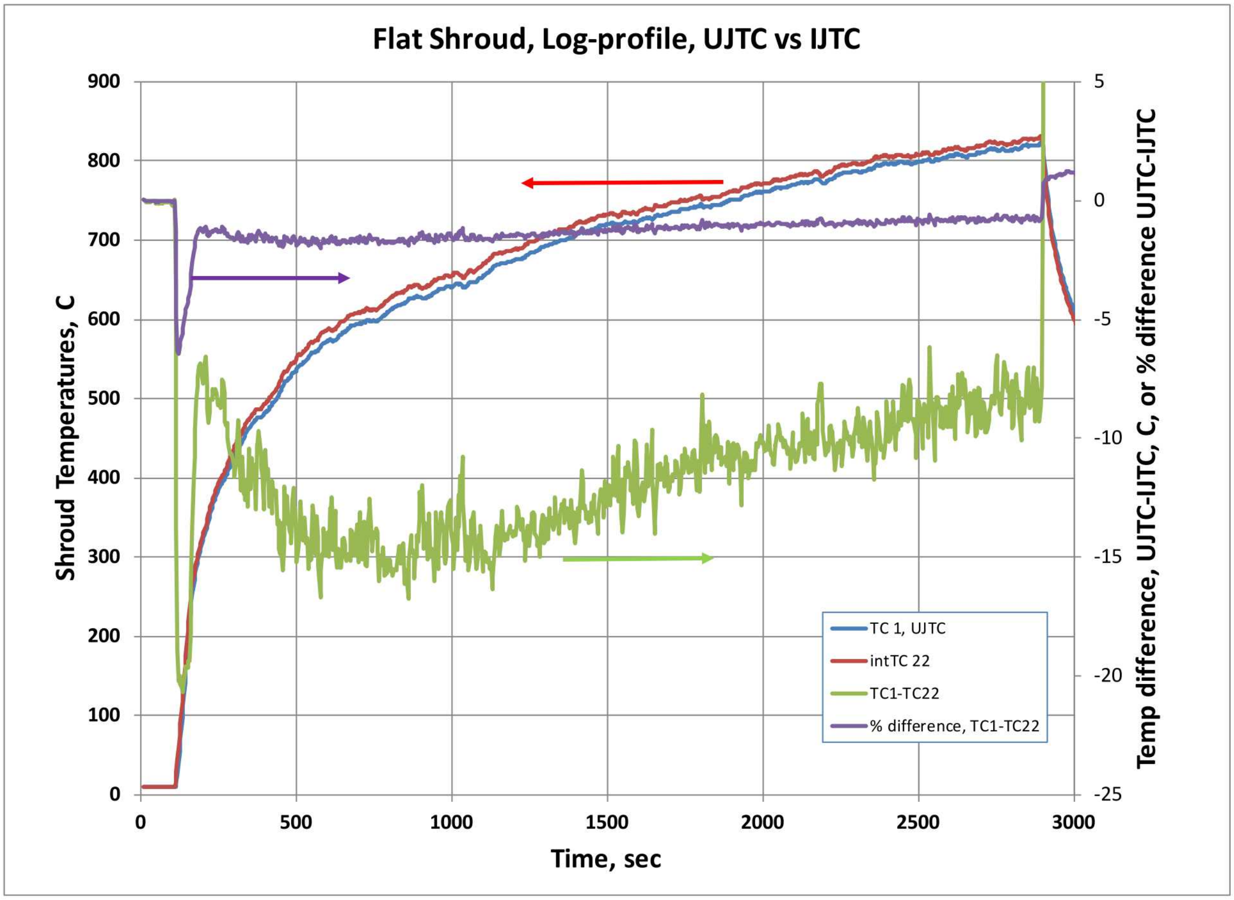

Figure 2-3: Typical TC response, flat shroud, log-profile, intrinsic TC (IJTC) and 62-mil diameter, ungrounded junction MIMS TC (UJTC)

The test begins at about 100 s. There is a rapid rise on both TCs. Because the intrinsic TC (henceforth called the IJTC) has the wires individually welded to the surface, the surface is an "intrinsic" part of the thermoelectric circuit. Due to the "Law of Intermediate Metals", the plate does not contribute to the voltage generated, as long as the temperature is uniform. This assumption was used for the test.

The sensing wires (chromel and alumel) in the ungrounded junction MIMS TCs (UJTC) are protected from the environment by the compacted MgO (magnesium oxide) insulation and the metal sheath (usually Inconel). The UJTC will read lower than the IJTC and respond slower during the fast transient, due to the insulation and protective metal sheath.

Figure 2-3 shows that the difference between the UJTC and the IJTC (UJTC-IJTC, green curve) quickly goes negative to about -21°C, then rises almost as quickly to about -7°C. This shows that the IJTC reads higher than the UJTC, due to its faster response. This occurs in the first 100 s or so of the test, when the nominal shroud temperature is between 100-200°C, which is low.

The % error in K is also shown in Figure 2-3. The error drops to about -7% early, then settled out to about -2% for the remainder of the test. The -2% error is acceptable and small, especially at the end temperature of 825°C. The -7% error is also most likely acceptable, but larger errors can occur and those larger errors may not be acceptable.

The same setup was used to measure the response of IJTCs and UJTCs in "long step" and "short step" profiles. Long and short step data are shown in Figure 2-4 and Figure 2-5. The nominal shroud temperatures are on the left axis, and the error is on the right axis. In both cases, the % error is low, except for the initial transient.

Figure 2-6 shows data from one pair of TCs on a cylindrical shroud; Figure 2-7 shows all of the data from the cylindrical shroud.

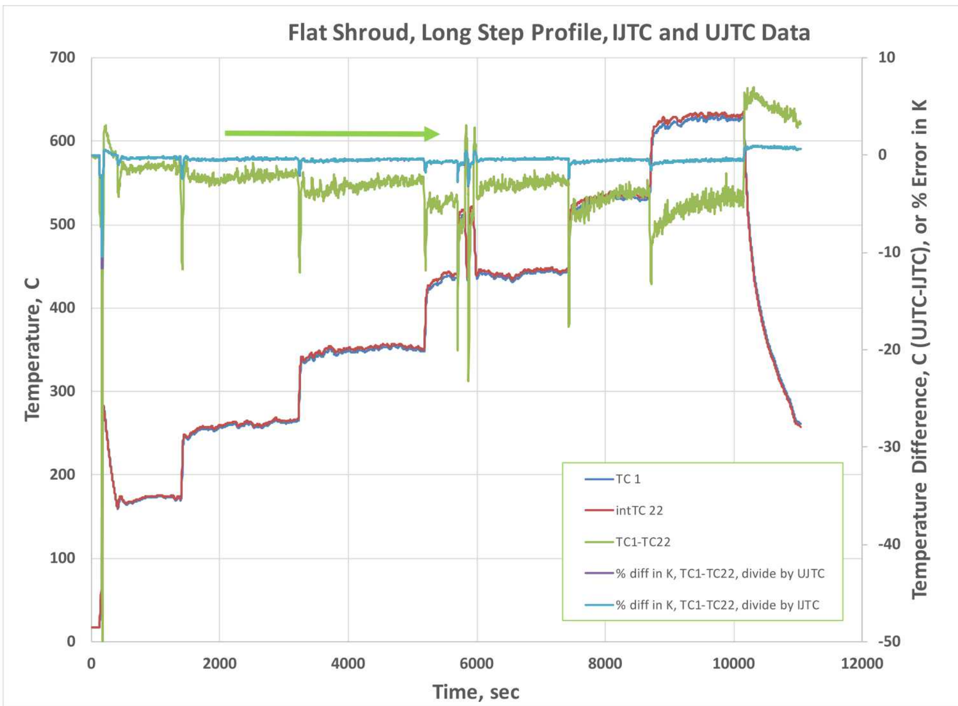

Figure 2-4: Typical TC response, flat shroud, long-step profile, intrinsic TC (IJTC) and 62-mil diameter, ungrounded junction MIMS TC (UGTC)

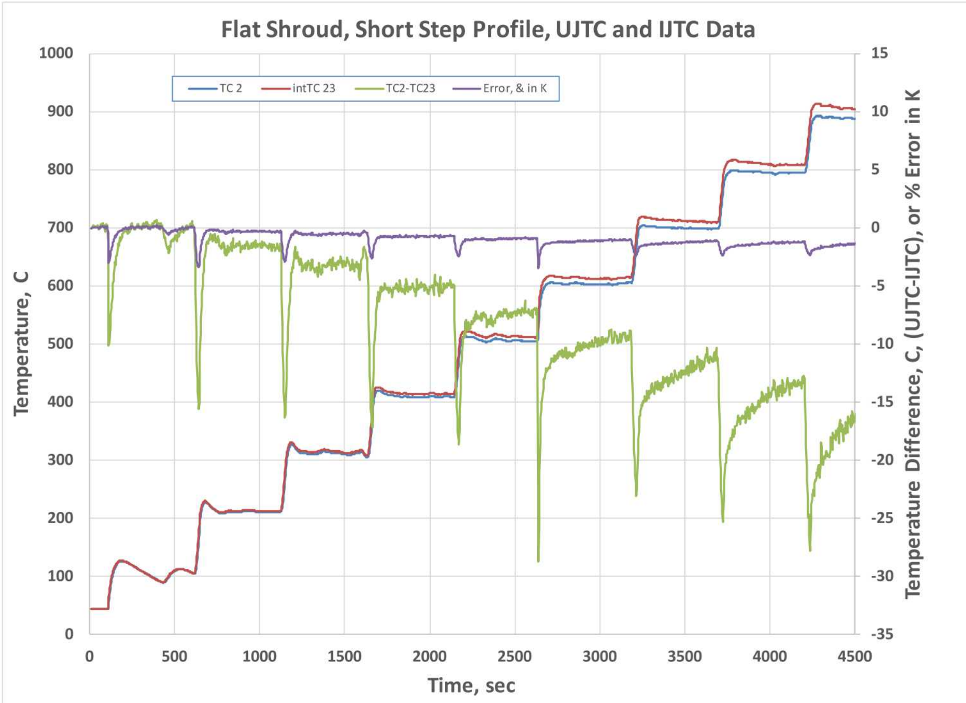

Figure 2-5: Typical TC response, flat shroud, short-step profile, intrinsic TC (IJTC) and 62-mil diameter, ungrounded junction MIMS TC (UJTC)

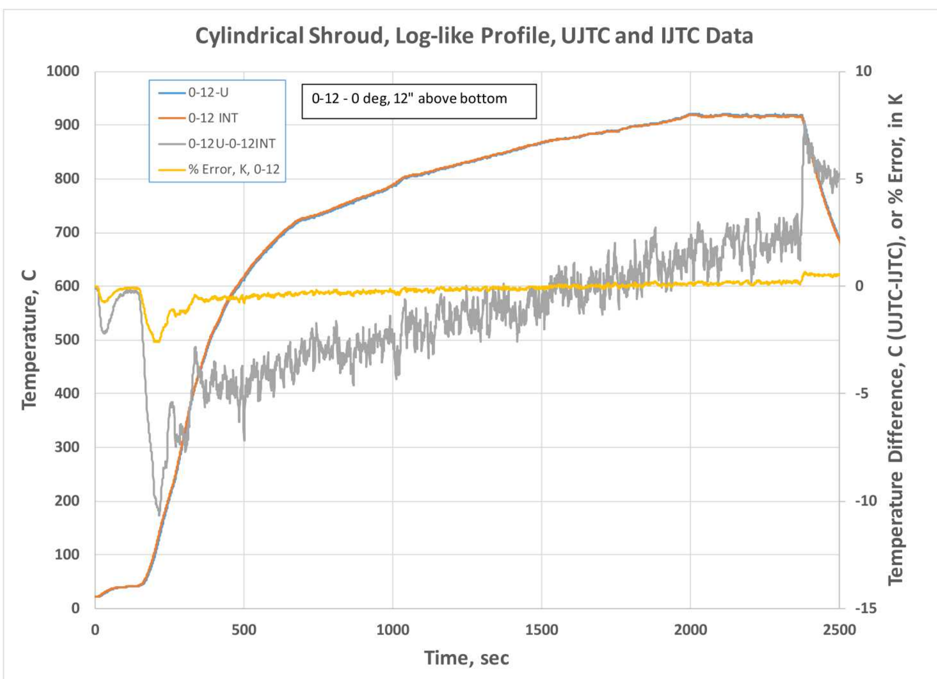

Figure 2-6: Typical TC response, cylindrical shroud, log-like profile, 24 gage intrinsic TC (IJTC) and 62-mil diameter, ungrounded junction MIMS TC (UJTC)

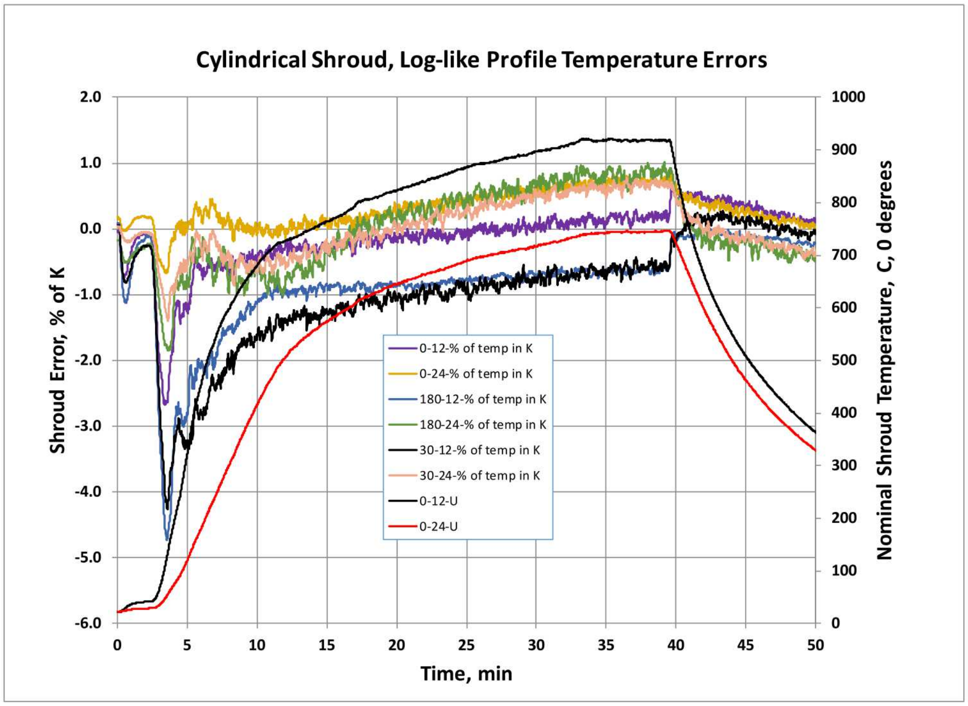

Figure 2-7: Response of 6 TC pairs, cylindrical shroud, log-like profile, 24 gage intrinsic TC (IJTC) and 62-mil diameter, ungrounded junction MIMS TC (UJTC)

In the case of the cylindrical shroud, the error starts negative similar to the other tests, but eventually reaches zero and goes positive in some cases. This is in part because the other side of the cylindrical shroud is at the same nominal temperature, so the loss term (see Section 3) is much lower.

To get a sense of the magnitudes of the errors for the various data, Table 2-1 is provided. It shows approximate data from the plots shown in Figure 2-3 through Figure 2-7.

Table 2-1: Comparison of approximate values of early and late time errors, % in K

Shroud Shape	Temperature Profile	Max% Error	% Error at about 700°C	Comments
Flat	Logarithmic	-6.5%	-1.5%	Shroud TCs faced flat surface with increasing temperature
Flat	Long Step	-10%	-0.5%	Shroud TCs faced flat surface with increasing temperature
Flat	Short Step	-3%	-1%	Shroud TCs faced flat surface with increasing temperature
Cylindrical	Log-like	-4.5%	±1%	Shroud TCs faced other side of cylindrical shroud at similar temperatures

For late times, the error is quite small for all cases. There is little chance of reducing this error, so no additional work is warranted. However, at early times the transient error can be large (e.g., 10%) at least in one case, so the transient adjustment will be explored.

3. THEORY OF TRANSIENT CORRECTION & MODEL

The first order correction theory for TC response was used by Gill, Keltner, Beck, and others [1] [4] [5]. It consists of using a first order correction based on the time rate of change of temperature and a "time constant" "tau" (τ) as follows:

$$T_{adjusted} = T_{measured} + tau*dT_{measured}/dt \qquad \{1\}$$

The time constant tau in equation {1} is estimated from data of the "true" temperature and measured temperature from the UJTC. Tau (τ) is approximated as a 100% correction, not 63 percent[2].

The assumed true temperature is from the intrinsic TCs, and the measured temperature is from the MIMS TCs. It is known that the IJTCs do not indicate the exact true temperature, so from a practical measurement viewpoint, the most reasonable assumption was made.

A relatively simple energy balance on the TC is the starting point for the model. An earlier model was more detailed but in this case, the TC is approximated as a lumped mass of average properties [6]. Results from the earlier model and this model are consistent.

If a control volume is formed around the TC sheath, one can say:

$$E_{in} - E_{out} = E_{stored} \qquad \{2\}$$

Where, E_{in} is the energy into the TC from the shroud, E_{out} is the energy lost from the TC to the surrounding environment, and E_{store} is the energy stored in the TC. If one approximates the TC as a solid body of uniform temperature T_{TC}, then the E_{store} term can be expressed as follows:

$$E_{store} = \rho_{avg} * c_{p-avg} * V_{tc} * dT_{TC}/dt \qquad \{3\}$$

ρ_{avg} is the average density of the TC, V it's volume, and c_{p-avg} the average specific heat. The specific heat likely changes with temperature, but this model does not account for this change. dT_{TC}/dt is the temperature ramp rate calculated from MIMS data at each time step. The "energy in" is a function of the contact resistance and radiation from the shroud to the TC. This is expressed as follows:

$$E_{in} = (T_{sh} - T_{TC}) * \frac{A_{contact}}{R_{contact}} + \varepsilon_{sh} * A_{sh} * F_{sh-TC} * \sigma * (T_{sh}^4 - T_{tc}^4) \qquad \{4\}$$

Where T_{sh} is the shroud temperature (e.g., from the IJTC), T_{TC} is the temperature read by the MIMS TC (the UJTC), $R_{contact}$ is the contact resistance and $A_{contact}$ is the contact surface area. ε_{sh} is the

[2] The definition of a time constant is for response to 63.2% of the peak value.

shroud emissivity, A_{sh} the shroud area, $F_{sh\text{-}TC}$ is the view factor from the shroud to the TC (very small) and σ is the Stefan-Boltzmann constant (5.67E-08 W/m^2-K^4). The radiation term (second) in equation {4} turns out to be very small.

E_{out} may be expressed as follows:

$$E_{out} = A_{tc} * F_{tc-envt} * \varepsilon_{tc} * \sigma * (T_{tc}^4 - T_{envt}^4) \qquad \{5\}$$

Where A_{tc} is the surface area of the TC sheath, $F_{tc\text{-}envt}$ is the view factor from the TC sheath to its surrounding environment (0.5), ε_{tc} is the TC surface emissivity, and T_{envt} is the temperature of the surrounding environment. For the cylindrical shroud, T_{envt} may be approximated as the temperature of the shroud on the opposite side (180° from where the TC is located), which is the same as T_{sh}. For the flat shroud case, T_{envt} begins at 300 K then rises similar to but slower than T_{sh}.

Early in the test, the rate-of-change ("ramp rate") dT_{TC}/dt is high and the loss term is low. Using a first order approximation, one might say that E_{out} is small because both T_{TC} and T_{envt} are relatively low. So, equation {2} is reduced to:

$$E_{in} = (T_{sh} - T_{TC}) * \frac{A_{contact}}{R_{contact}} = E_{store} = \rho_{avg} * c_{p-avg} * V_{tc} * dT_{TC}/dt \qquad \{6\}$$

The temperature difference T_{sh}-T_{TC} is the same as the error we have been plotting (except for a negative sign). T_{sh} = surface temperature of shroud = IJTC and T_{TC} = UJTC. From equation {6} it is evident that the error is proportional to the temperature ramp rate. This is consistent with equation {1}.

Rearranging equation {6}, one arrives at the following:

$$(T_{sh} - T_{TC}) = \frac{R_{contact}}{A_{contact}} * (\rho_{avg} * c_{p-avg} * V_{tc} * \frac{dT_{TC}}{dt}) \qquad \{7\}$$

All parameters except dT/dt can be lumped into a single parameter with the dimensions of time, which I call *tau* (τ):

$$tau = \frac{R_{contact}}{A_{contact}} * (\rho_{avg} * c_{p-avg} * V_{tc}) \qquad \{8\}$$

Equation {8} shows that the time constant is affected by the contact resistance and the thermal mass of the TC.

Returning to equation {2}, and substituting for all the terms, one arrives at the following:

$$E_{in} = (T_s - T_{TC}) * \frac{A_{contact}}{R_{contact}} + F_{sh-TC} * \epsilon_{sh} * A_{sh} * \sigma * (T_{sh}^4 - T_{TC}^4) = E_{store} + E_{out} = \rho_{avg} * c_{p-avg} * V_{tc} * \frac{dT_{TC}}{dt} + A_{TC} * F_{TC-envt} * \epsilon_{tc} * \sigma * (T_{TC}^4 - T_{envt}^4) \qquad \{9\}$$

Several of the terms in equation {9} are difficult to estimate. One such term is the contact resistance between the cylindrical TC sheath and the flat shroud. The nichrome strap which holds the TC in place complicates any estimation of the contact conductance. Another is the contact area ($A_{contact}$) between the TC sheath and the shroud. This makes accurate modeling difficult. But the model (using best available parameters) can be used to determine which of the terms in equation {9} are the most important, and the approximate magnitude of each of the terms.

Equation {9} can be rearranged to solve for the error:

$$(T_s - T_{TC}) = \frac{R_{contact}}{A_{contact}} * (\rho_{avg} * c_{p-avg} * V_{tc} * \frac{dT_{TC}}{dt} + A_{TC} * F_{TC-envt} * \epsilon * \sigma * (T_{TC}^4 - T_{envt}^4) - F_{sh-TC} * \epsilon_{sh} * A_{sh} * \sigma * (T_{sh}^4 - T_{TC}^4)) \qquad \{10\}$$

The first term (right side of {10}) is related to the time rate of change of temperature, which is high at early times then drops to low values as the test progresses. The second term is related to the loss of energy from the TC to the environment, and the third term to the radiative energy from the shroud intercepted by the TC. The second term is small at early times but increases as the TC temperature increases. The third term is always small due to a small value for the view factor and the small difference in temperatures T_{sh} and T_{TC}.

Equation {10} was solved using an Excel spreadsheet to gain a better understanding of the three terms, their overall magnitude, and when they were most important.

Figure 3-1 shows results assuming an environment temperature that begins at 300K and increases with the shroud temperature (using log-profile data). An arbitrary factor of 0.9 was used to modify the shroud temperature to estimate the environment temperature, which was a large flat structure close to the shroud.

Each of the three terms in the model is shown in Figure 3-1. The overall trends and approximate magnitudes of the errors agree reasonably with typical experimental results shown below.

As one might expect, at early times the term related to energy stored is largest. The term related to energy loss to the environment is small early, and rises with time. The term related to radiation input to the TC from the shroud to the TC is negligible at all times.

Appendix A provides numerical values for the inputs so the reader can duplicate the results here and change as better data become available. The early time error is greatly affected by increasing or decreasing the contact resistance. The used values are similar to what is in the literature.

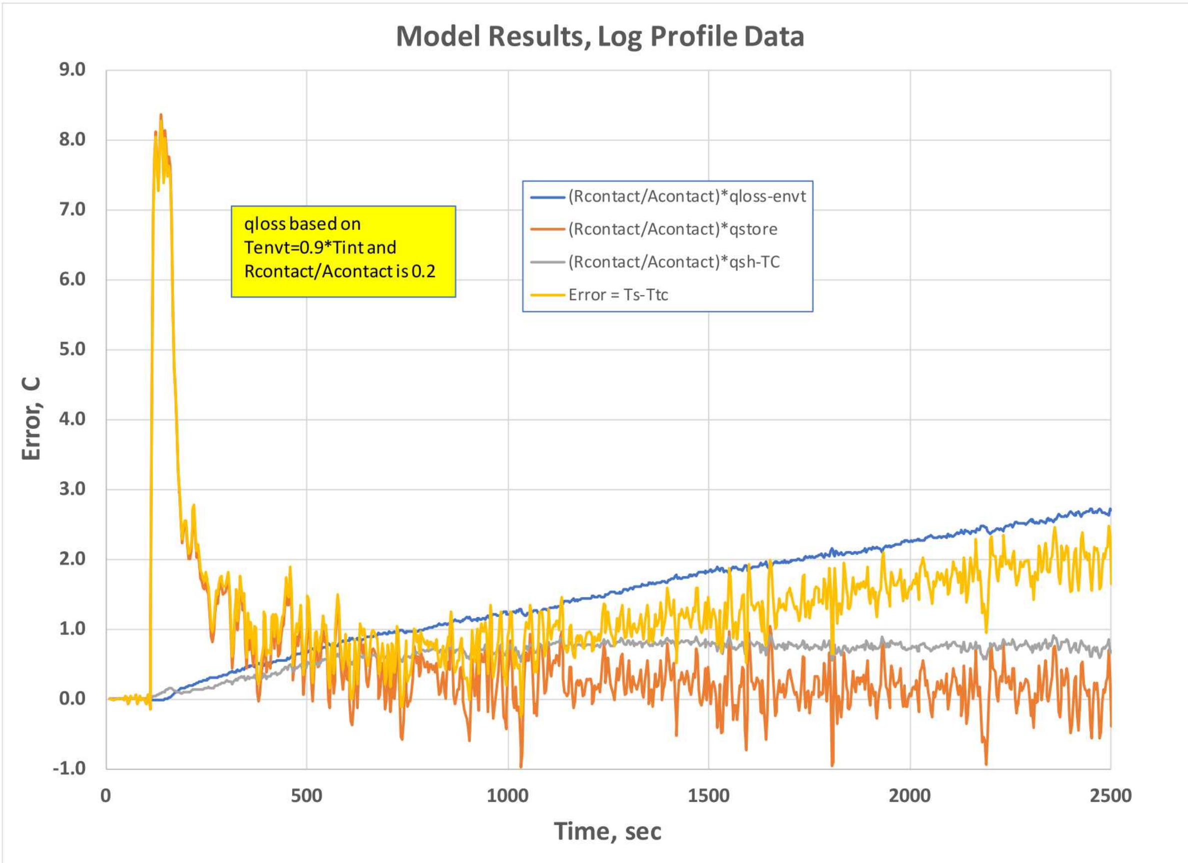

Figure 3-1: Model results for 3 terms, environment temperature 0.9*shroud temperature

The error in Figure 3-1 rises rapidly at early times similar to the experimental data, then drops soon thereafter. The magnitude of the error (about 8°C) is reasonable but should not be taken as an accurate value, due to the parameter uncertainties. Because the environment temperature is assumed to be 0.9*shroud temperature, the error continues to grow with time as the shroud heats up. The store term is largest early in the test, then drops to essentially zero as the TC temperature rises. The loss term (blue) continually rises because the shroud is radiating to a cold environment. The term related to the energy from the shroud intercepted by the TC (gray) is small and remains small for the entire test.

Two other environment temperatures were used. The first was assuming that the environment temperature was the same as the shroud temperature, as measured by the IJTC. Figure 3-2 shows the results. The error rises rapidly to the same value (8°C) as in Figure 3-1, but then drops to slightly below zero towards the end of the test. This behavior is similar to what was observed in cylindrical shroud tests (see below); the errors shown in Figure 4-16 crossed the x-axis during the test, same as the model.

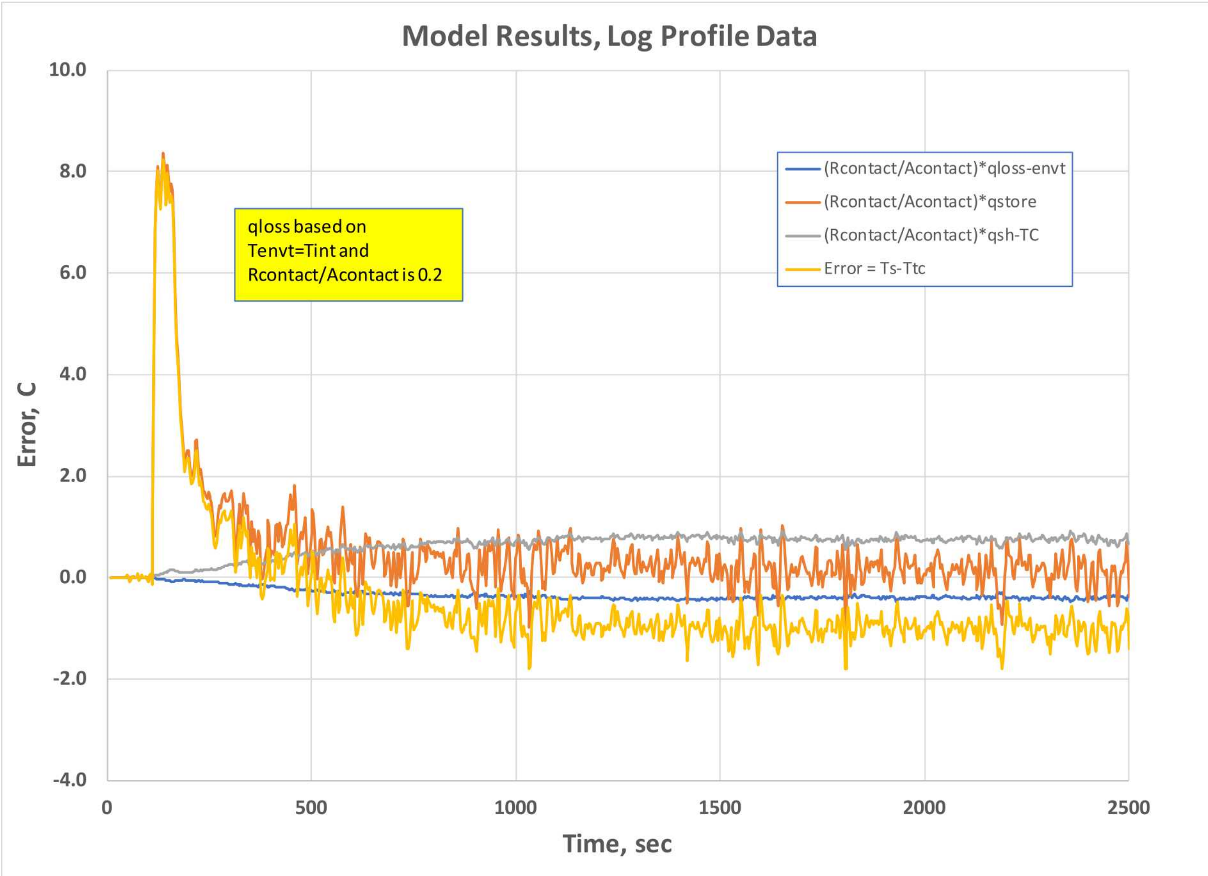

Figure 3-2: Model results assuming Tenvt = Tshroud (Tijtc)

Last, the model was used with a constant T_{envt} of 300K. This simulates a flat shroud radiating to a cold environment.

Figure 3-3 shows the model results using the environment temperature of 300K. The early time error is the same as the earlier two plots, then the error drops, then rises with time with the loss term.

The model shows that the store term is largest early in the test and dominates the error. At late times, the store term is small. The term related to radiation from the shroud intercepted by the TC is small throughout the test. The term related to loss from the TC to the environment is the dominant factor late in the test, and either can be large (flat shroud radiating to a cold environment) or small (cylindrical shroud radiating to itself).

Results of this model were qualitatively compared with the more detailed model [6]. The comparisons are favorable and the trends are consistent.

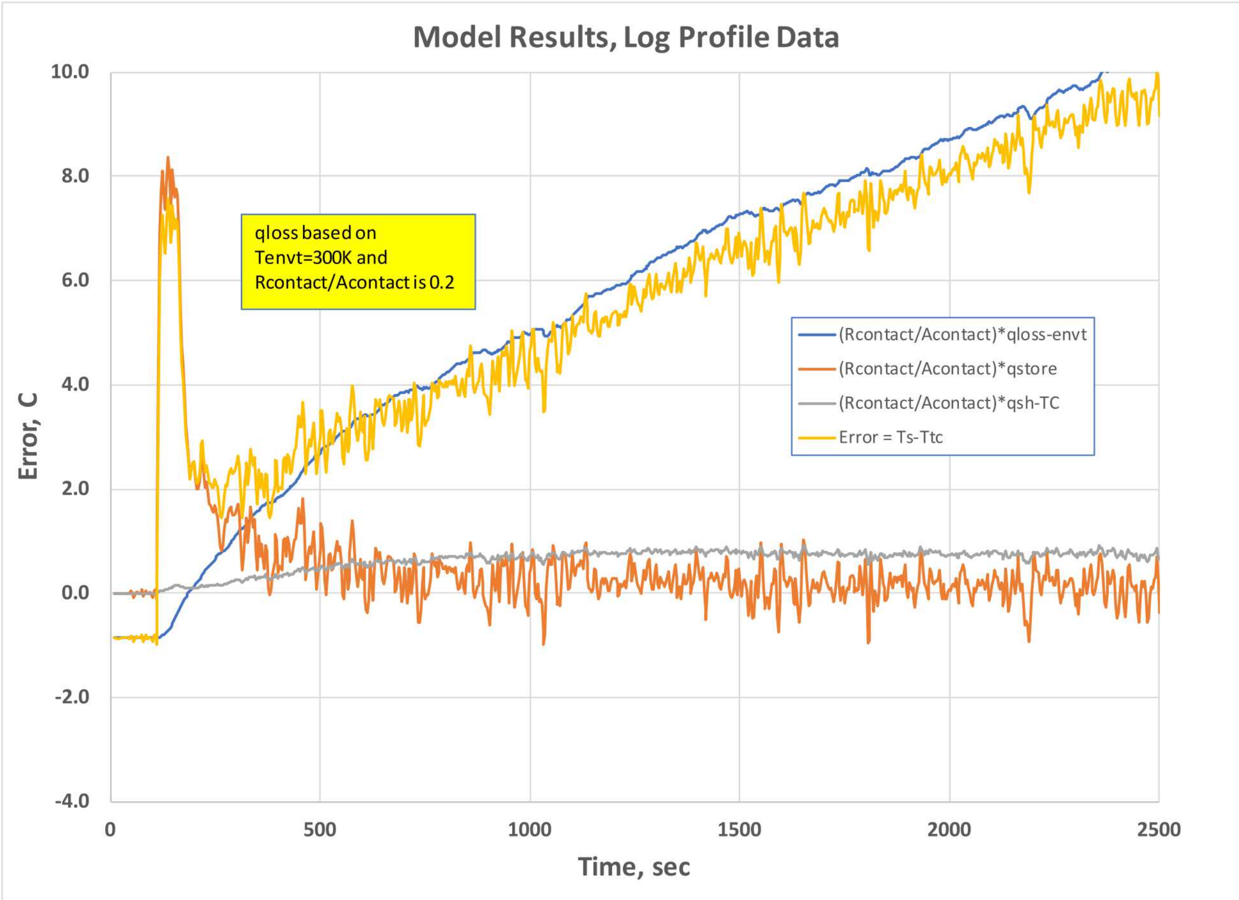

Figure 3-3: Model results for Tenvt = 300K

4. EXPERIMENTAL RESULTS

Estimating the time constant (tau, τ) is difficult. It involves varying the time constant using equation {1} until the error between the UJTC and the IJTC is minimized. The correction factor is relatively large at early times, but drops at late times.

The method has to account for both: 1) a temperature discontinuity, which is due to the contact resistance between the true shroud temperature and the measured TC temperature; and 2) the delay due to the thermal mass of the TC. Therefore, the correction should not result in zero error at early time.

An adjustment procedure was chosen, using the assumption that the UJTC lags the IJTC and should be corrected forward in time (called the "graphical method"). Adjustments were made as follows:

1. For a perfect linear temperature rise, the UJTC should be delayed due to the contact resistance and the thermal mass. The TC response should be parallel but delayed, as compared to the intrinsic TC [1].
2. The magnitude of this discontinuity (a time delay) was adjusted graphically to match (as good as possible) the early time error. See the following figures for examples.
3. The adjustments were made to change the MIMS TC reading to substantially reduce the early time error, but not the late time error.
4. No effort was made to estimate the time constants to better than 2 significant digits because of the variations in the results.

An alternate method was used in [1]. Equation {1} was rearranged and solved for tau; see equation {11}:

$$tau = (T_{adjusted} - T_{measured})/dT_{measured}/dt \qquad \{11\}$$

A plot of the error ($T_{adjusted} - T_{measured}$) vs $dT_{measured}/dt$ is used to estimate tau using a linear regression. This was done for a single TC pair when exposed to a step increase in temperature. As stated earlier, the result for that case was τ = 5.4 s. This method was used on a TC pair from the logarithmic profile test, but the results did not show a clear τ value. Therefore, the graphical method described above was used with the four data sets analyzed in this report.

4.1. Flat Shroud, Logarithmic Profile

Figure 4-1 shows an example of the original UJTC data (blue) and adjusted UJTC data (green) using a time constant of 4.0 s. That is, the time file for the UJTC (TC1) was adjusted back in time by (in this case) 4.0 s. The resulting response adjusts the UJTC to approximately the same as the IJTC (TC22) during the almost linear rise from about 115 to 165 sec. Then, the adjusted UJTC (green) slowly approaches the UJTC (not adjusted) because at late time, the transient correction should be less. The method used to arrive at the 4.0 s time adjust was just trial and error. In some cases, the temperature rises are not parallel, so an estimate of the best tau is an approximation.

See Figure 4-2 for another good fit, and Figure 4-3 for a fit that is not as good.

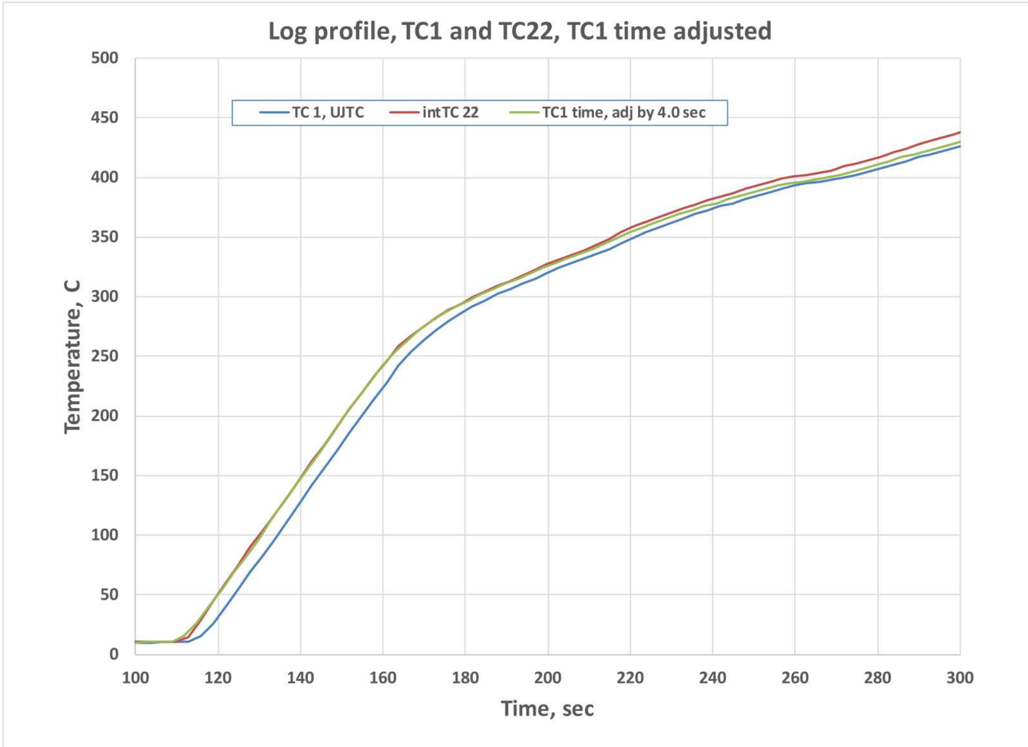

Figure 4-1: Flat shroud, log-profile, TC1 & TC22, tau = 4.0 s correction

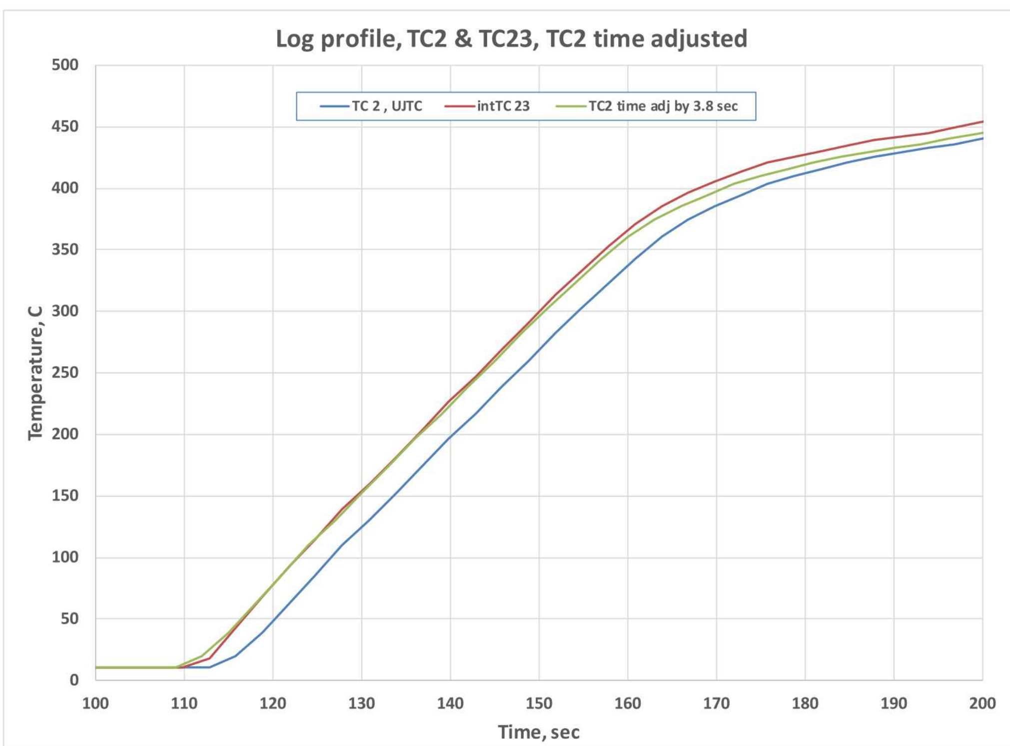

Figure 4-2: Flat shroud, log-profile, TC2 & TC23, tau = 3.8 s correction

Figure 4-3: Flat shroud, log-profile, TC7 & TC28, tau = 6.0 s correction

Looking at Figure 4-3, it can be seen that the model does not adjust the data to match perfectly because the temperature rises are not parallel.

A model was used with both first order terms (see equation {1}) and included a second order term ($tau2*d^2T/dt^2$) and adjusted the tau2 constant to see if the adjustments were any more satisfactory (keeping the original tau constant). The results changed very little, so the second order term was not used.

Similar results were observed for other pairs of TCs. Ten (10) pairs were analyzed and the resulting values of the time constant are shown in Table 4-1. The best values to 2 significant digits are shown. The average value using the nine data points was 5.1 s, with a standard deviation of 1.0 s.

Figure 14 shows the adjusted temperatures using the tau value from Table 4-1. As expected, the early time errors were reduced.

Table 4-1: Approximate values of the TC time constant (s) for 10 TC pairs, log profile

TC Pair	Approximate Time Constant, s
TC1 and TC22	4.0
TC2 and TC23	3.8
TC3 and TC24	5.1
TC4 and TC25	3.8
TC5 and TC26	6.2
TC6 and TC27	5.5
TC7 and TC28	6.0
TC8 and TC29	6.2
TC9 and TC30	4.5
TC10 and TC31	5.9
Average	***5.1***
Std deviation	***1.0***

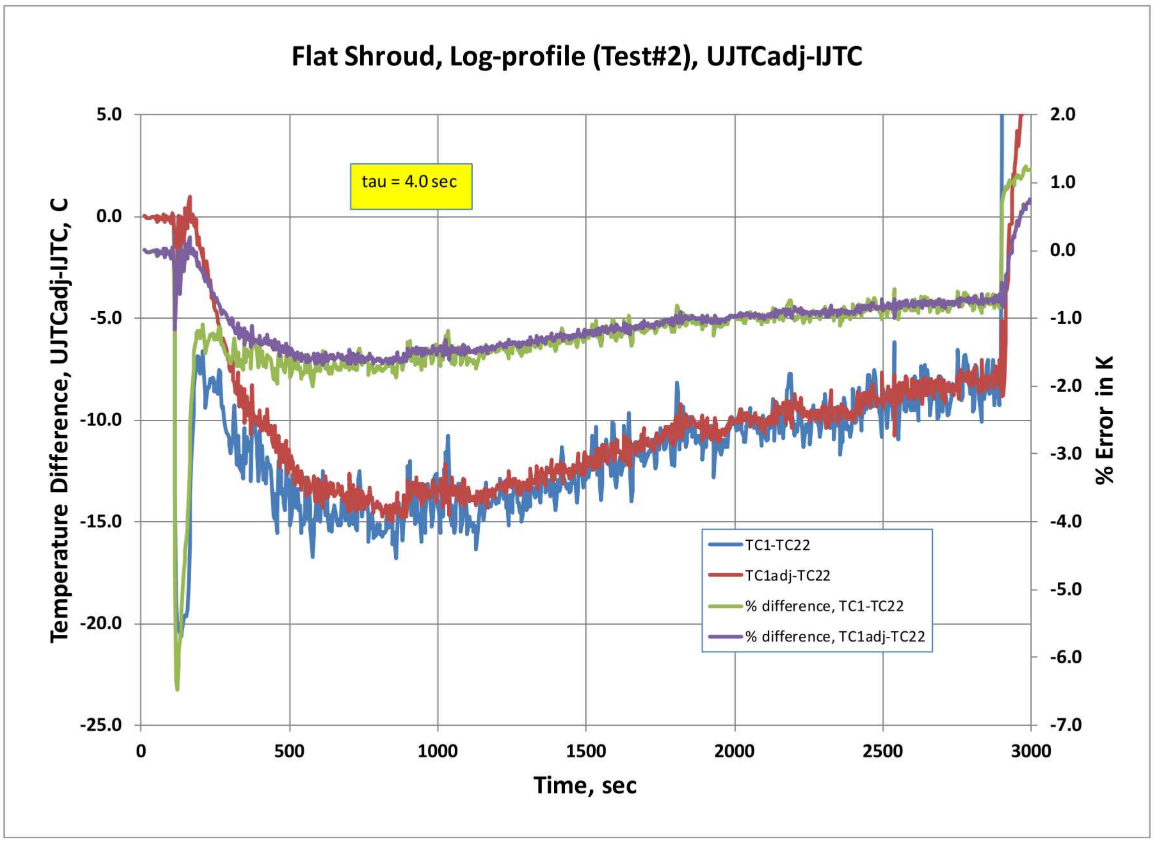

Figure 4-4: Flat shroud, log-profile, TC-TC22 errors before and after adjustment

4.2. Flat Shroud, Long Step Profile

A similar procedure was used for data from the "long step" profile. Referring back to Figure 2-4, the goal is to adjust the MIMS TC to reduce the spikes observed in the temperature difference, TC1-TC22.

Figure 4-5 shows results from a single pair of TCs (TC1 and TC22). As before, TC1 is a UJTC and TC22 is an IJTC. The figure shows the nominal temperatures as they step up from ambient to about 640ºC and the error in C and the % error in K. The % error was determined from both the UJTC and the IJTC; results were so close that it made no difference.

Figure 4-6 and Figure 4-7 show results of adjusted MIMS TC time data, given the indicated time constant tau for two pairs of TCs: TC1 and TC22 (Figure 4-6), and TC2 and TC23 (Figure 4-7). The time was adjusted backward so the temperatures more closely agreed. Agreement is good on those two pairs but not quite as good on others, see Figure 4-8. Ten (10) pairs were evaluated to get more data; see Table 4-2.

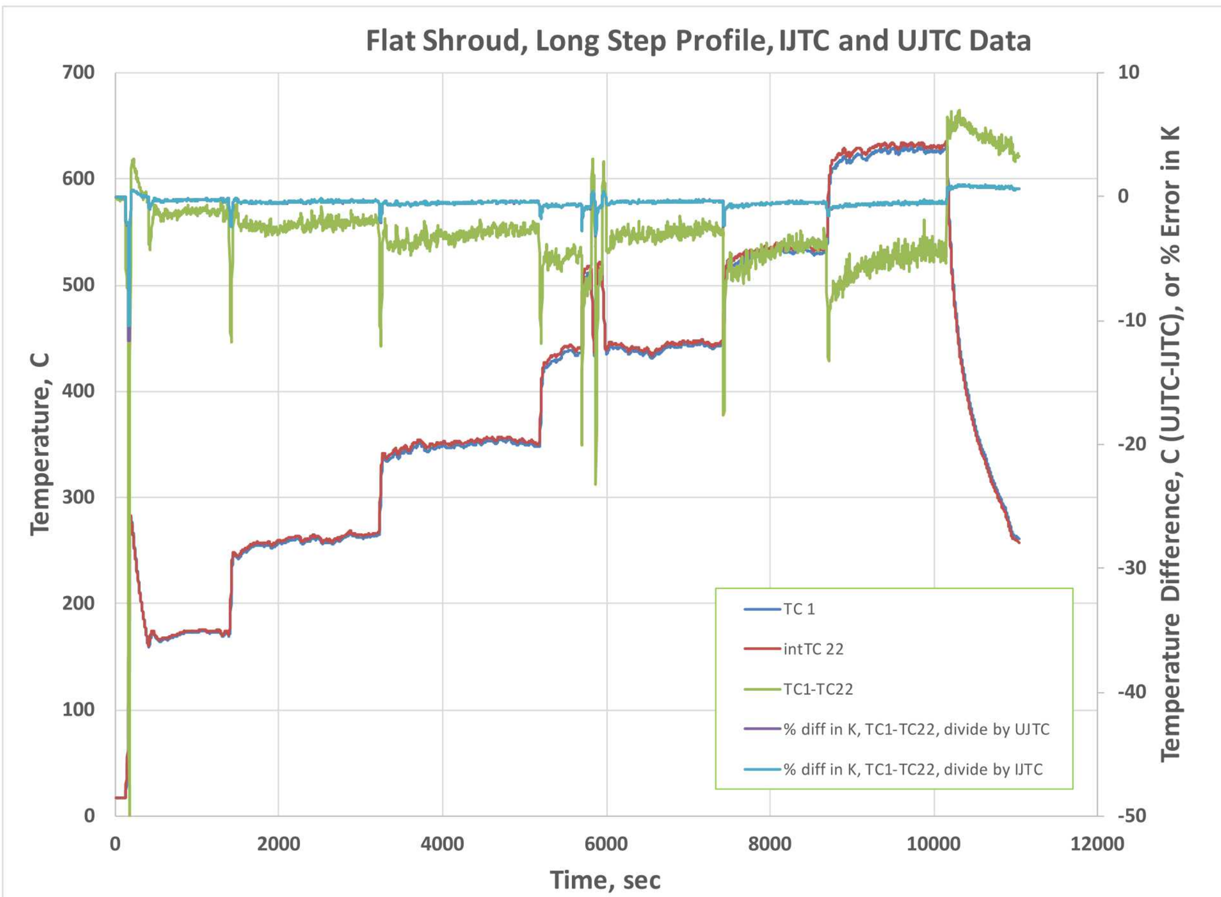

Figure 4-5: Flat shroud, long-step profile, TC1 and TC22, tau = 3.3 s correction

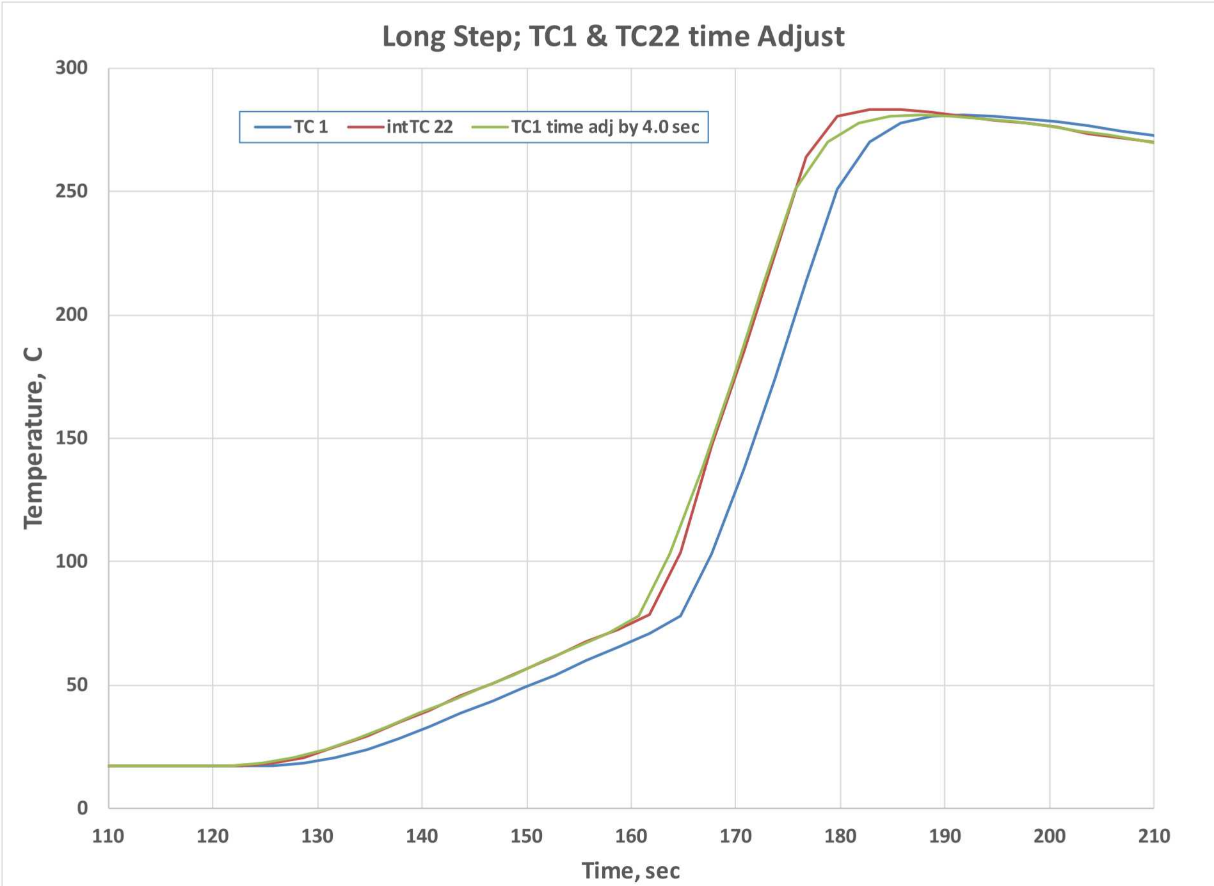

Figure 4-6: Flat shroud, long-step profile, TC1 and TC22, tau = 4.0 s correction

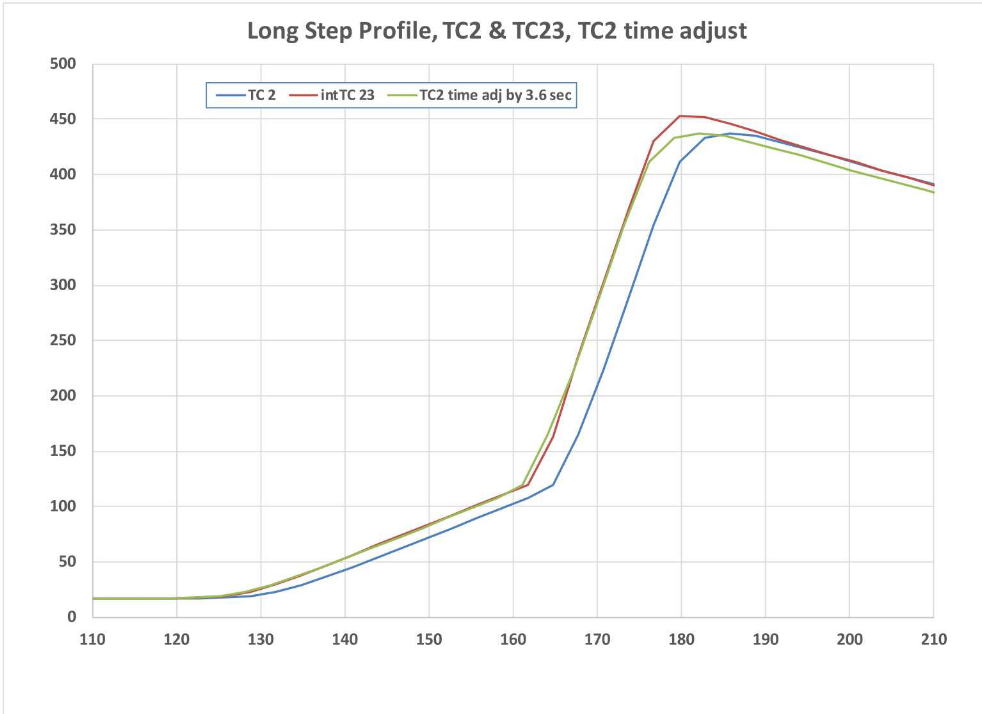

Figure 4-7: Flat shroud, long-step profile, TC2 and TC23, tau = 3.8 s correction

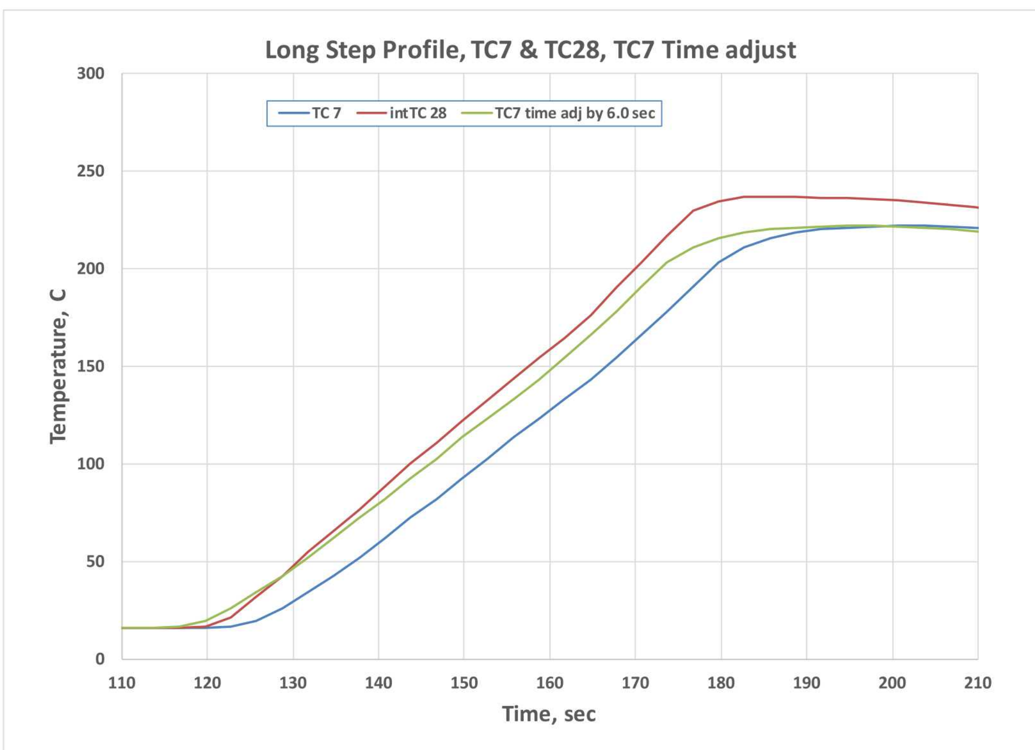

Figure 4-8: Flat shroud, long-step profile, TC7 and TC28, tau = 6.0 s correction

Figure 4-9 shows the adjusted temperature data using tau of 4.0 s for TC1 & TC22. As can be seen, the error is lower with the correction.

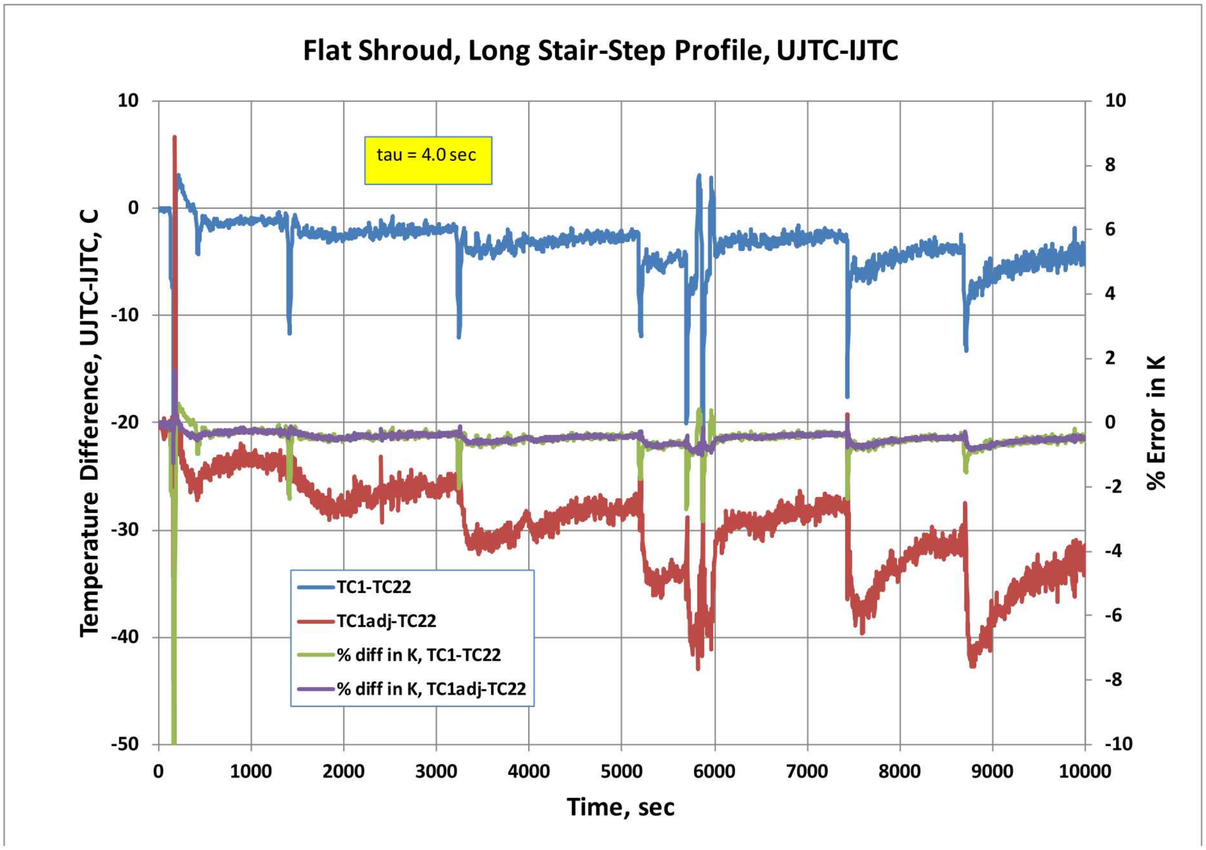

Figure 4-9: Long step profile, TC1 & TC22, TC1 adjusted for tau = 4.0 s

Table 4-2: Approximate values of the TC time constant (s) for 10 TC pairs, long step profile

TC Pair	Approximate Time Constant, s
TC1 and TC22	4.0
TC2 and TC23	3.6
TC3 and TC24	4.2
TC4 and TC25	3.5
TC5 and TC26	5.0
TC6 and TC27	5.5
TC7 and TC28	6.0
TC8 and TC29	5.5
TC9 and TC30	3.9
TC10 and TC31	5.0
Average	**4.6**
Std deviation	**0.9**

From Table 4-2, the average of the 10 data points is 4.6 s with a standard deviation of 0.9 s.

4.3. Flat Shroud, Short Step Profile

Using the same setup and TCs from the logarithmic profile test and long-step profile test, a test was performed that is called the "Short-Step Profile" test. One such pair of TCs is shown in Figure 4-10 below.

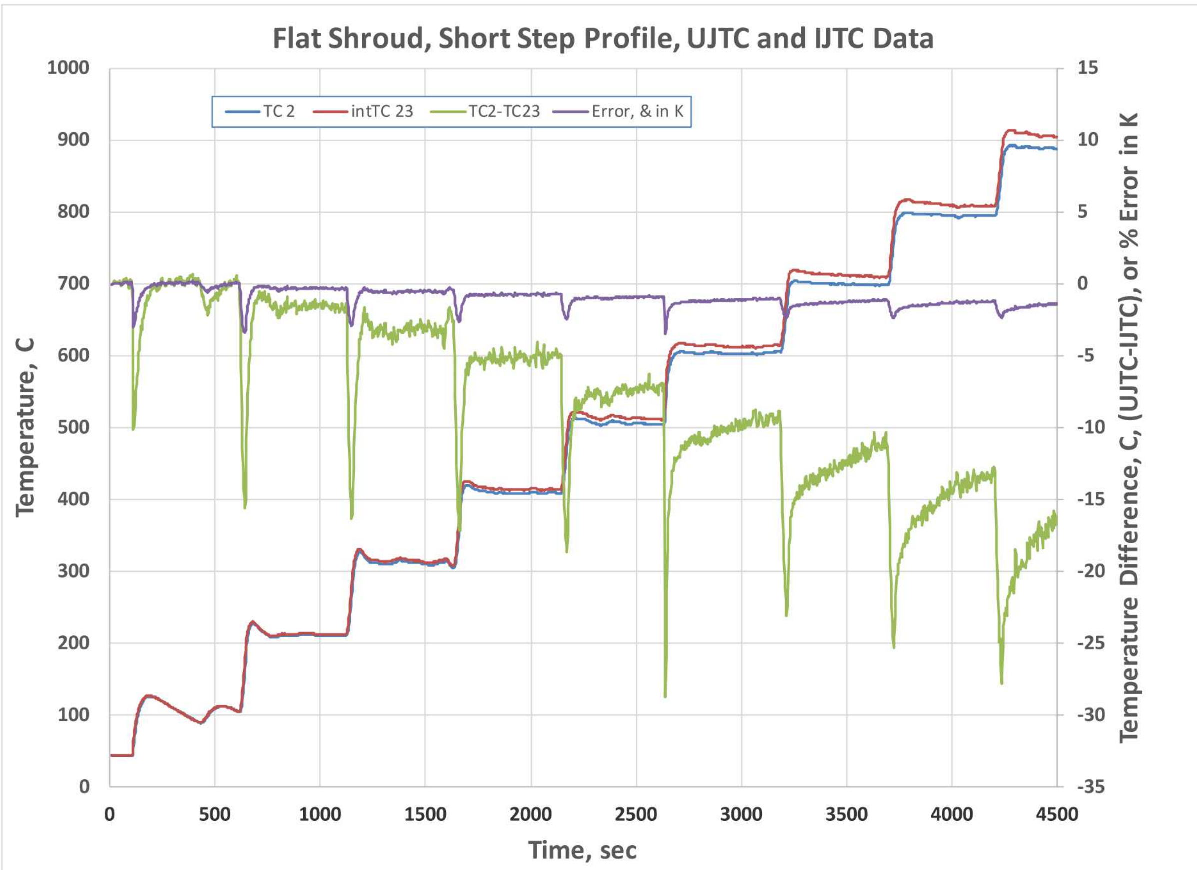

Figure 4-10: Flat shroud, short-step profile, TC2 and TC23, shroud temperatures and error

The error in Figure 4-10 rises with temperature (i.e., a larger negative error) and the % error in K is relatively small, always less than -4%. The % error during the steady times increases with time, which is at higher temperatures (as expected). An effort was made to reduce the early time errors, observed as large negative spikes.

Figure 4-11 shows results of adjusting the MIMS TC data using tau = 3.5. The results are good in that the error spikes are removed. Similar data are shown in Figure 4-12 for a second pair of TCs. Table 4-3 shows a summary of 10 sets of data, the average, and standard deviation.

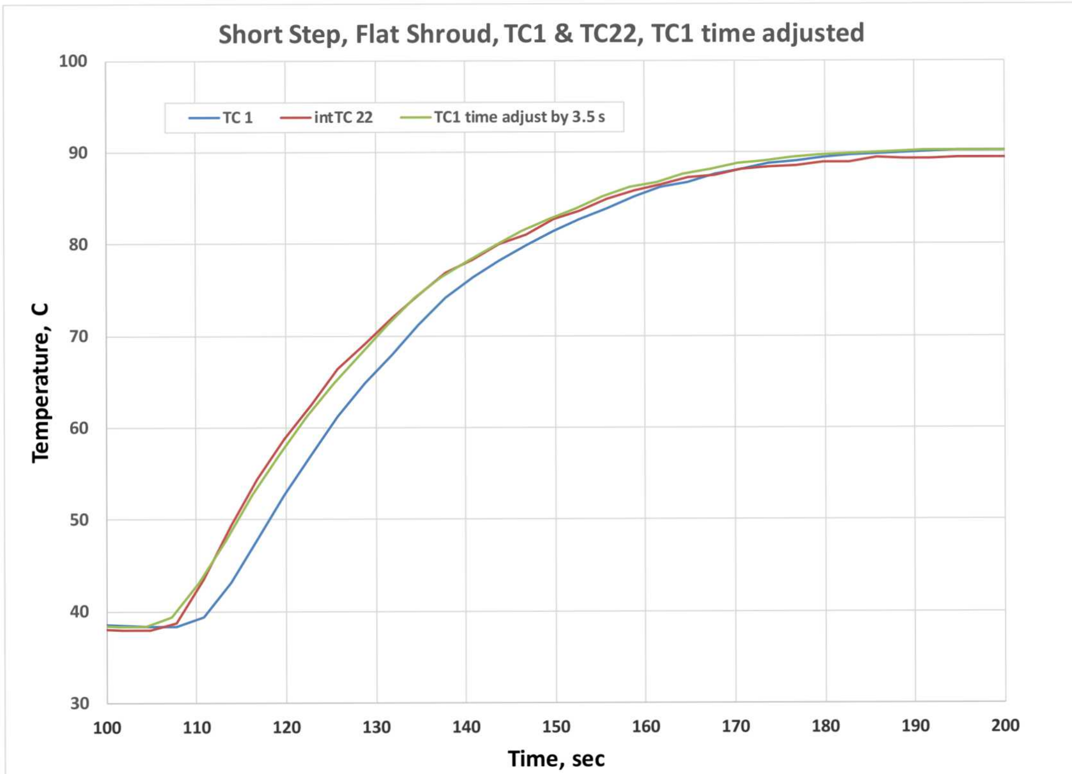

Figure 4-11: Flat shroud, short-step profile, TC1 and TC22, Tau = 3.5 s

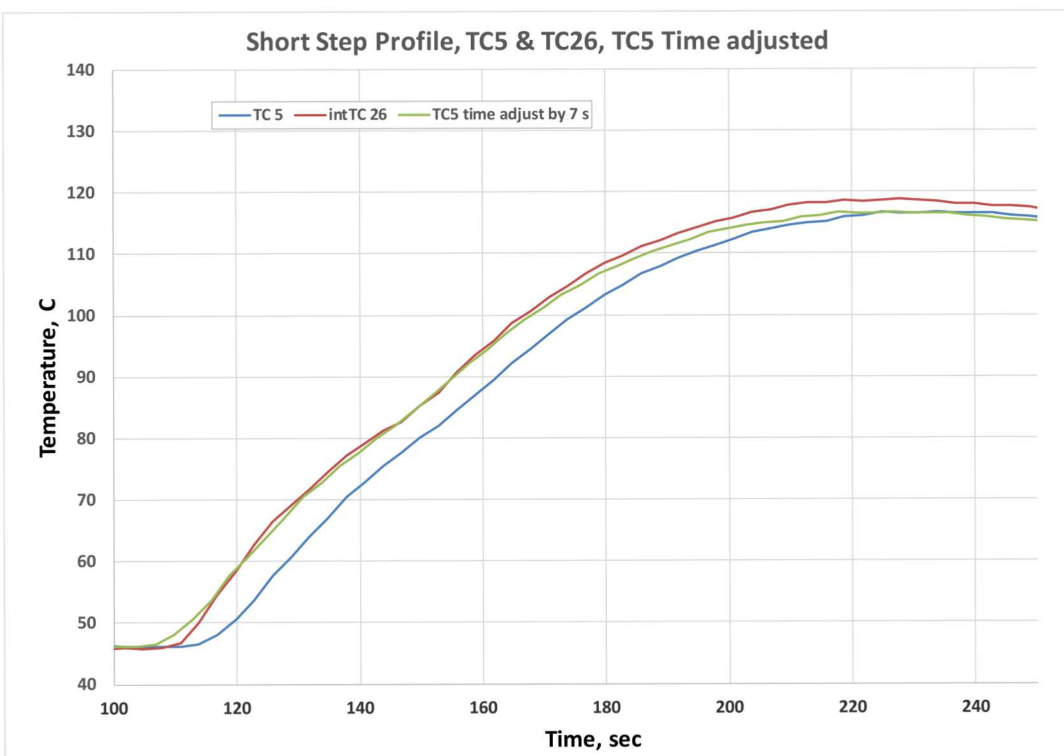

Figure 4-12: Flat shroud, short-step profile, TC2 and TC23, tau = 3.5 s

Table 4-3: Approximate values of the TC time constant (s) for 10 TC pairs, short step profile

TC Pair	Approximate Time Constant, s
TC1 and TC22	3.5
TC2 and TC23	3.5
TC3 and TC24	6.5
TC4 and TC25	4
TC5 and TC26	7
TC6 and TC27	5.5
TC8 and TC29	7
TC9 and TC30	6.5
TC10 and TC31	4.5
Average	***5.4***
Std deviation	***1.4***

From Table 4-3, the time constants from the short step test (avg = 5.4 s) varied by a factor of 2x, but the average was similar to the first 2 data sets. Figure 4-13 shows the temperature adjusted on TC2 & TC23 for the short step profile. As can be seen, the error is reduced.

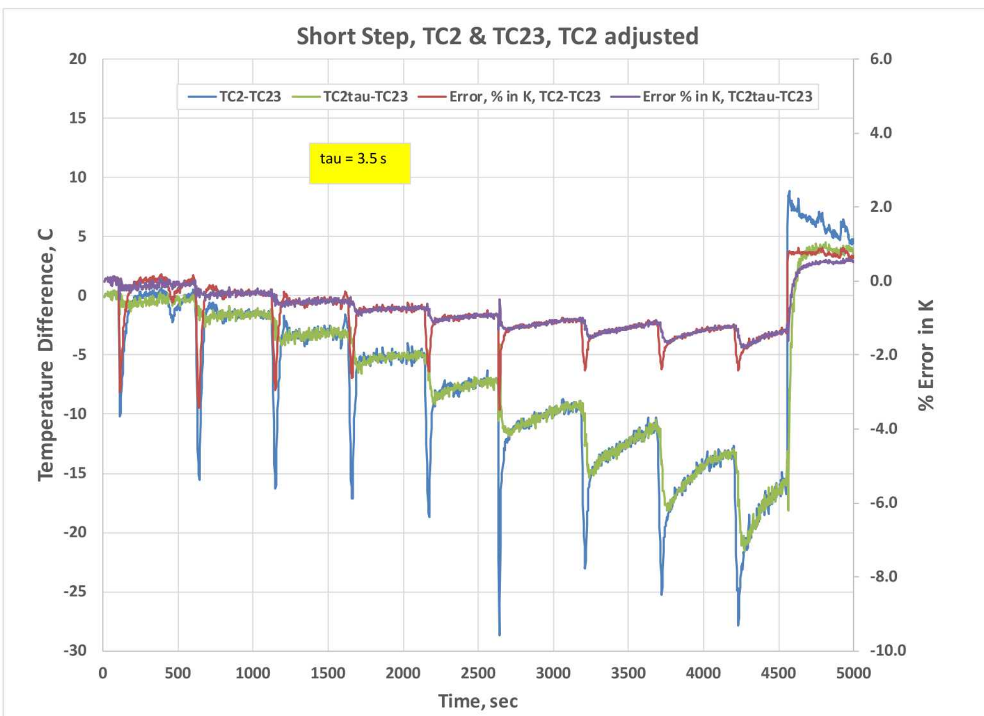

Figure 4-13: Flat shroud, short step profile, TC2 & TC23, TC2 adjusted, tau = 3.5 s

4.4. Cylindrical Shroud, Log-like Profile

Figure 4-14 and Figure 4-15 show nominal shroud temperature data from a test using a cylindrical shroud. The shroud was about 18-in diameter x 48-in tall, and 0.11 inches thick and made from Inconel 600.

Temperatures followed a log-like profile from ambient to a peak of about 925ºC at 40 minutes. The TCs at 12 inches from the bottom (0-12-U) faced the heated portion of the shroud while TCs at 24 inches above the bottom (0-24-U) faced a shroud location above where the lamps were located.

Six pairs of TCs were installed on the inside surface of the shroud, similar to what was done on the flat shroud (62-mil diameter MIMS TCs and 24-gage intrinsic TCs). All MIMS TCs were 0.062-in diameter, but in this case the intrinsic TCs were made from 24-gage fiberglass insulated wire (Figure 2-2), rather than from MIMS TCs with the end of the sheath cut off (exposing the wires). We did not expect the intrinsic TCs to last very long at these temperatures. However, for the first test (data shown is from the first test), the intrinsic TCs survived and seem to have provided good data, except for the TC pair at 0-24. For an unknown reason, the TC pair at 0-24 read almost the same, which was unexpected and cannot be logically explained. Therefore, data from this pair were not included in the results. Note the very slow rise for the first 150-200 s, which results in smaller errors. This was due to warming the lamps at low power before high power was applied. But as soon as the shroud temperature begins to rise faster, the error rises as well.

Figure 4-16 shows errors for all six pairs. Similar to the data from the flat shrouds, the error goes negative early, then rises closer to zero. But in this case, the errors actually rise from negative to positive as the test progresses. The error for almost all of the TCs for most of the test is within ±1%, which is quite good. Nonetheless, an attempt is made to correct the early time readings.

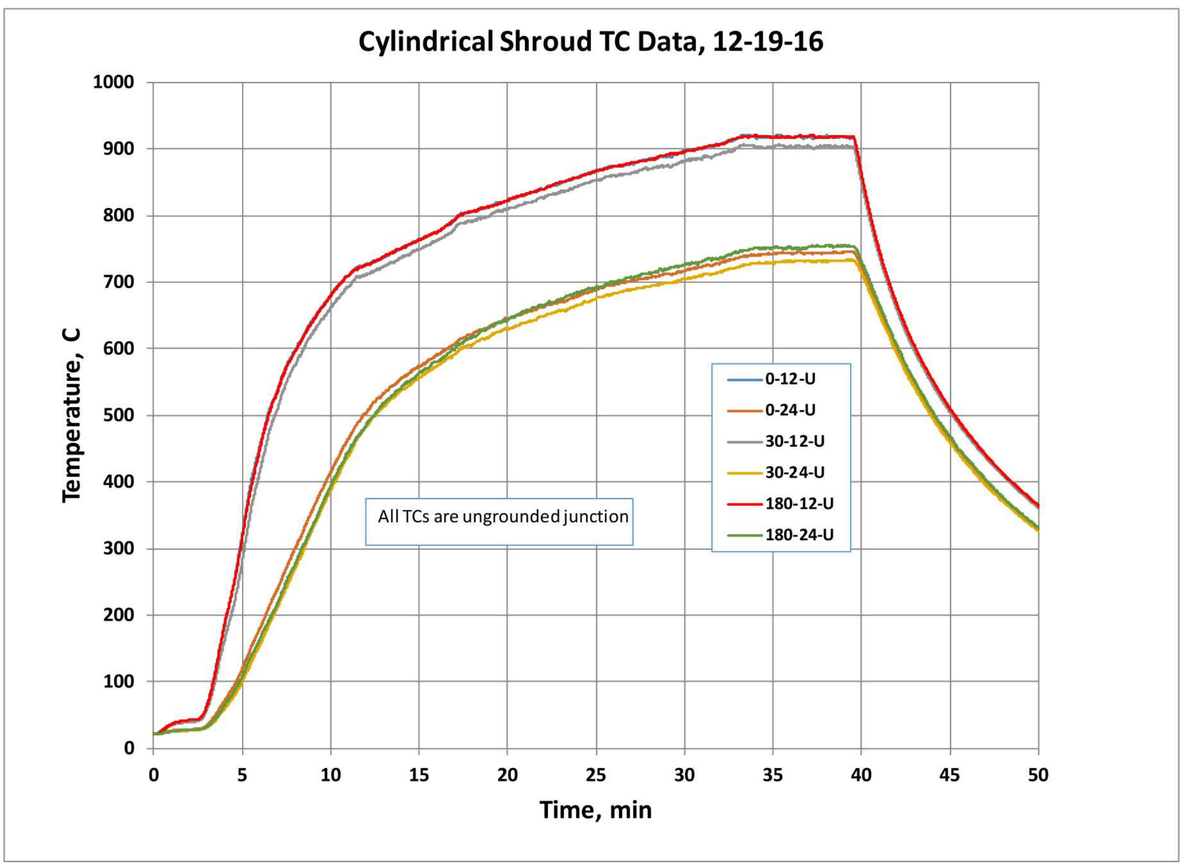

Figure 4-14: Shroud temperature data, cylindrical shroud, UJTCs

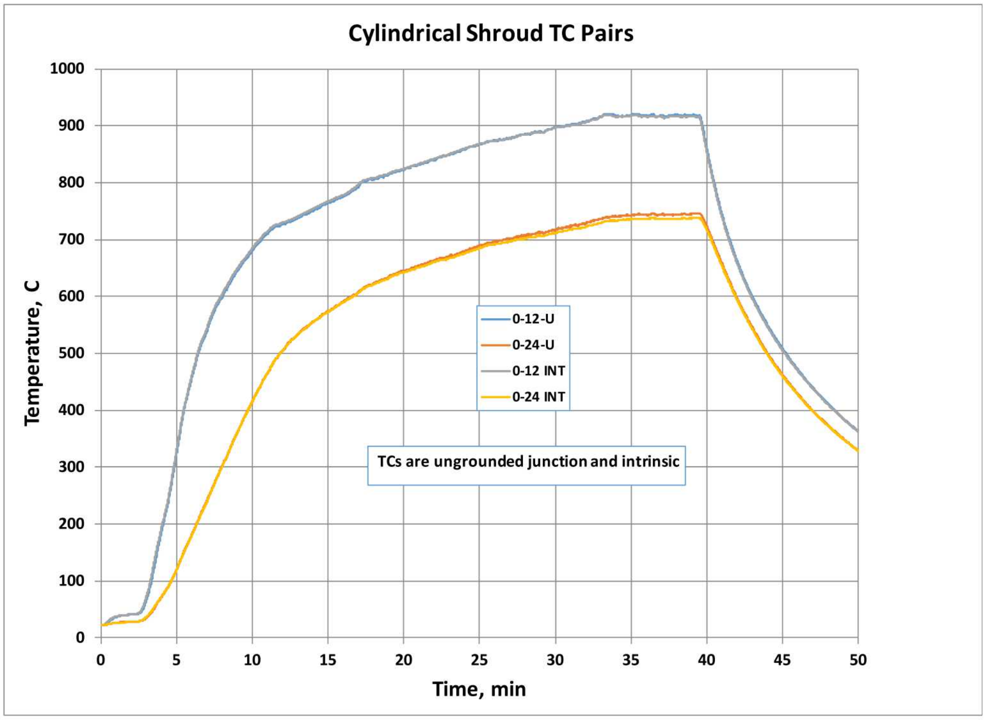

Figure 4-15: Shroud temperature data, cylindrical shroud, UJTCs and IJTCs

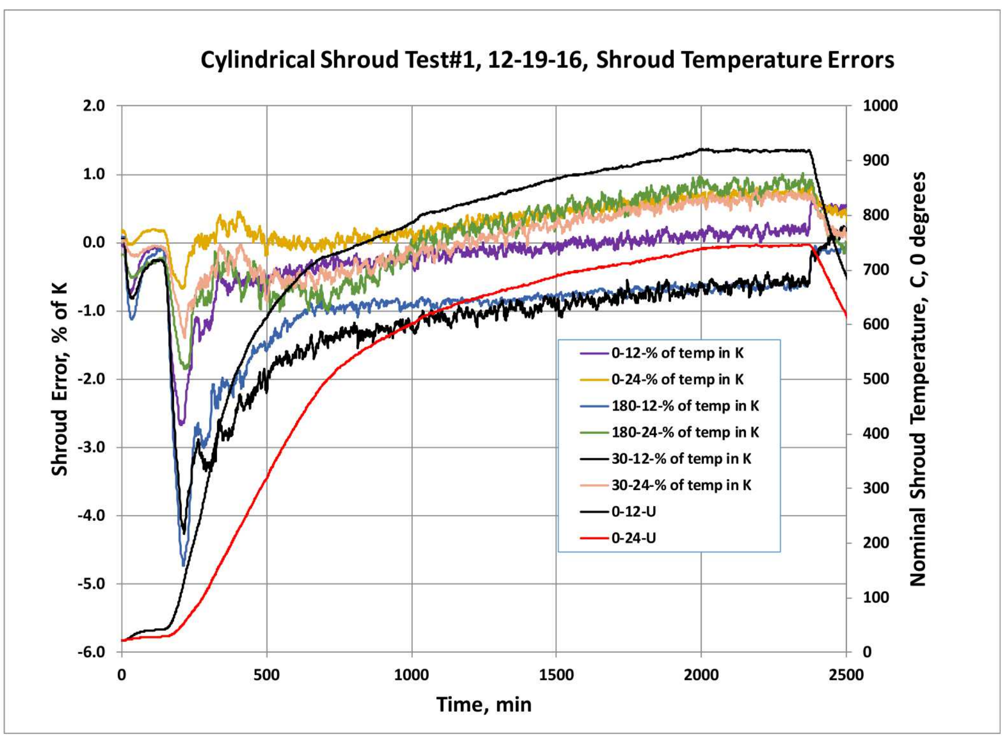

Figure 4-16: All 6 pairs, shroud temperature errors, cylindrical shroud

The same method was used to estimate the time constant. Data were plotted early in the test and the UJTC time was adjusted so that the MIMS TC shifted to the left to coincide with the IJTC data. Figure 4-17 shows the result of this for the TCs at 0-12 (0-12-U and 0-12-int). The time constant in this case is about 2.9 s. The same procedure was used for the remaining pairs (except for 0-24). One pair, 0-24, had the UJTC and IJTC almost the same, as noted above. This can be seen in Figure 4-18.

Table 4-4 shows summary data for the five TC pairs on the cylindrical shroud. The average time constant is 4.7 s with a standard deviation of 1.8 s. This is similar to the results from the previous three data sets.

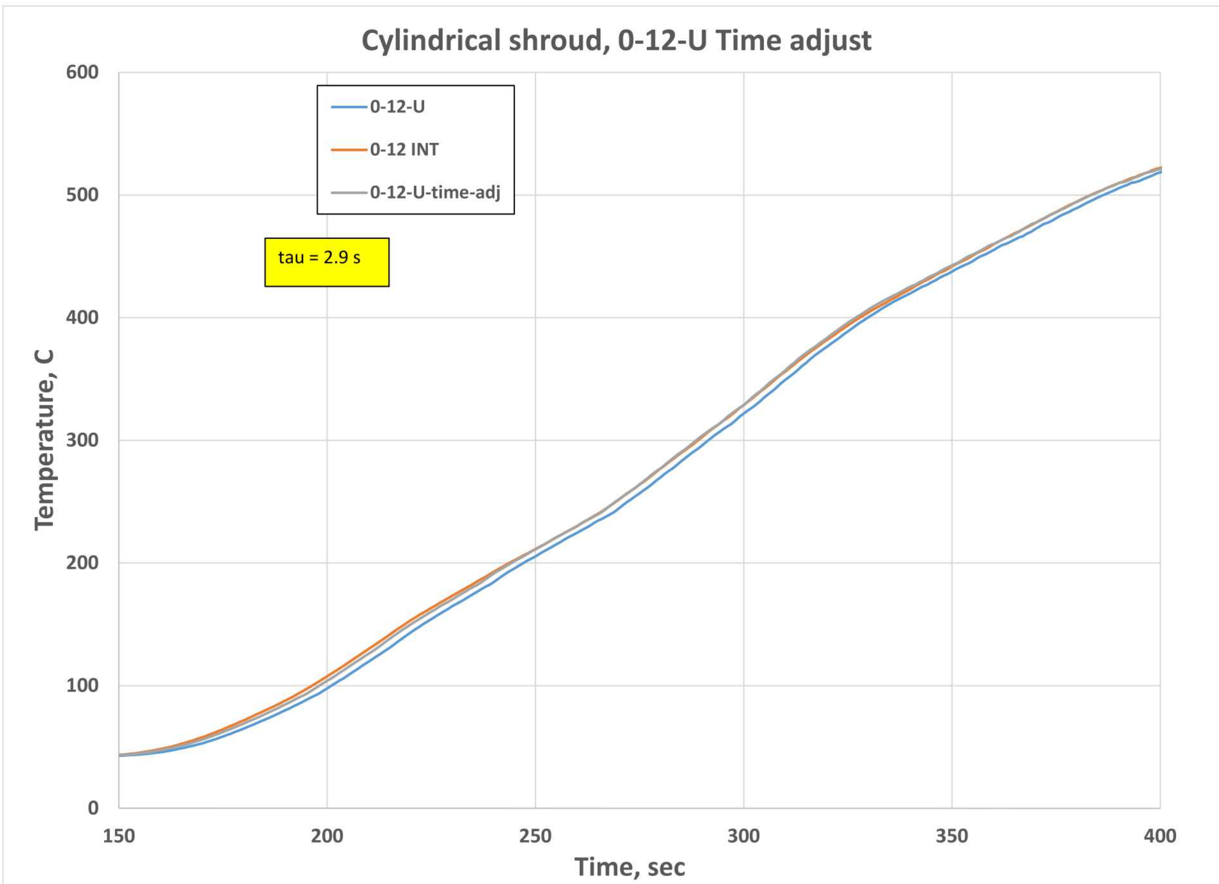

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Figure 4-17: Cylindrical shroud, 0-12 TC pair, UJTC adjusted time by 2.9 sec

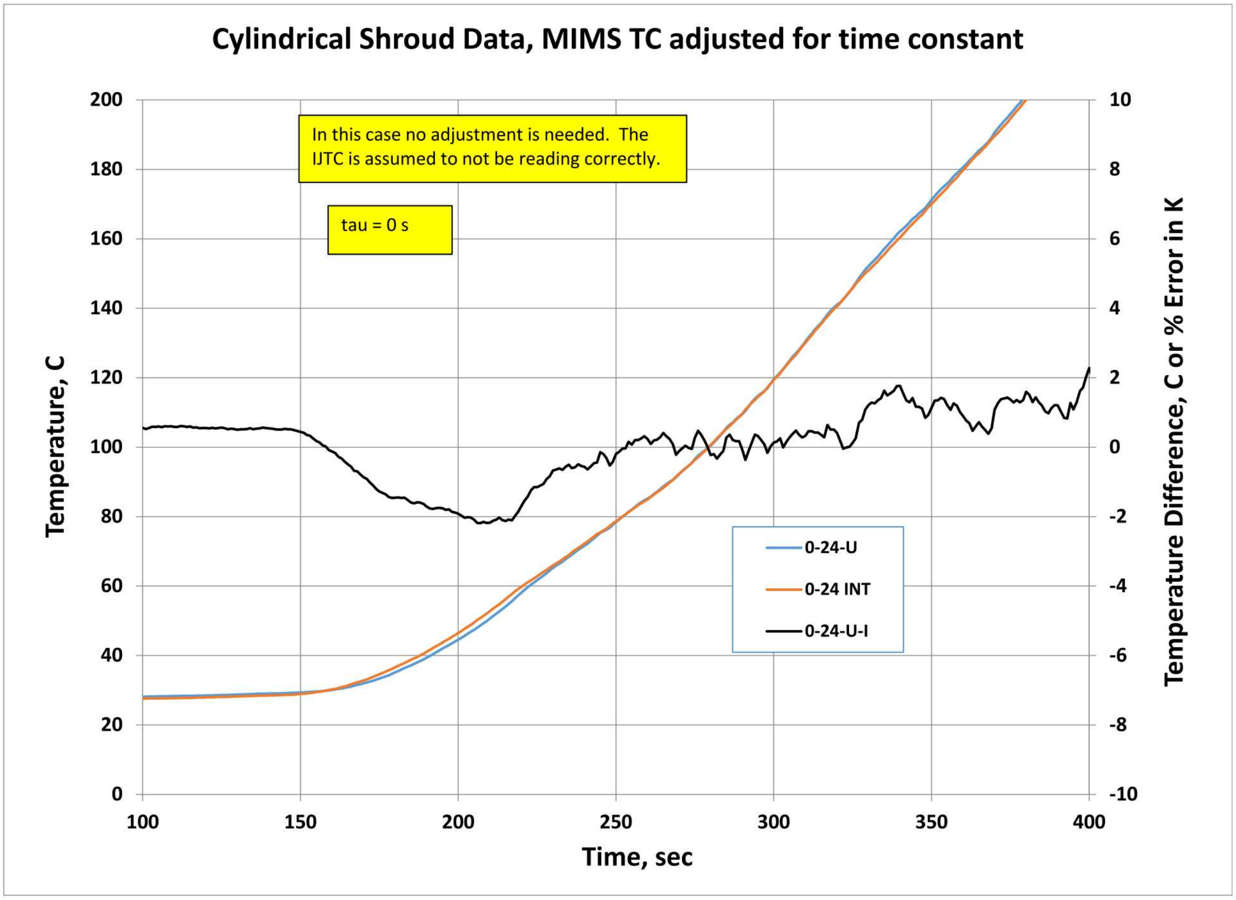

Figure 4-18: Cylindrical shroud, 0-24 TC pair, no adjustment

Table 4-4: Approximate values of the TC time constant (s) for 6 TC pairs, cylindrical shroud, log-like profile

TC Pair	Approximate Time Constant, s
0-12 and 0-12int	2.9
30-12 and 30-12int	6.5
30-24 and 30-24int	3.0
180-12 and 180-12int	6.5
180-24 and 180-24int	4.4
Average	**4.7**
Std deviation	**1.8**

The averages for all data sets span from 4.6-5.4 s, and the standard deviations from 0.9-1.8 s. These data are consistent. The average of all values was 5.04 s. The deviation from the average of all averages is about 5.0 ±9%. Average of all standard deviations is about 1.1 s.

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5. SUMMARY & CONCLUSIONS

1. Four sets of data were analyzed for the time constant of 62-mil diameter ungrounded junction, MIMS TCs mounted on a metal plate.
2. Three data sets were from a flat shroud, one from a cylindrical shroud.
3. The "true" temperature was assumed to be from measurements made by intrinsic junction TCs, even though it is known that IJTCs do not measure the true temperature.
4. The MIMS TCs are used due to their reliability and reasonable cost.
5. A model was developed and solved in a spreadsheet. Qualitative behavior of the model is consistent with experimental results, but due to highly uncertain parameters, quantitative results are not accurate (although the model does predict errors in the same range as observed in testing). For example, estimations of the contact resistance can vary by an order of magnitude or more.
6. The process by which the time constants were approximated was to first adjust the time lag on the UJTC to match, as closely as possible, to the IJTC. This was not very accurate, but the variations from one TC pair to another led the author to believe 2 significant digits was close enough. Some of the time constants varied by a factor of almost 2 on the same test.
7. The process used was to vary the assumed first order time constant until the adjusted MIMS temperature agreed as close as possible to the IJTC.
8. The individual estimated time constants varied from about 3.5-7.0 s. Average values for each test ranged from a low of 4.6 s (long step profile) to a high of 5.4 s (short step profile). But for the four data sets, average values were 5.1 s, 4.6 s, 5.4 s and 4.7 s, reasonably consistent.
9. Standard deviations ranged from a low of 0.9 s to a high of 1.8 s. The average standard deviation was about 1.1 s.
10. The time constant did not seem to vary in a recognizable manner with the time rate of change of the MIMS temperature.
11. **A constant value of about 5.0 s ±9% was estimated from all the data and is recommended for use**. **Alternatively, one can use an average of 5.0 s and standard deviation of 1.1 s.**
12. Flat shroud errors started and stayed as negative throughout the test. Cylindrical shroud errors started negative but rose above zero to slightly positive at the end of the test.
13. Errors in the cylindrical shroud case were lowest of all, and changed from negative to positive as the test progressed. This was due in a large part because the TCs exchanged energy with the opposite side of the shroud, which was at the same nominal temperature.
14. In many cases, it likely does not make sense to perform this correction because the nominal temperatures are so low (e.g., 100-200°C) when the error is greatest, and therefore would not make much difference in radiative heat transfer calculations.
15. However, in other cases [2], the correction is warranted.

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6. REFERENCES

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[6] J. T. Nakos, "Understanding the Systematic Error of a Mineral-Insulated, Metal-Sheathed (MIMS) Thermocouple Attached to a Heated Flat Surface," *Thermal Measurements, The Foundation of Fire Standards, ASTM STP 1427, Editors: L.A. Gritzo and N. Alvarez,* December 3, 2001.

APPENDIX A. PARAMETER ESTIMATION FOR MODEL

Use 1st order correction to approximate the response of a MIMS TC vs an intrinsic tC.								
Analysis:								
Ein-Eout=Estore								
					TC diameter:			
Ein = (Ts-Ttc)*Acontact/Rcontact + emiss(s)*sigma*Fs-tc*As*(Ts^4-Ttc^4)					1/16" diameter	0.0015748	meters	
Eout=emiss(TC)*sigma*Atc*Ftc-envt*(Ttc^4-Tenvt^4)								
Estore = rho*cp*Vtc*(dTtc/dt)								
Ts-Ttc = error between shroud and MIMS TC. Shroud temp is approximated by instrinsic TC.								
Ts-Ttc = ((Rcontact/Acontact)*(emiss(tc)*Atc*sigma*Ftc-envt*(Ttc^4-Tenvt^4)+rho*cp*Vtc*DTtc/dt-emiss(sh)*sigma*Fs-tc*(Ts^4-Ttc^4)))								
Inputs:								
Rcontact:	1	**Rcontact:**						
Acontact		metal to metal						
emiss(tc)					m^2-K/W	m^2-K/W		
Atc		From jeff:	0.1 to 10 cm^2-K/W		0.00001	0.001		
sigma		Data from SS to SS	0.000263	m^2-K/W				
Ftc-envt		Rcontact-SS =	0.000263					
Ttc	2	**Acontact:**	contact area between TC (cylinder) and shroud (flat plate)					
Tenvt		No idea, really						
rho		w/o strap area is very small.	say have +/-10 deg arc where TC is flat enough to contact shroud					
cp		Amin = pi*d*Length = 3.14*0.062"*(20/360) = 3.14*d*Length/18						
Vtc		Amax = W/ strap, say contact area is larger, 1/2 of circumference (neglect other 20 deg) = pi*d*Length*180/360 = pi*d*Length/2						
dTtc/dt		Amin =	0.0002747	x length, m^2				
		Amax =	0.0024724	x length, m^2				
		Aavg=	0.0013736					
	3	**emiss(tc) & emiss(shroud)**						
		Assume strap and TC sheath are both oxidized:						
		emiss(tc) = 0.6 +/- 0.2	0.6					
		emisstcmax = 0.8	0.8					
		emisstcmin = 0.4	0.4					
		emiss(sh), min =	0.6					
		emiss(sh), max =	0.8					
		emiss(sh), avg =	0.7					
	4	**Atc**						
		area=pi*d/2*Length; d = 0.062"	0.0024724	xL, m^2				
		say you re only looking at 1/2 of the circumference						
	5	**sigma = constant = 5.67E-08 W/m^2-K^4**						
			5.67E-08	W/m^2-K^4				
	6	**Ftc-envt = 0.5**	0.5					
		Fs-TC = 0.002	0.002					
	7	**Ttc & Ts**						
		equals MIMS TC measurement (Ttc)						
		equals intrinsic TC measurement (Ts)						
	8	**Tenvt**						
		Tenvt is the temp of the FCU						
		At early times Tenvt - 300K	300	K				
		At late times it is much hotter, say						
		1000K	1000	K				
	9	**Rho (tc) and specific heat of TC**						
		Take a 62 mil TC; cut to known length, weigh it, then estimate density						
	10	**Volume of TC**						
		V = L*pi*(d/2)^2	1.947E-06	xL, m^3				
	11	**Ashroud**						
			1.219	xL, m^2				

TC is a composite of an inconel sheath, cromel and alumel wires, and MgO insulation					
Do an area composite to get approx density and specific heat.		Density, kg/m^3	Specific heat, J/kg-K	Area, in^2	
For inconel (C-750):		8510	435		
For chromel or alumel wires:		8700	485		
For MgO:		3600	923		
From manual on the use of TCs:	D=	0.062	inches		
for sheath diameter = D:					
sheath thickness = 0.16*D	tn =	0.00992			
wire diameter = 0.19*D	dn =	0.01178			
Total area of TC = pi*r^2 =	0.0030175	in^2	1		
Area of sheath = pi*r^2-pi*(r-tn)^2	0.0016222	in^2	0.5376	sheath has 53.8% of total	
Area of 2 wires = 2*pi*(dn/2)^2	0.0002179	in^2	0.0722	wires have 7.2% of total	
Area of insulation = total area-sheath area-wire area	0.0011774	in^2	0.3902	Mgo has 39.0% of total	
Approx of TC density = .538*rho-inconel+0.072*rho-wires+0.390*rho-Mgo	**6609**	**kg/m^3**			
Approx specific heat of TC:	**629**	**J/kg-K**			

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