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Thermocouple Errors when Mounted on Cylindrical Surfaces in Abnormal Thermal Environments

James Nakos, Jill Suo-Anttila, Ethan Zepper, Jerry Koenig, and Vincent Valdez

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Thermocouple Errors when Mounted on Cylindrical Surfaces in Abnormal Thermal Environments

James Nakos, Jill Suo-Anttila, Ethan Zepper, and Jerry Koenig
Fire Science & Technology Department 01532, MS-1135
Sandia National Laboratories
P. O. Box 5800
Albuquerque, New Mexico 87185

Vincent Valdez
ECI Inc., Albuquerque, NM 87108

Abstract

Mineral-insulated, metal-sheathed, Type-K thermocouples are used to measure the temperature of various items in high-temperature environments, often exceeding 1000°C (1273 K). The thermocouple wires (chromel and alumel) are protected from the harsh environments by an Inconel sheath and magnesium oxide (MgO) insulation. The sheath and insulation are required for reliable measurements. Due to the sheath and MgO insulation, the temperature registered by the thermocouple is not the temperature of the surface of interest. In some cases, the error incurred is large enough to be of concern because these data are used for model validation, and thus the uncertainties of the data need to be well documented. This report documents the error using 0.062” and 0.040” diameter Inconel sheathed, Type-K thermocouples mounted on cylindrical surfaces (inside of a shroud, outside and inside of a mock test unit). After an initial transient, the thermocouple bias errors typically range only about ±1-2% of the reading in K. After all of the uncertainty sources have been included, the total uncertainty to 95% confidence, for shroud or test unit TCs in abnormal thermal environments, is about ±2% of the reading in K, lower than the ±3% typically used for flat shrouds. Recommendations are provided in Section 6 to facilitate interpretation and use of the results.
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Support from several NW System teams is also gratefully acknowledged (W88-ALT-370, W88-0, and Mk21/W87).

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NOMENCLATURE

ºC	Degrees Celsius
ID	Inside diameter
IJTC	Intrinsic junction thermocouple
K	Degrees Kelvin
MIMS	Mineral-insulated, metal-sheathed
MgO	Magnesium oxide insulation
OD	Outside diameter
Shroud	Inconel cylinder that acts as a heat source of known temperature
SS	Stainless steel
T	Temperature
TC	Thermocouple
TTC	Thermal Test Complex
Type-K	Chromel-alumel wire pair
UJTC	Ungrounded junction thermocouple

1. INTRODUCTION

High temperature tests (e.g., 1273 K or 1000 °C) are commonly performed at the Thermal Test Complex (TTC) in Tech Area 3, Sandia National Laboratories, Albuquerque, NM. Temperature measurements are required to verify that the test objectives and test environments meet requirements. Temperature measurements are also used for model validation purposes. Frequently, these temperature measurements are used to qualify high-consequence hardware and for model validation of the same hardware. To provide the required pedigree for these data, detailed measurement uncertainties must be provided.

Making accurate measurements at high temperatures is challenging due to a number of issues: thermocouple (TC) reliability in reactive, burning environments from organic materials decomposition, electrical noise from the heat source, and from the construction of the thermocouple itself. The TC wires have to be protected from the environment to provide reliable measurements, which results in a bias error in the measurement. The bias error is due to contact resistance, the MgO insulation or air gap (see below) and the thermal capacitance of the TC.

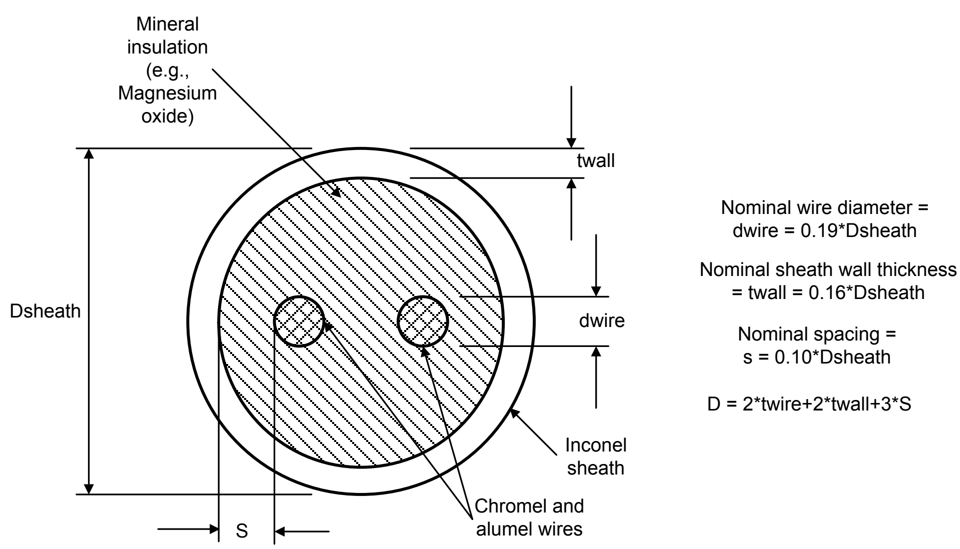
It is important for model validation purposes to accurately measure the temperature of the inside surface of the radiating surface (called the "shroud"), because it forms a critical part of the model used to simulate the response of the test unit. The test unit is mounted inside the shroud. If the measured shroud temperature is in error from the actual inside surface temperature of the shroud by (say) 3%, then the heat flux error is about 12%, or 4 times the temperature error. This is due to the 4th power relationship between temperature and heat flux in a radiative environment. Therefore, a seemingly small error in the temperature measurement (e.g., ±3%) can result in a relatively large error in heat flux (i.e., ±12%).

SAND2004-1023 (ref. [1]) documented the uncertainties in TC measurements in normal and abnormal thermal environments. In that report, it was recommended that the uncertainty in TC measurements in abnormal thermal environments was about ±2-3% in K. For a measurement at 1000 K, the uncertainty was estimated to be about ±20-30 K. Most of that 2-3% came from the bias error of TCs attached to flat shrouds. For normal environments, the estimate was ±1% of the reading in K. The higher value for abnormal environments came directly from SAND2004-5080 (ref. [2]) which analyzed the TC errors on flat surfaces (as opposed to cylindrical surfaces addressed in this report).

We wish to estimate the error incurred when using mineral-insulated, metal sheathed (MIMS) thermocouples (TCs) attached to commonly used cylindrical metal surfaces (Inconel and stainless steel), and to provide guidance to test engineers and thermal analysts. With this information, they can decide if a correction to temperature measurements is required, and/or be better able to accurately quantify the uncertainties in these temperature measurements.

2. BASIC SETUP

Figure 1 shows the basic construction of a MIMS TC, ref. [3]. The outer sheath material is typically Inconel or stainless steel (SS). Inconel is typically used at the TTC because potentially corrosive effects occur when using stainless steel that don't occur when using Inconel. The TC wires are chromel and alumel (Type-K), and the insulation separating the wires from each other and the sheath is high purity magnesium oxide (MgO). At the end of the TC, a junction is formed by welding the 2 wires together to form a "bead" (an almost spherical junction). The end cap on the sheath is then formed to cover the junction. Figure 2 shows a cutaway view of one TC at the junction. The components can be clearly seen (sheath, junction, MgO insulation). Somewhat surprisingly, an air gap was found at the junction. It was expected that the junction would be enclosed in MgO insulation. It is not clear whether this air gap is typical of all TCs, but one can surmise the air gap is difficult to eliminate. When forming the junction and installing the tip of the sheath, it may be difficult to pack the tip with insulation. It is possible that the air gap actually improves the thermal response if the thermal resistance of the air gap is lower than that of the MgO.



Mineral-insulated, metal-sheathed (MIMS) Thermocouple Construction
Source: Manual On the Use of Thermocouples In Temperature Measurement, Fourth Edition, 1993, pg109.

Figure 1: MIMS TC Construction.

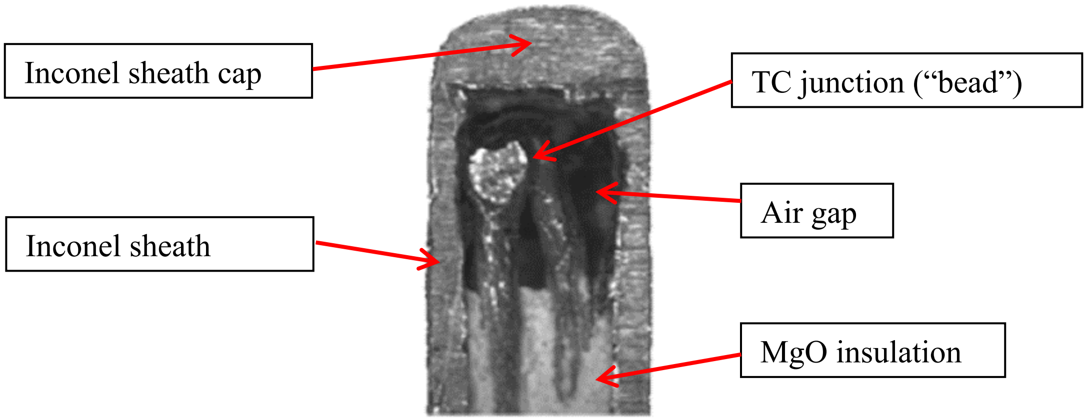


Figure 2: Cutaway View of MIMS TC

TCs of various outside sheath diameters (OD) are made by first assembling the sheath, wires and insulation, then extruding the assembly until successively smaller diameter TC cable is formed. TCs are made with diameters as small as 10 mils and up to about 0.25", but, in our application, the ideal sizes are 0.062" diameter for shrouds and 0.040" diameter for test units (both internal and external TCs) on the mock test unit. These sizes provide a combination of flexibility, thermal response, and reliability. The TCs on the hottest surfaces are typically the largest (0.062"), and those inside the test units are the smallest (0.040"). We infrequently use TCs as small as 0.032" and 0.020" diameter, as they are less reliable.

The best method we've found for attaching TCs to surfaces whose temperature is being measured, is to use a nichrome strap (e.g., 3-5 mil thick x 1/4" wide) "tack" welded over the surface using a capacitive-discharge welder. Figure 3 shows a photograph of a typical installation and Figure 4 shows a sketch of such an attachment, with more detail. One must be careful to weld the strap to the surface, avoiding the sheath, as the sheath can be penetrated during the welding process.

A common setup for radiant heat testing at the TTC is to use lamps to heat an Inconel cylinder of thickness 0.06 to 0.13 inches, while monitoring the temperature of the inside surface. Figure 5 shows a typical setup with a 6-panel lamp array and a mock test unit.

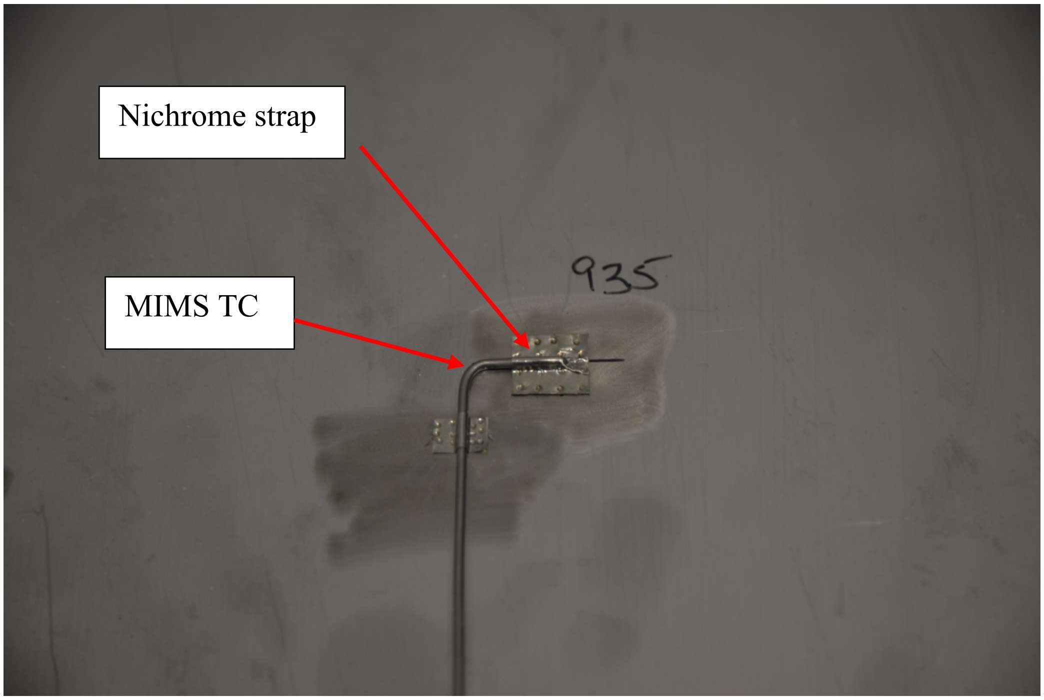


Figure 3: Typical TC Installation on Metal Surface.

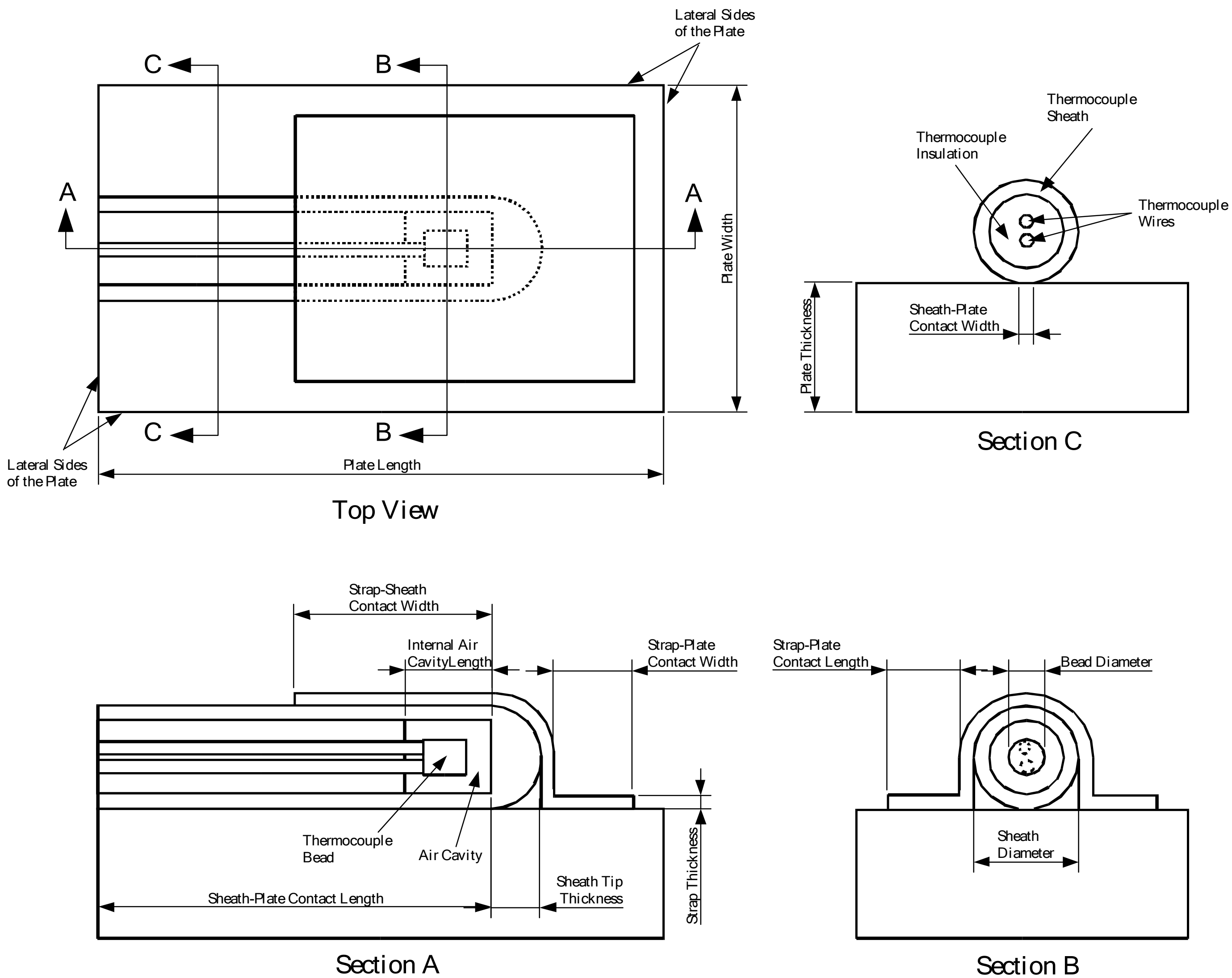


Figure 4: TC Attachment to Metal Plate

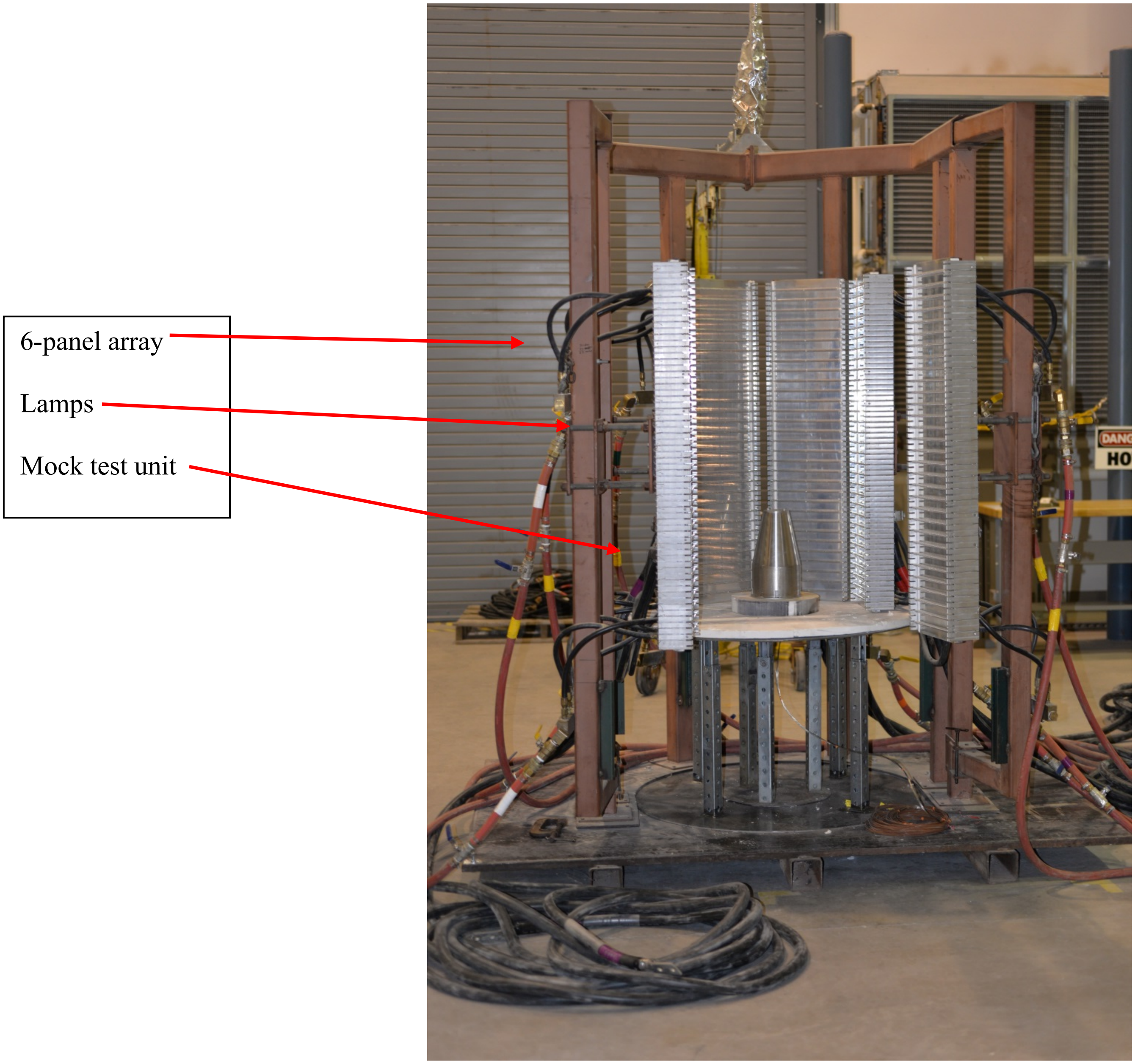


Figure 5: 6-Panel Lamp Array and mock Test Unit.

The shroud (see Figure 6 below) is placed so it surrounds the test unit, inside the lamp panels. It was oxidized from previous testing but not painted black before testing. See Figure 7 for a view with a typical shroud in place.

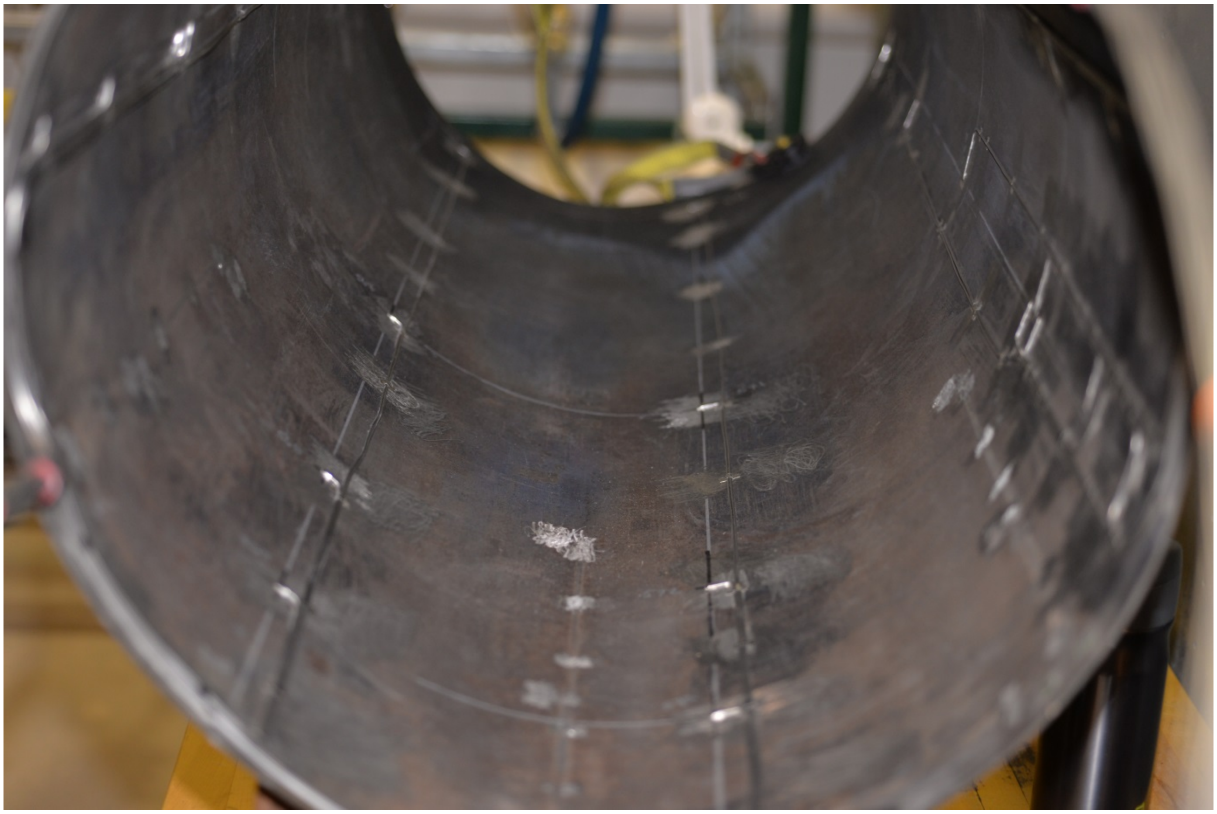


Figure 6. Inside Surface of Shroud with TCs Installed.

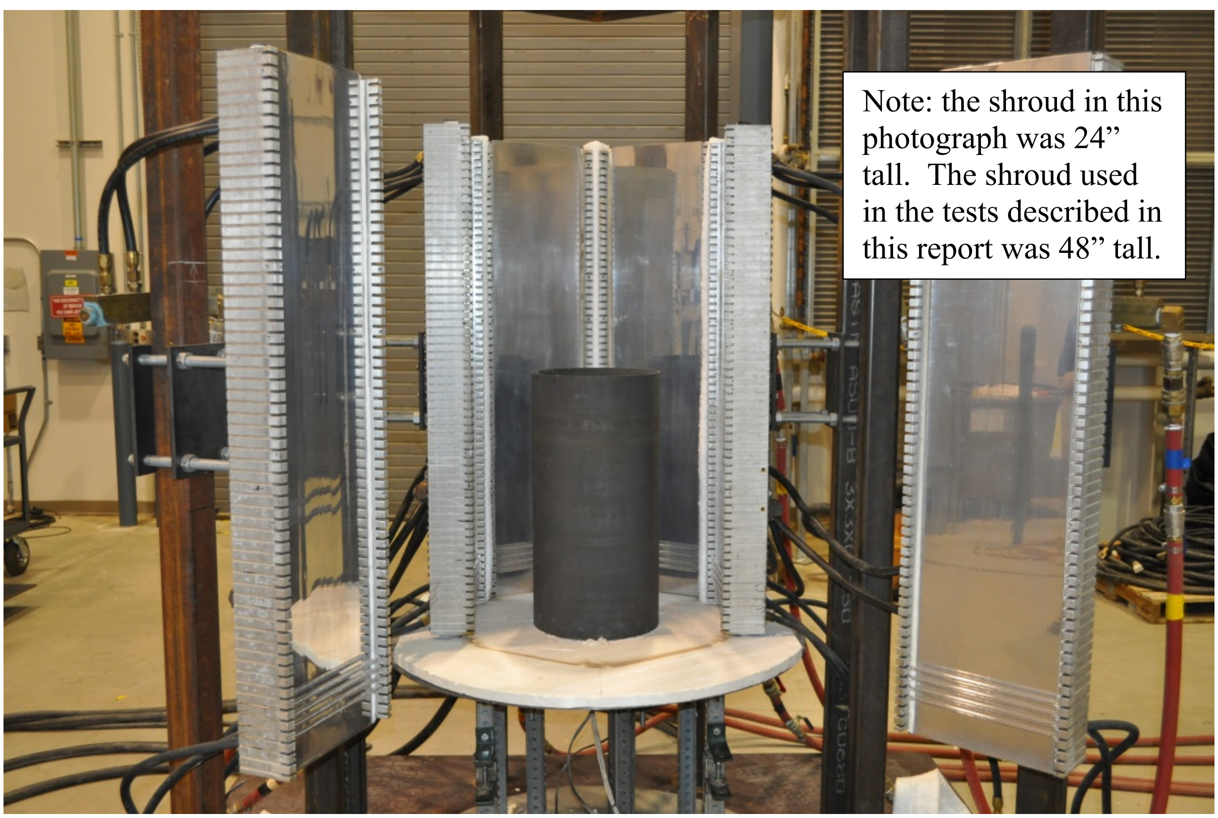
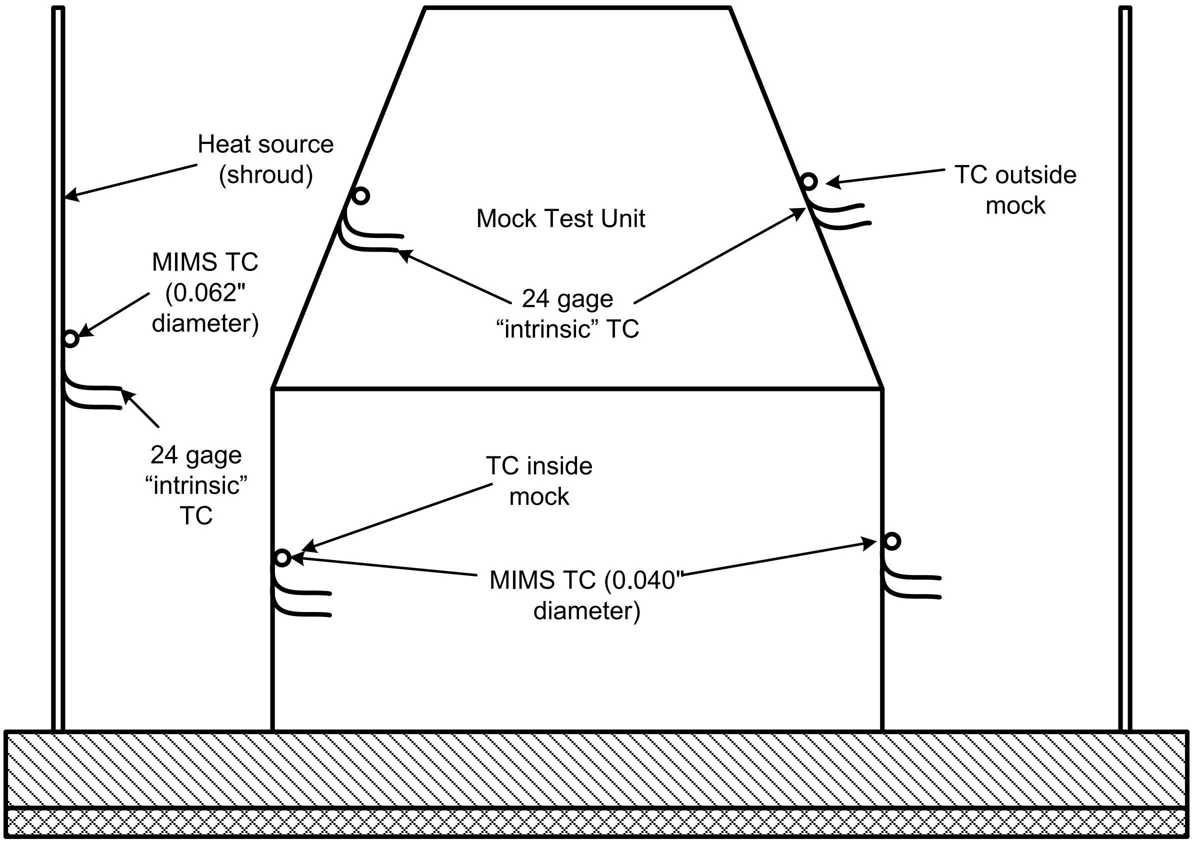
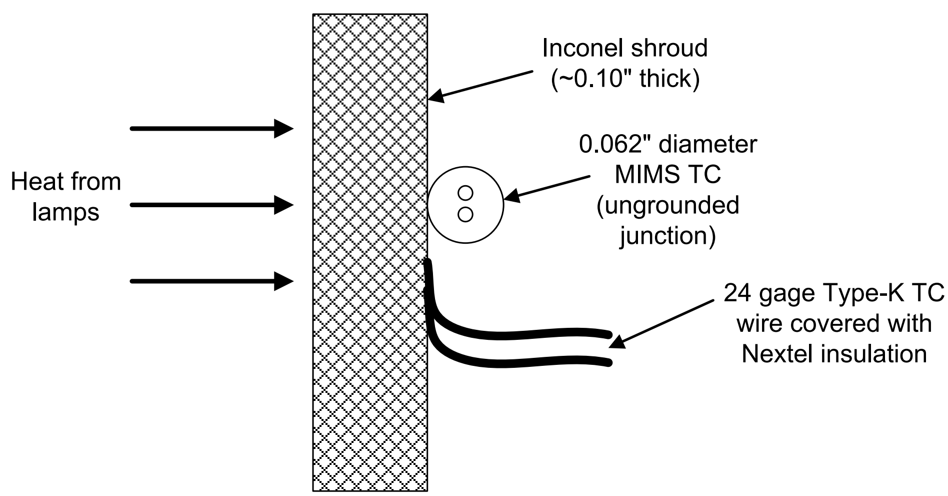


Figure 7. Typical Setup with Shroud in Place



Setup used for MIMS TC Error Analysis



Detailed Schematic of TCs and Shroud

Figure 8: TC Locations on Shroud, External and Internal Surfaces of “Mock”

Figure 8 (upper drawing) shows a sketch of the TC locations used in this report. At several locations, the shroud had 0.062” diameter, ungrounded junction, Type-K TCs attached to the inside surface using the method shown in Figure 3. There were TC pairs mounted on both the outside and inside surfaces of the mock test unit. “Intrinsic” junction TCs made from Type-K wire were mounted as close as possible to the ungrounded junction TC. The intrinsic TCs were made from 24 gage wire covered with high temperature Nextel insulation. Each wire was welded to the surface. See Figure 9 for a typical installation on the outside of the mock unit.

The lower part of Figure 8 shows a more detailed sketch of the a pair of TCs on the shroud. For the data presented here, the shroud was about 0.10” thick. Heat from the lamps originated from the left side; TCs are located on the inside, or unheated side. The ungrounded junction MIMS TC (UJTC) is shown as a circle with the two wires (chromel and alumel) inside. In intrinsic TC is shown as two thick, dark lines. The UJTC is attached via the straps shown in Figure 3; each of the wires that make up the intrinsic junction TC (IJTC) are welded to the inside surface of the Inconel shroud. Figure 9 shows a photograph of a typical pair of TCs (UJTC and IJTC).

Figures 10 and 11 show a top view of the setup (Figure 10) and a side view of the mock test unit (Figure 11). The base of the mock test unit was not painted, but the cone was painted with black paint. Figures 10 and 11 are for the actual setup used in these tests.

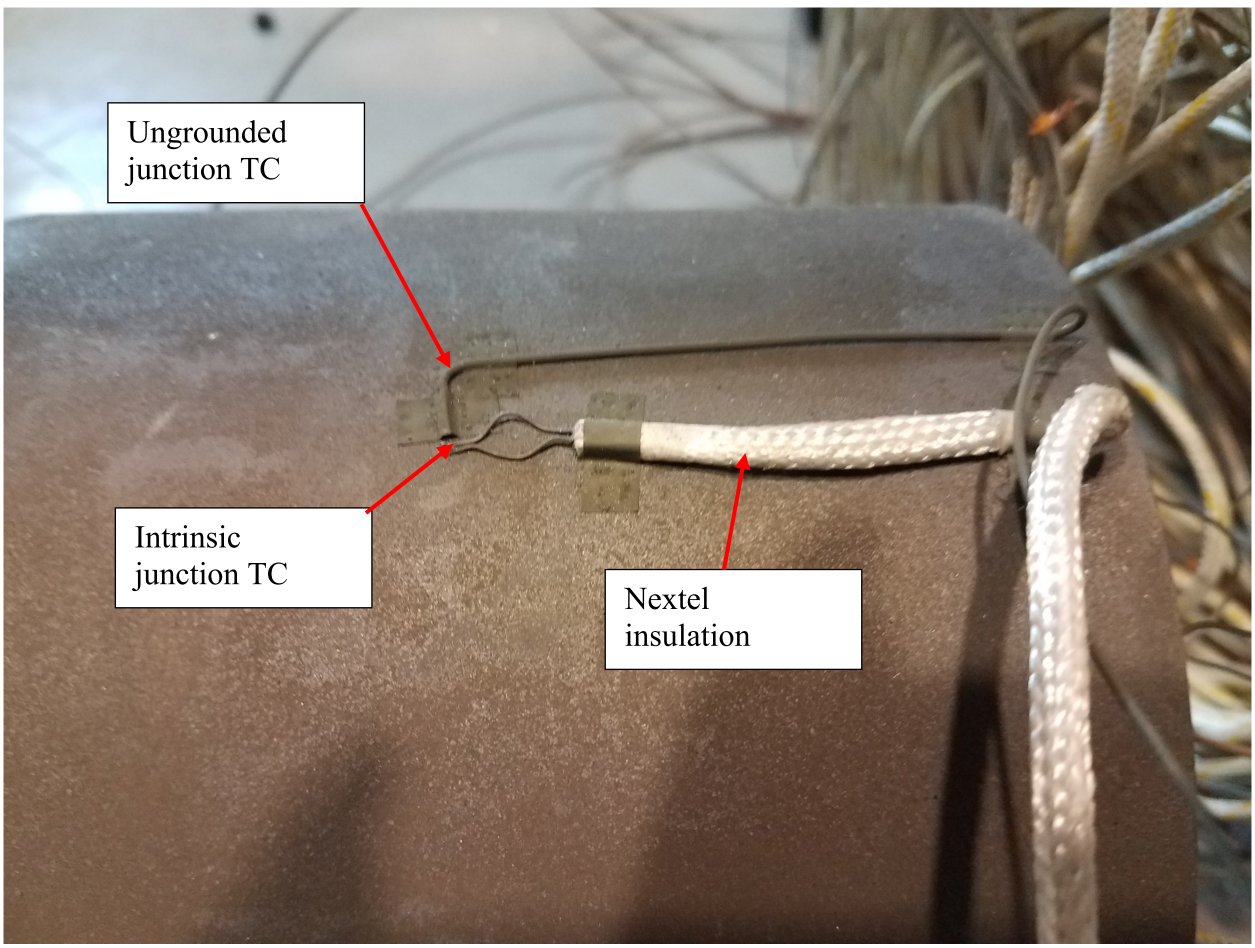


Figure 9: Typical TC Installation Pair (Ungrounded Junction and Intrinsic TCs)

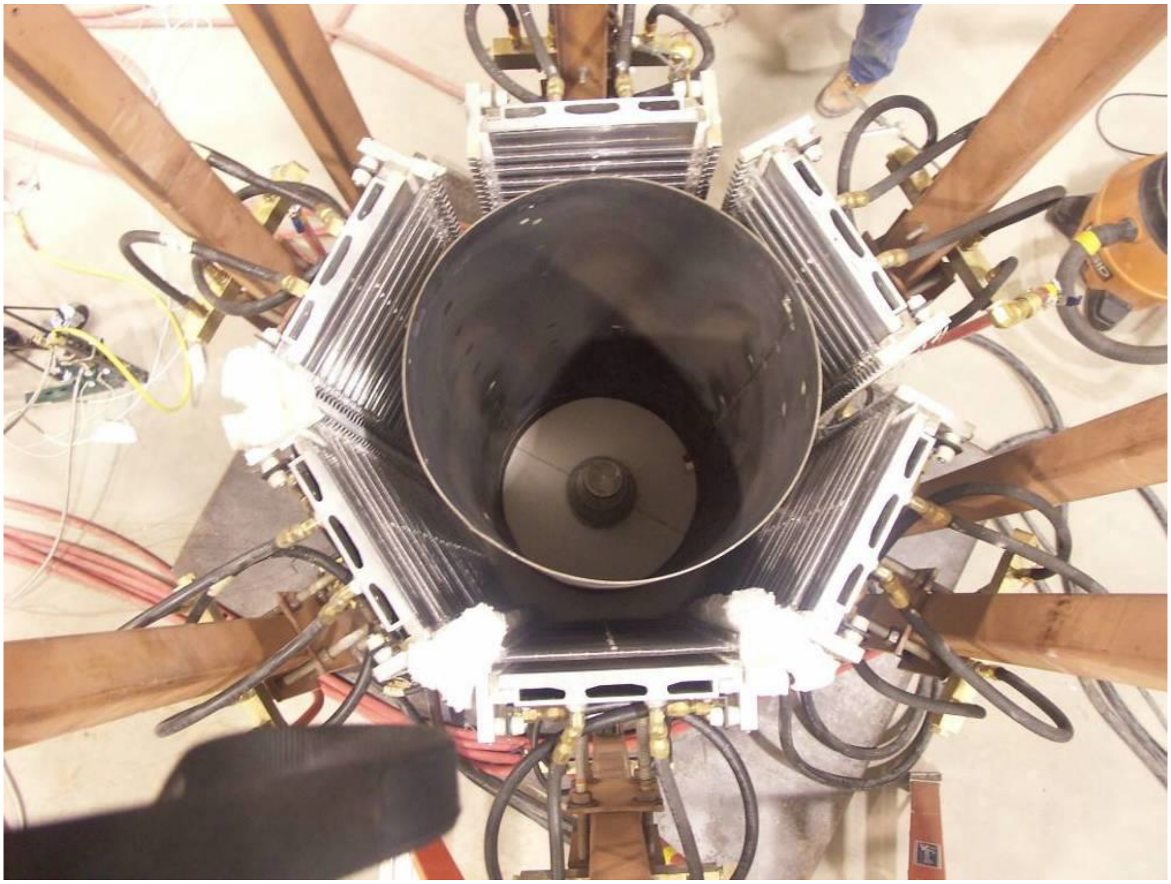


Figure 10: Top View of Setup, Including the Inconel Shroud

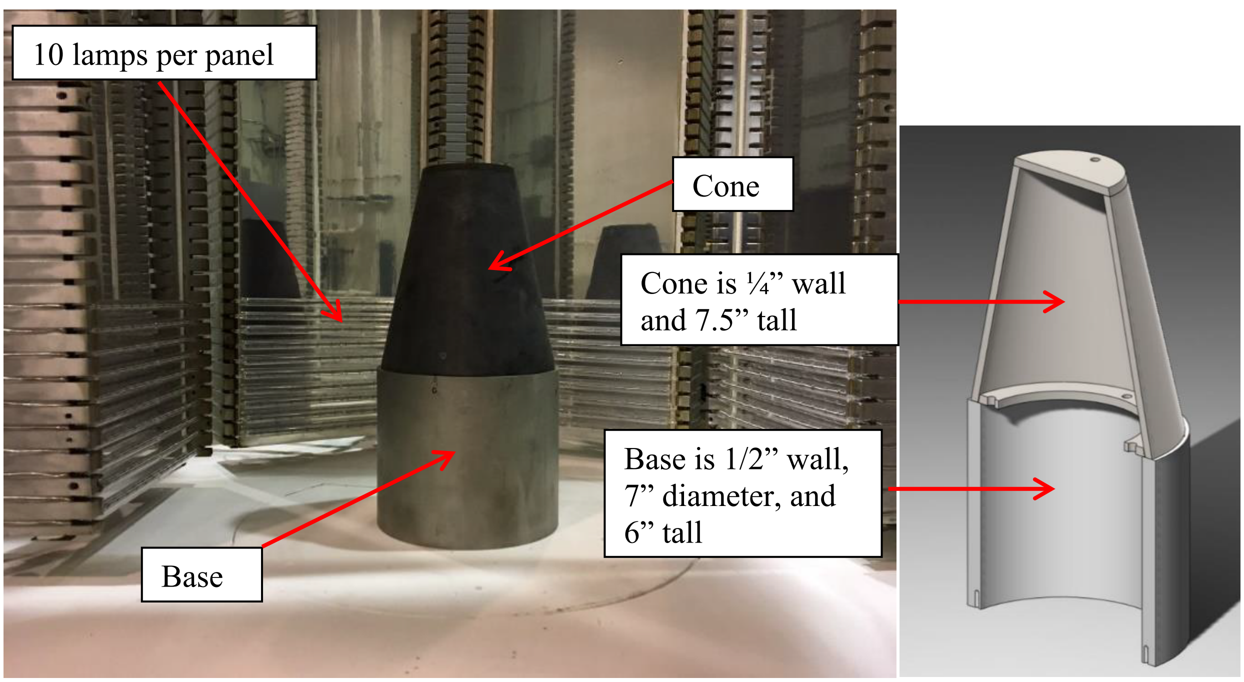


Figure 11: View of Mock Unit with the Inconel Shroud Removed

3. INSTRUMENTATION

There were additional TCs on the shroud and test unit that will not be discussed here. We only focus on locations on the shroud and the test unit that had pairs of TCs because we are looking to quantify the error, and that is only possible by using pairs of TCs. One was a 0.062" or 0.040" diameter ungrounded junction MIMS TC (UJTC) and the other a 24 gage "intrinsic" junction TC (IJTC). An intrinsic TC is formed by individually welding the chromel and alumel wires to the metal surface. In this approach, a TC is formed with the surface material as part of the electrical circuit; the surface is an "intrinsic" part of the thermocouple. It is believed that intrinsic TCs are the most accurate method (of the available options) in high temperature environments. However, IJTCs are not often used because they generally have poor reliability.

We note that we did not use grounded junction MIMS TCs. In past testing with high voltage power sources (typical of radiant heat tests) there have been serious grounding issues that have resulted in poor temperature measurements when using grounded junction TCs. Therefore, we typically do not use grounded junction MIMS TCs.

Table 1 provides a list of the TC pairs on the shroud and the mock unit. There were 6 pairs on the shroud, 4 pairs on the external surface of the mock test unit, and 5 pairs on the inside of the mock test unit.

Calibrations of the TCs used in this report was not performed, because it is known that just the process of calibrating Type-K TCs above 320°C changes the properties of the chromel and alumel wires, ref. [4]. We therefore assume the ASTM specifications apply for type K TCs: ±2ºC or 0.75% of the reading in C, whichever is greater.

In addition, there are a number of other sources of uncertainty that are possible other than the bias error (e.g., TC wire accuracy, voltage to temperature conversion polynomial, common mode errors, electrical noise, channel cross-talk, etc.) The interested reader should refer to ref. [1] for more details.

Table 1: Pairs of TCs on Shroud and Mock Unit

Mounted on	Location	MIMS TC	Intrinsic TC	Comments
Shroud	0 deg., 12"	0.062" dia., ungrounded junction, Inconel sheath, Type-K	24 gage, Type-K, Nextel insulation cover.	
Shroud	0 deg., 24"	0.062" dia., ungrounded junction, Inconel sheath, Type-K	24 gage, Type-K, Nextel insulation cover.	
Shroud	180 deg., 12"	0.062" dia., ungrounded junction, Inconel sheath, Type-K	24 gage, Type-K, Nextel insulation cover.	
Shroud	180 deg., 24"	0.062" dia., ungrounded junction,	24 gage, Type-K, Nextel insulation	

Mounted on	Location	MIMS TC	Intrinsic TC	Comments
		Inconel sheath, Type-K	cover.	
Shroud	30 deg., 12”	0.062” dia., ungrounded junction, Inconel sheath, Type-K	24 gage, Type-K, Nextel insulation cover.	
Shroud	30 deg., 24”	0.062” dia., ungrounded junction, Inconel sheath, Type-K	24 gage, Type-K, Nextel insulation cover.	
Mock unit outside	Base, 0 deg., 3” up from bottom	0.040” dia., Type-K ungrounded junction, Inconel sheath	24 gage, Type-K, Nextel insulation cover.	
Mock unit outside	Cone, 0 deg., 3” down from top	0.040” dia., Type-K ungrounded junction, Inconel sheath	24 gage, Type-K, Nextel insulation cover.	
Mock unit outside	Cone, 90 deg., 3” down from top	0.040” dia., Type-K ungrounded junction, Inconel sheath	24 gage, Type-K, Nextel insulation cover.	Intrinsic failed on 1-18-17 test, repaired for next test
Mock unit outside	Base, 180 deg., 3” up from bottom	0.040” dia., Type-K ungrounded junction, Inconel sheath	24 gage, Type-K, Nextel insulation cover.	
Mock unit inside	Cone, 0 deg., 3” down from top	0.040” dia., Type-K ungrounded junction, Inconel sheath	24 gage, Type-K, Nextel insulation cover.	
Mock unit inside	Base, 0 deg., 3” up from bottom	0.040” dia., Type-K ungrounded junction, Inconel sheath	24 gage, Type-K, Nextel insulation cover.	
Mock unit inside	Cone, 90 deg., 3” down from top	0.040” dia., Type-K ungrounded junction, Inconel sheath	24 gage, Type-K, Nextel insulation cover.	
Mock unit inside	Base, 180 deg., 3” up from bottom	0.040” dia., Type-K ungrounded junction, Inconel sheath	24 gage, Type-K, Nextel insulation cover.	Questionable data for several tests.
Mock unit inside	Base, 270 deg., 3” down from top	0.040” dia., Type-K ungrounded junction, Inconel sheath	24 gage, Type-K, Nextel insulation cover.	Questionable data for several tests.

Table 2 provides some detail on the tests performed in support of this effort.

Table 2: Test Matrix

Test#	Test Date	Differences
1	12-14-16	Same shroud profile for all 4 tests; fast temperature rise began at about 2-3 minutes.
2	1-12-17	Fast rise began at about 1 minute on plots.
3	1-18-17	Fast rise began at about 2-3 minutes on plots.
4	1-19-17	Fast rise began at about 2-3 minutes on plots.

4. RESULTS

4.1 Test#1

Test #1 did not have any TC pairs on the mock unit, so only shroud TC data are presented. Figure 12 shows the shroud temperatures from only UJTCs on the locations shown in Table 1.

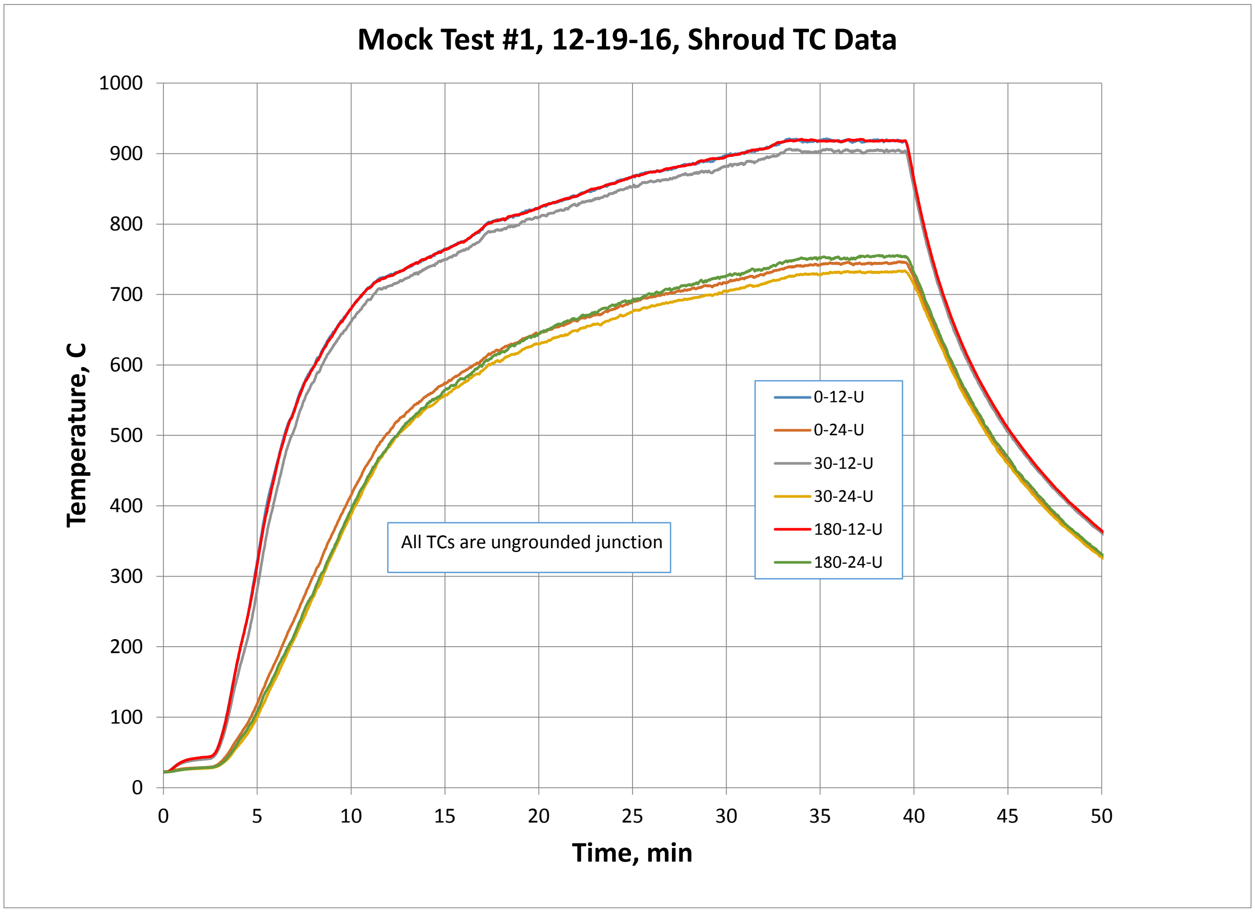


Figure 12: Shroud TC Data, Mock Test#1

From Figure 12 one can see that the six shroud TCs are grouped into two temperature ranges. The TCs at 24" above the bottom measured lower temperatures than the ones at 12". The reason for this was because the shroud was heated only in the lower part. There were only 10 lamps per panel, and so the shroud temperature dropped off fast above the highest lamp (see Figure 11). The three TCs in each height group responded in a similar manner. The small differences in each grouping are due to slight differences in the shroud temperature.

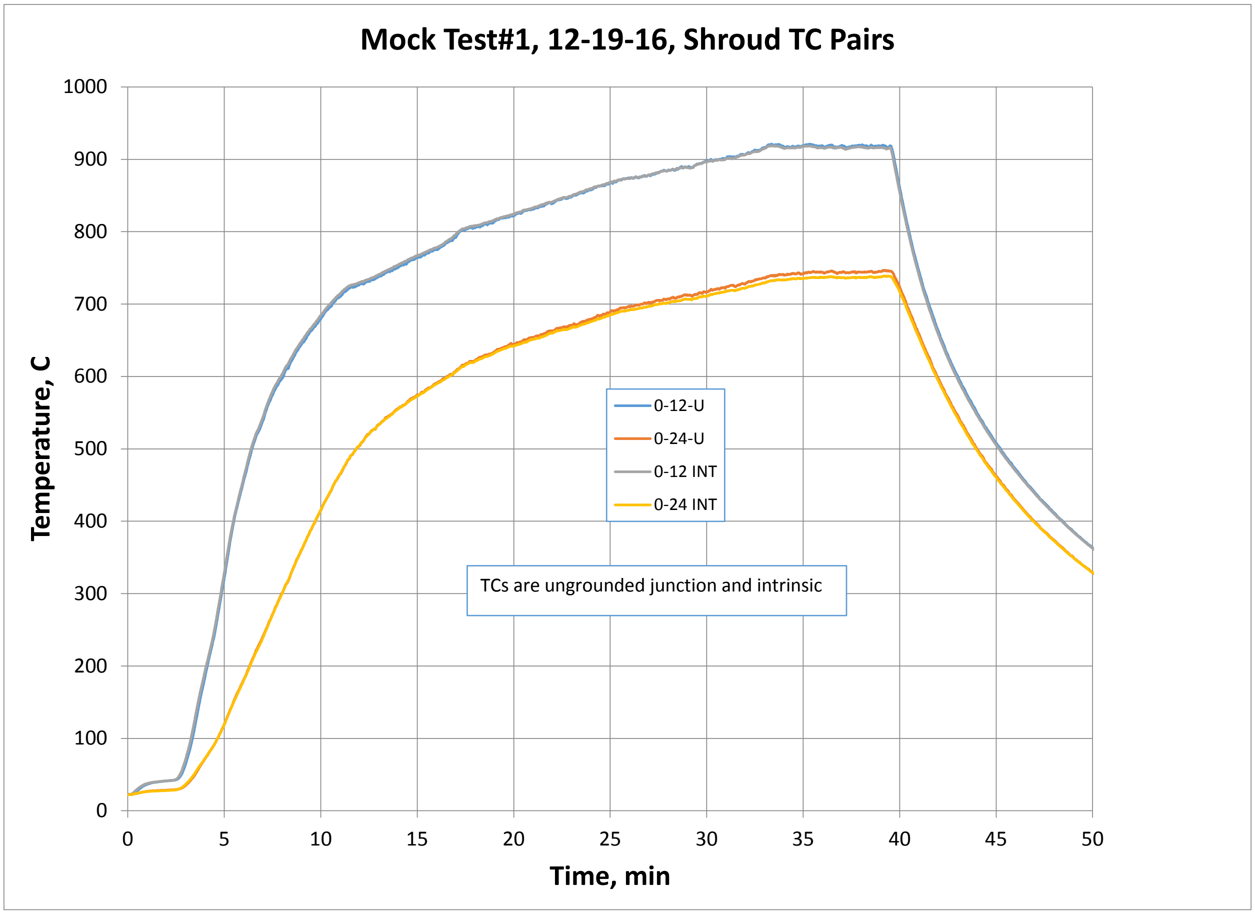


Figure 13: Mock Test#1, Shroud TC Data from Pairs at 0 degrees

Figure 13 shows two typical pairs (12" and 24") of TCs at 0 degrees on the shroud. It is evident from Figure 13 that the two pairs of TCs respond almost identically, as expected.

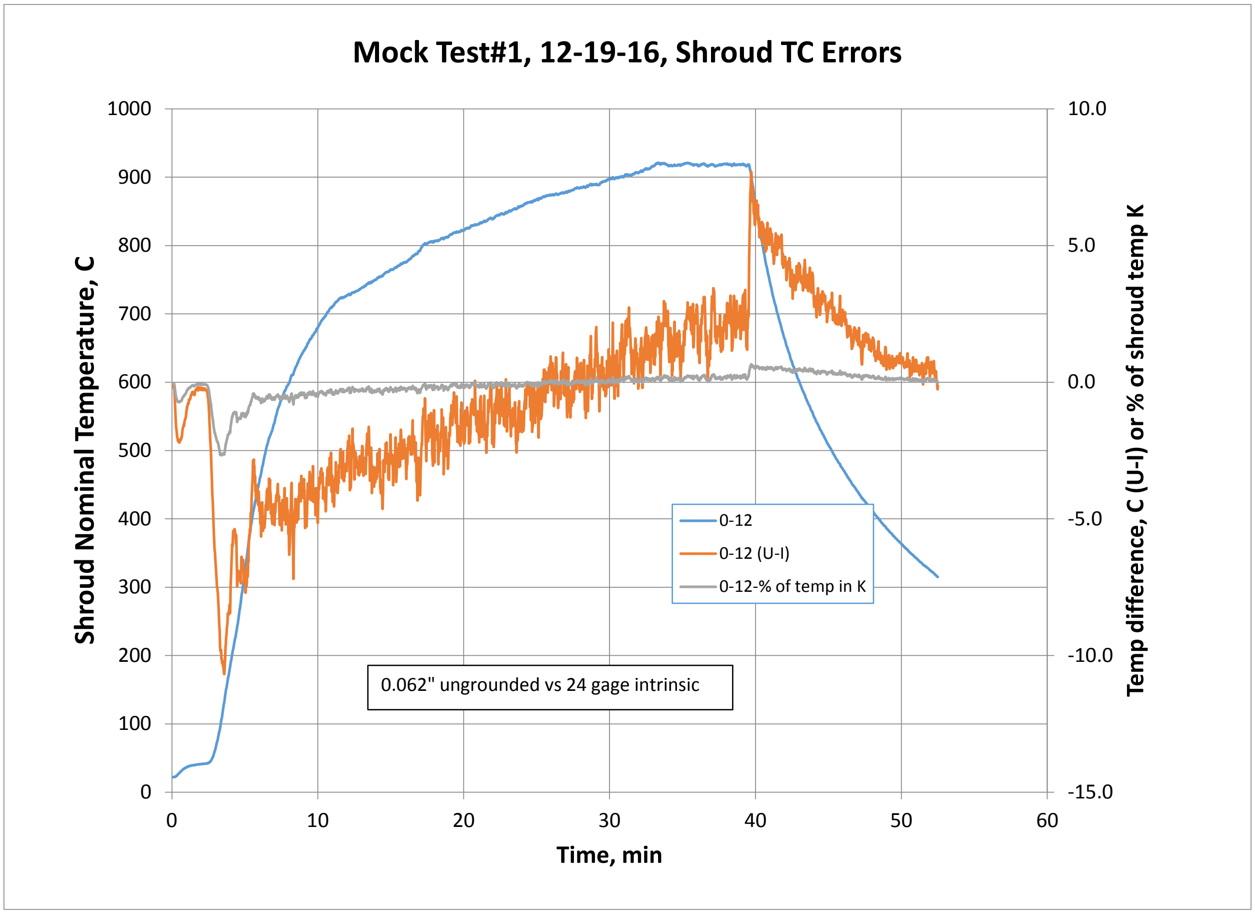


Figure 14: Mock Test#1, Shroud Data, 0 degrees 12"

Figure 14 shows the data from one pair of TCs (0 degrees and 12"). For the TC pair shown, the nominal temperature from the UJTC is shown as well as the difference between the ungrounded and the intrinsic (intrinsic subtracted from the ungrounded) and the % error in K (difference divided by UJTC).

For the first 30 minutes of the test, the difference (UJTC-IJTC) is negative, which means the IJTC reads higher than the UJTC. After about 30 minutes, the UJTC reads higher than the IJTC. The test ends at about 40 minutes.

The reason why the IJTC reads higher than the UJTC in the first 30 minutes is at least partially explained by reviewing the lower sketch in Figure 8. Heat has to penetrate through the shroud and into the UJTC before reaching the chromel and alumel wires. There is contact resistance between the shroud and the sheath and resistance between the sheath and the wires due to the air gap – see Figure 2. There is also thermal capacitance that slows the response. Compared to the UJTC, the IJTC has less thermal resistance (lower thermal contact resistance, no sheath, no air gap). Thus, the difference is negative early in the test.

The difference between the response of the UJTC and the IJTC lessens with time. This is likely due to several reasons. One reason is that the shroud radiates to itself, so the UJTC (and IJTC) both receive heat from multiple directions. Another reason is the drop in temperature rate-of-change (the "ramp rate") as the test progresses. The error crossing zero could be a constant positive offset in the TC calibrations.

The % error in K, shown as the gray line, is always less than about ±2.5%, and, after about 6 minutes, is always less than about ±1%.

Other shroud TC pairs respond in a similar manner but with different magnitudes. All shroud TC pairs are shown in Figure 15. Four of the six pairs had errors less than ±1% after about 5 minutes. Two of the six pairs (30-12 and 180-12) took longer for the error to drop below 1% (about 20 minutes).

Note that in Figure 15, all 3 pairs at 24" had smaller errors than the 3 pairs at 12". Reasons for this difference are 1) the pairs at 24" were above the top of the mock unit while the TCs at 12" faced the cone of the mock unit, and 2) the temperature gradient was significantly steeper at 12" than at 24".

The mock unit was about 13.5" tall. The shroud TCs are affected by the presence of the mock unit because it acts as a heat sink. Also, the TCs at 24" have more exposure from the other sides of the shroud, but a lower heating rate because the 10 lamps per panel were concentrated at the bottom of the shroud.

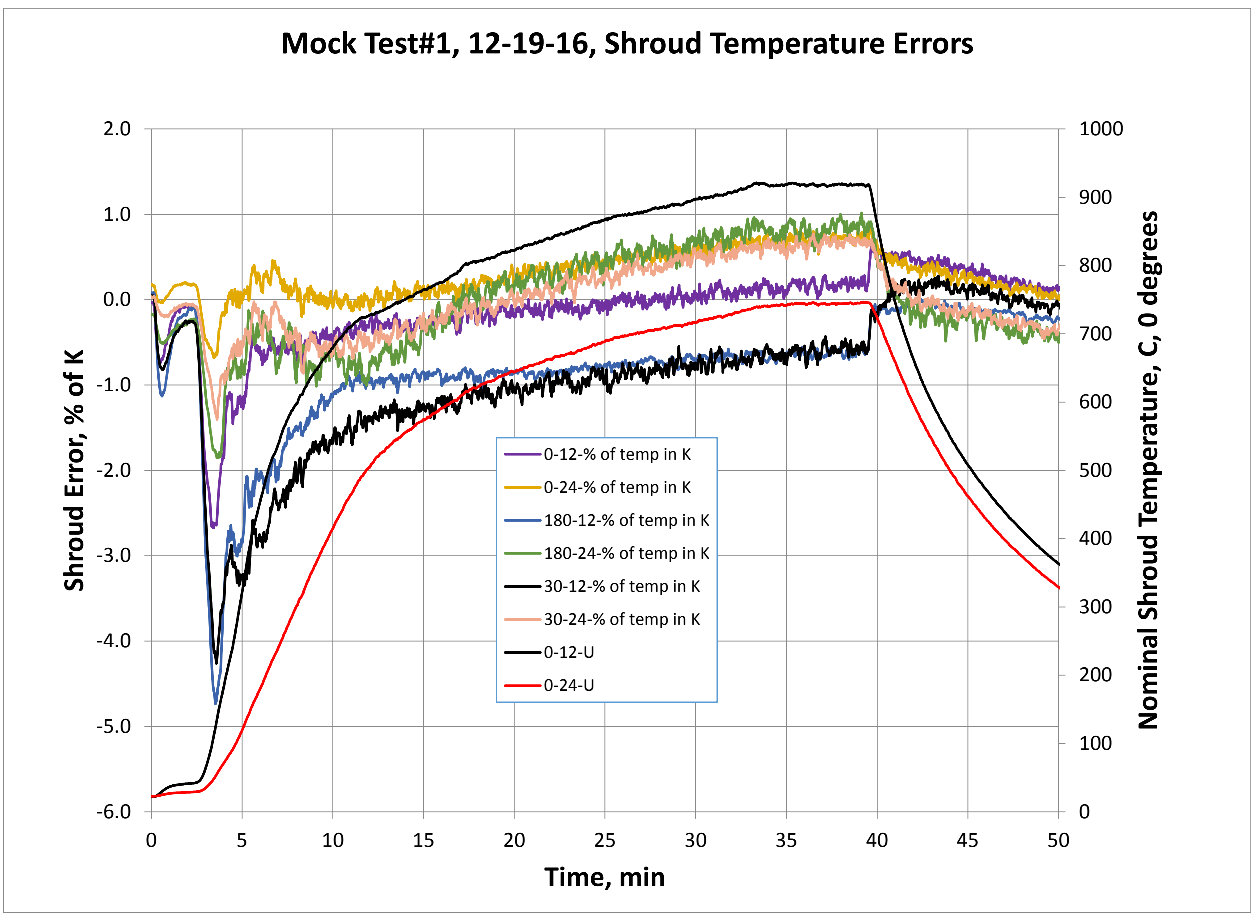


Figure 15: Mock Test#1 All Shroud TC Pair Errors

The 3 pairs at 12" had the largest error early in the test. The 12" location maximum errors ranged from about -2.6% to -4.7% at about 3.4 minutes and a nominal shroud temperature of only about 120 °C. As the shroud temperature rose, and the ramp rate slowed, the absolute error dropped. At about 10 minutes (~700 °C shroud temperature) the 12" location errors were only -0.4% to -1.6%. At about 20 minutes (825 °C), the errors at 12" ranged from -0.2% to -1.1%. At 40 minutes, just before the test was terminated, the 12" location errors ranged from +0.2% to -0.6%.

Errors at 24" were less than those at 12". The maximum error ranged from -0.7% to -1.8% at about 3 minutes and 50 °C nominal shroud temperature. At 20 minutes and 650 °C nominal shroud temperature, the errors ranged from 0.0% to +0.4%.

End of test errors were all small, a maximum of about ±1%, but errors at the beginning of the test were higher. Early in the test, the nominal shroud temperatures were low, therefore so was the radiant heat transfer. As a result, the bias error might not have a significant effect on the reported temperature at early times (less than ~ 5 minutes).

Errors less than ±0.6% of the reading in K corresponds to about ±0.75% of the reading in ºC. The ±0.75% accuracy is the ASTM standard for standard limits of error Type-K TCs. Therefore, and shroud TC errors less than about ±0.6% of the reading in K could be due to just TC inaccuracies. Therefore, end of test errors may not have any bias errors.

During the initial transient (Figure 15) the error oscillates due to the control system. The control system is optimized for control at high temperatures, so is not optimally configured for low temperature control. The result is that the error oscillates as the power is turned on and off.

Figure 16: Shroud Temperature Ramp Rates, C/min, Test#1

Figure 16 shows approximate temperature ramp rates calculated from shroud data at 0, 30, and 180 degrees at 12” and 24”, using a 5-point moving average to smooth out the data. The maximum rate is about 175 °C /min for the 12” location and 80 °C /min for the 24” location. Data from all 6 TC pairs are shown; the data are close from the 3 sets at 12” and similarly close for the 24” data. We will use these data to better understand what affects the error at early times.

The general behavior of the shroud error has been analytically modeled in ref. [5] for flat shrouds. The model is not predictive as there were too many unknown parameters, but the overall behavior of MIMS TCs on a flat shroud was successfully modeled. A key difference between the flat shroud data and the cylindrical shroud errors are that the flat shroud errors do not settle to close to zero but have a constant offset, while the cylindrical shroud errors do approach errors close to zero, or within the inaccuracies of the TCs. The reader is referred to that reference for further information.

Test#1 Summary

Results from Test#1 are for shroud TCs only. The early time errors for the 12” TCs were higher than for the 24” TCs due mostly to the higher ramp rates, but the error reduced rapidly as the test progressed and the ramp rates slowed. The error for all TCs was less than 1% at the end of the test, much of which could be due to just the Type-K TC inaccuracies. Errors were affected by ramp rate and exposure to a test object. Maximum temperature ramp rates were about 175 °C/min at 12” and 80 °C/min at 24”.

4.2 Test#2

TC pairs (UJTC and IJTC) on the mock unit were included in Test#2. Shroud data are presented first, followed by the mock unit external TCs, and finally the mock unit internal TCs.

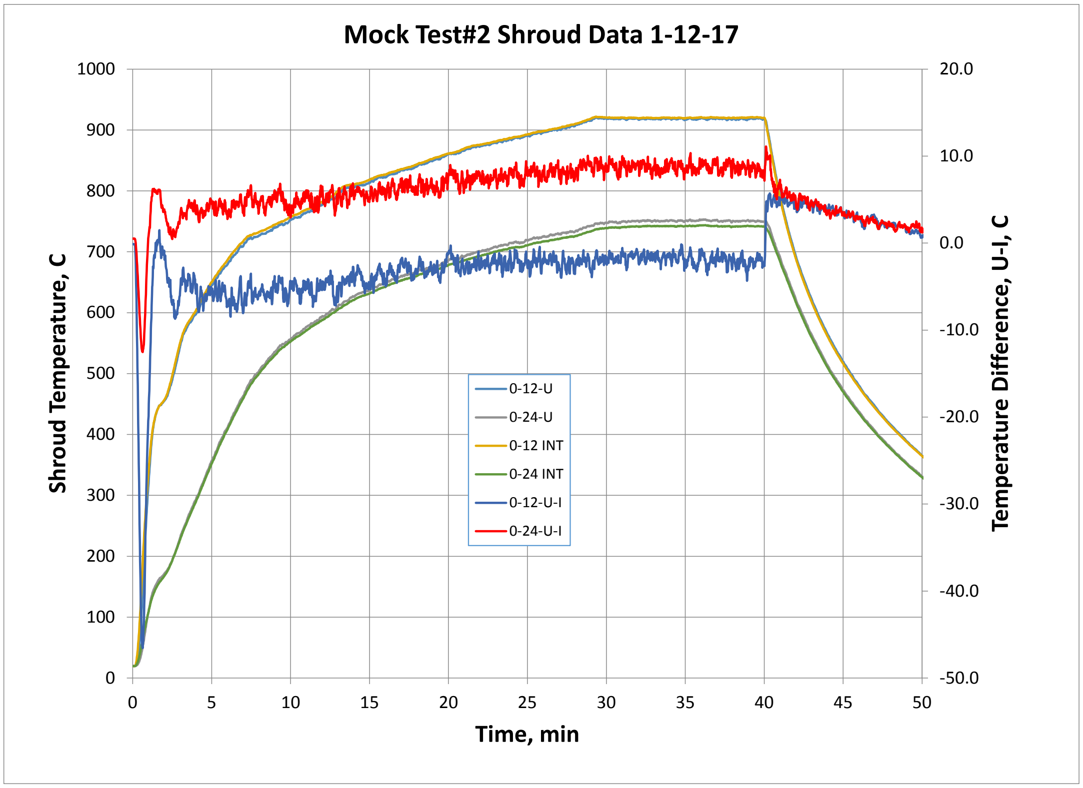


Figure 17: Test#2 Shroud TC Data

Figure 17 shows data from a shroud TC pair from Test#2. The same basic behavior of the shroud temperature seen in Test#1 is visible in Test#2. The temperature difference for the 2 pairs is also shown in Figure 17. The difference is initially negative, then drops to smaller absolute values (e.g., ±5 °C), after only a few minutes.

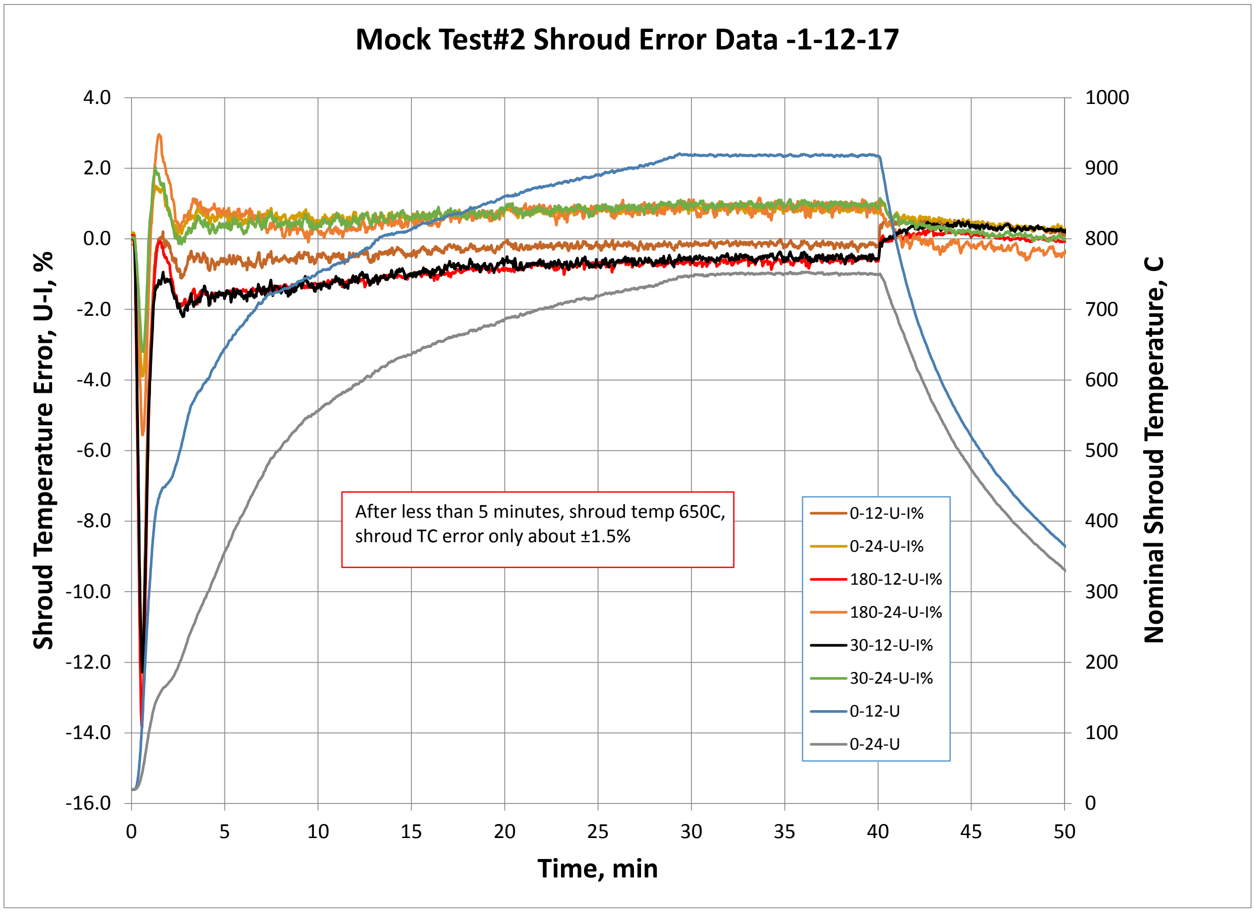


Figure 18: Mock Test#2 Shroud Temperature Errors, % in K

Figure 18 shows all of the shroud errors for Test#2. The maximum errors are about -13.7% early in the test, but quickly drop to ±2% within the first 2 minutes, then to about ±1% after about 15 minutes, remaining there for the remainder of the test (about 40 minutes overall). The largest negative errors occur on the TC pairs at 12", directly opposite the test unit and lamps, and occur at early times when the nominal shroud temperature is less than about 150 °C. The ramp rates on both the 12" and 24" TCs were more than on Test#1. End of test errors at the 12" location were about 0% to -0.6% and at 24" they were about +1%. These errors are considered small.

See Figure 19 for the shroud ramp rates for Test#2; the time scale is expanded to better show the high ramp rates. Past 20 minutes the rates change little and are close to zero. The maximum ramp rate was about 550 ºC/min at the 12" location and 170 ºC/min at the 24" location. These higher ramp rates were a direct cause of the larger errors on Test#2.

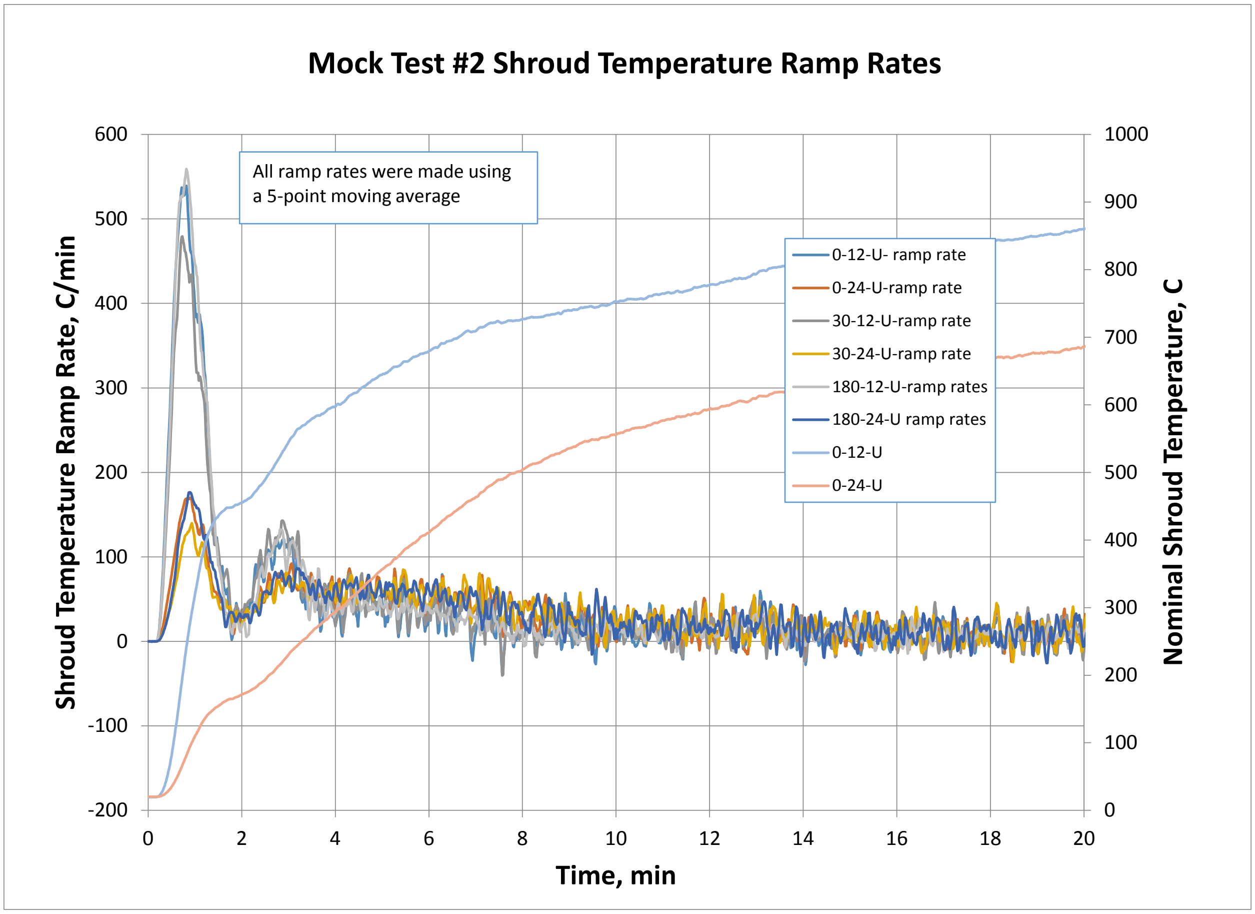


Figure 19: Mock Test#2 Shroud Temperature Ramp Rates, C/min

Recall the construction of the mock unit from Figure 11. The "base" refers to the cylindrical piece constructed from ½" thick stainless steel (SS), measuring 6" high and 7" diameter, and not painted. Mated to the base is the "cone", which is ¼" thick SS, with a 7" diameter bottom to mate with the base, and is 7.5" tall. The top cap on the cone is a flat ¼" thick SS disc.

In Test#2, the mock unit base had a 1" insulation blanket on the inside surface, but the cone was uninsulated. In Tests#3 and #4, the insulation was removed from the base.

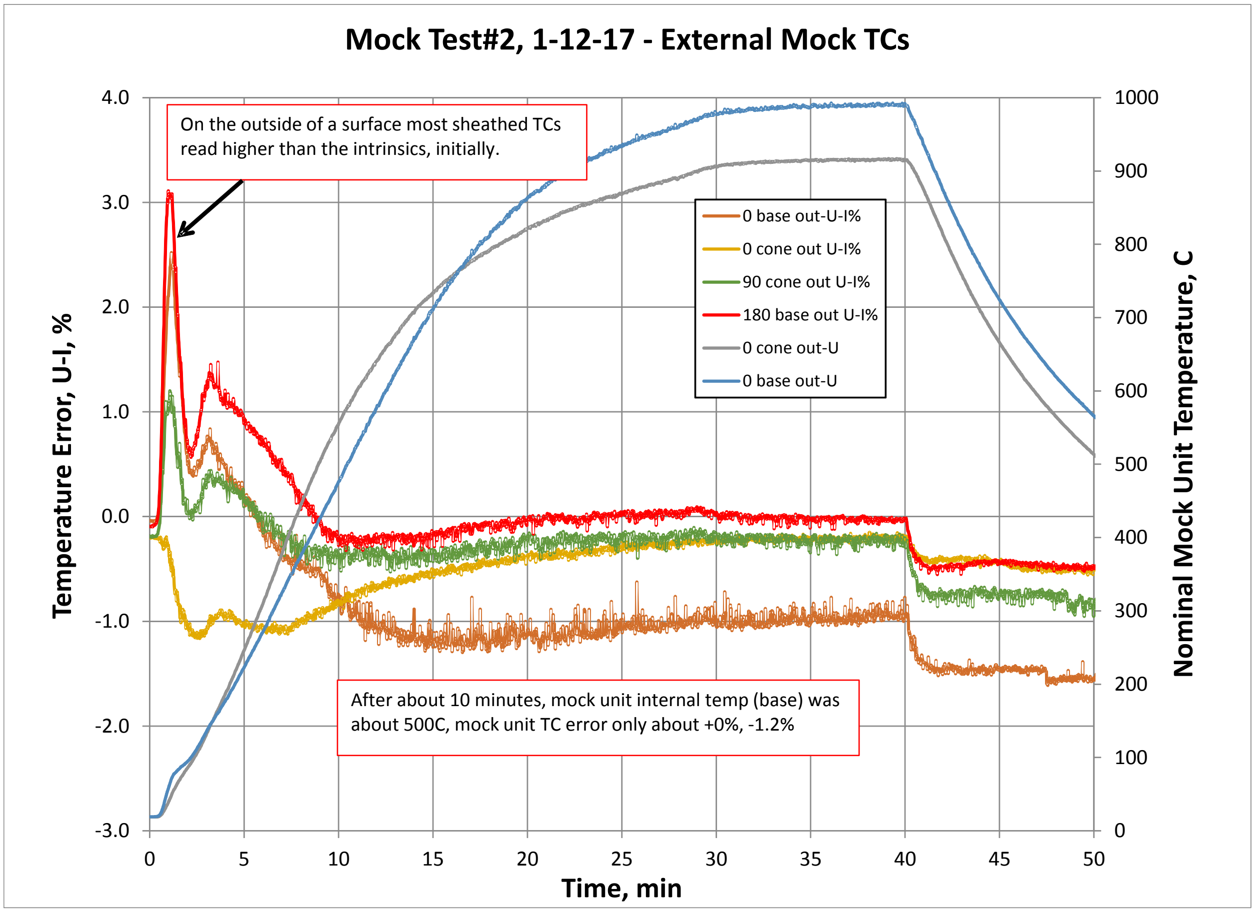


Figure 20: Mock Test#2, External Mock TC Errors

Figure 20 shows TC errors from the pairs on the outside of the mock unit along with nominal mock unit external temperatures. Note the nominal mock unit temperatures are higher than the shroud temperatures shown in Figure 18. This is because the only shroud temperatures shown in this report are the ones at 12" and 24". Shroud temperatures lower than 12" were higher than the mock temperatures shown in Figure 20.

In Figure 20 there are 4 pairs, 2 on the cone and 2 on the base. Three of the four pairs have a positive error early in the test (max of about +3.1%), then the errors drop after about 10 minutes to +0.0 to -1%. Overall the base had larger errors than the cone.

The fourth pair ("0 cone out") initially goes negative rather than positive, then rises to values almost the same as the other pairs. This behavior was not expected. It was expected that, for TCs mounted externally on a heated surface, the radiant heat flux would cause the UJTC to heat faster than the surface, due in part to the larger mass of the surface, meaning the difference (UJTC-IJTC) initially would be positive. This behavior was observed on 3 of the 4 pairs.

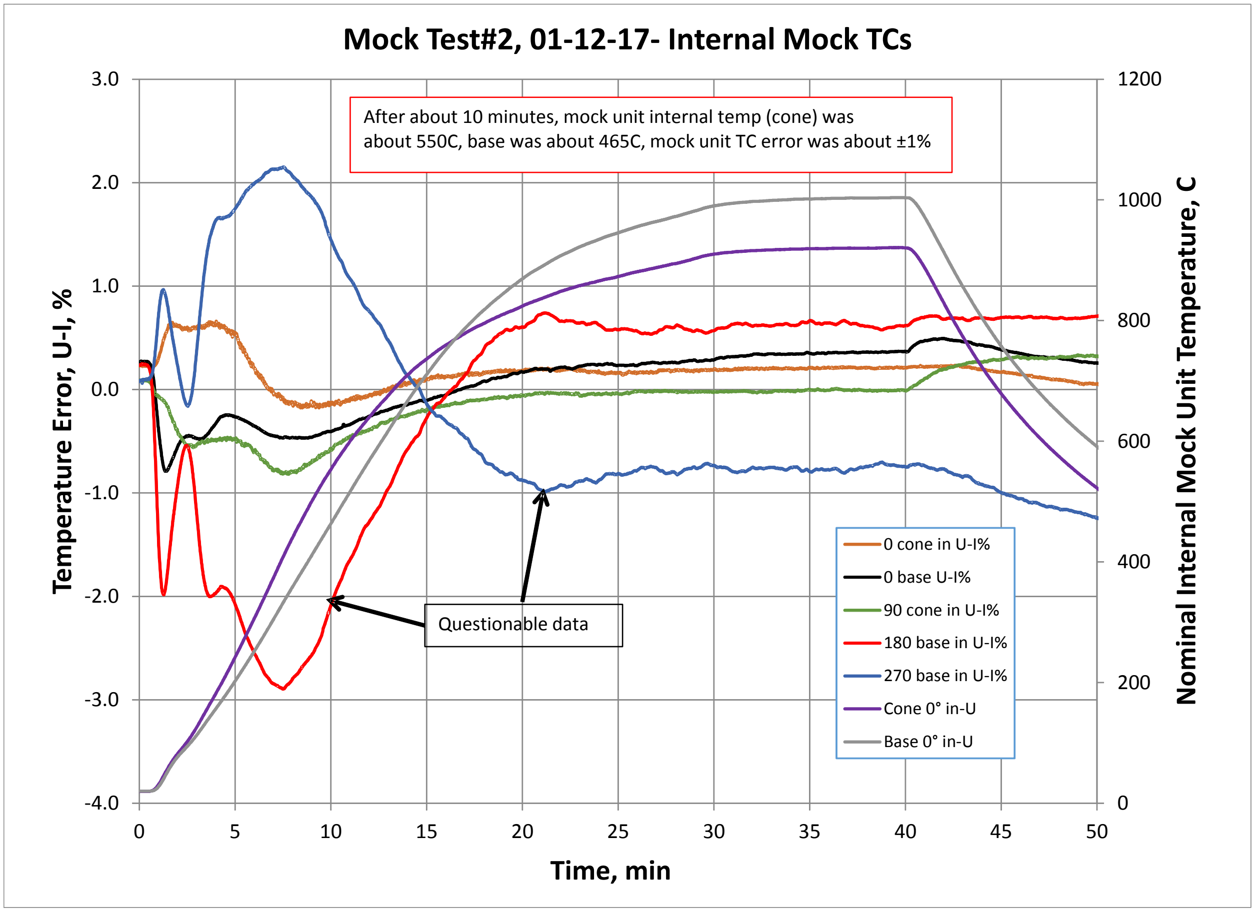


Figure 21: Test#2, Internal Mock TC Errors

Internal mock TC data is shown in Figure 21. Data from the "180 base in" TC seems questionable, as it varies more than the others. Data from the "270 base in" TC pair is more questionable, because it initially goes positive, not negative. The remaining 3 internal pairs are believed to be good data. The "0 cone in" TC rises above its initial value as the test begins, then drops and settles out to about 0.25% error. The initial rise on this pair was not expected but is small enough that the difference could be due to Type-K TC inaccuracies. The other two pairs ("0 base" and "90 cone in") drop from their initial value before slowly rising to about 0.0% error (90 cone in) or about 0.4% error (0 base in) at 40 minutes. None of these are large errors (including the two questionable data sets). Early in the test, the overall errors rapidly drop to less than ±1% at 5 minutes, and lower still (+0.6 to -0.0%) towards the end of the test (neither including the questionable data).

What was expected was that the errors would drop from their initial values similar to what occurs on the shroud TCs. This did occur on the "0-base" and 90-cone-in" curves. The "0 cone in" TC (brown) rose slightly from the initial value at the start, contrary to what was thought. But these errors are quite small, so it is difficult to make any judgements from only this data set. Data from the "270 base in" TC pair also goes positive, contrary to what was expected. Data from the "180 base in" TC pair goes negative, as expected, but takes much longer to get to smaller absolute values of error. As stated above data from the "270 base in" and "180 base in" TC pairs are questionable.

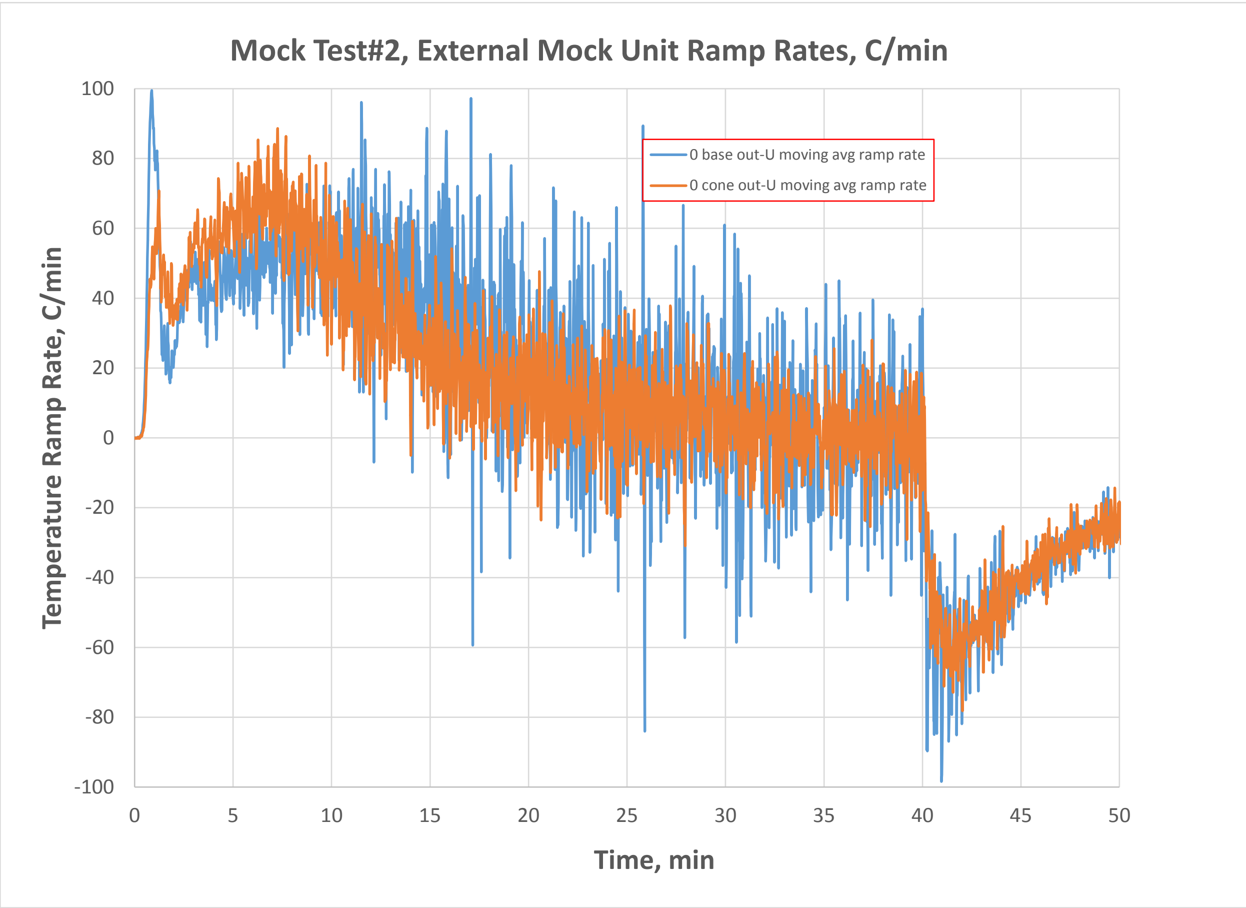


Figure 22: Test#2, External Mock TC Ramp Rates, Base and Cone

Figure 22 shows ramp rate data from external mock TCs on Test #2. These data show the ramp rates on the mock unit are lower than on the shroud, a maximum of about 100 °C /min. The data are quite "noisy", showing large fluctuations even though a 5-point moving average was used to reduce some of the noise. These fluctuations are not uncommon on TCs mounted on the outside of metal surfaces, and are one reason why temperature measurements are made mainly from TCs on the unheated side of the plate, rather than the heated side. As seen below in Figure 23, the data from internal mock TCs have less noise.

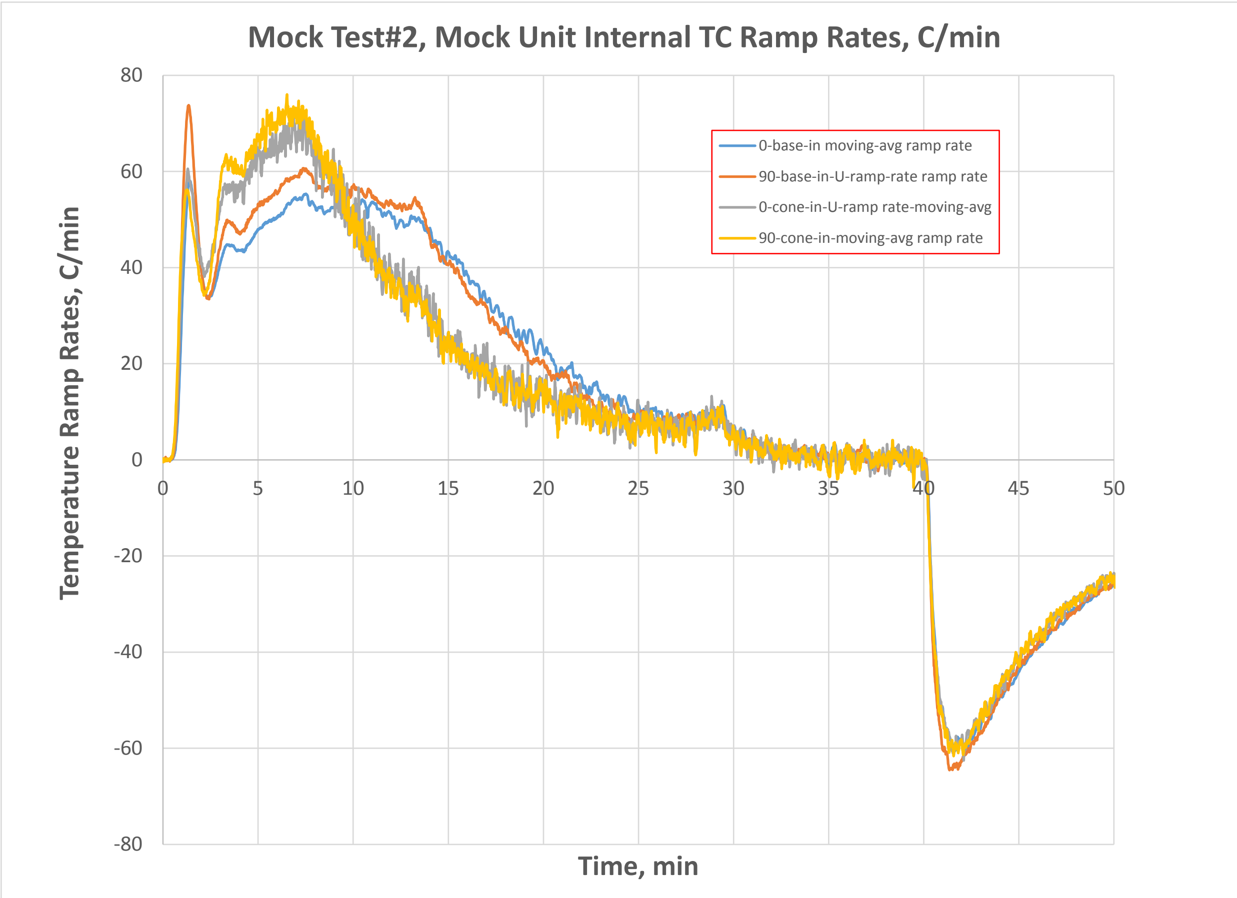


Figure 23: Test#2, Mock Unit Internal TC Ramp Rates

Data from internal TCs on the mock unit are shown in Figure 23 using the same 5-point moving average. The highest ramp rate shown is about 70-75 °C /min, on the cone. Ramp rates on the base, which is twice as thick, are slightly lower (~60 °C /min), and less noisy.

Test#2 Summary

Results from Test#2 are for shroud TCs, external, and internal mock unit TCs. The maximum shroud errors are about -13.7% early in the test, but quickly drop to ±2%, then to about ±1% after about 15 minutes, and remain there for the remainder of the test, about 40 minutes. The larger early shroud errors were due to the very fast initial ramp rates on the 12" locations. For external mock unit TCs, three of the four pairs have a positive error early in the test, then drop after about 10 minutes to +0.0 to -1% error. The fourth pair ("0 cone out") initially goes negative rather than positive, then rises to values almost the same as the other pairs. This behavior was unexpected, but, since the errors were so low, it is believed to be good data. For internal mock TCs, early in the test the overall errors rapidly drop to less than ±1% at 5 minutes, and even lower +0.6 to 0.0% towards the end of the test (ignoring the questionable data).

These errors are quite low considering the high nominal temperatures being measured.

4.3 Test#3

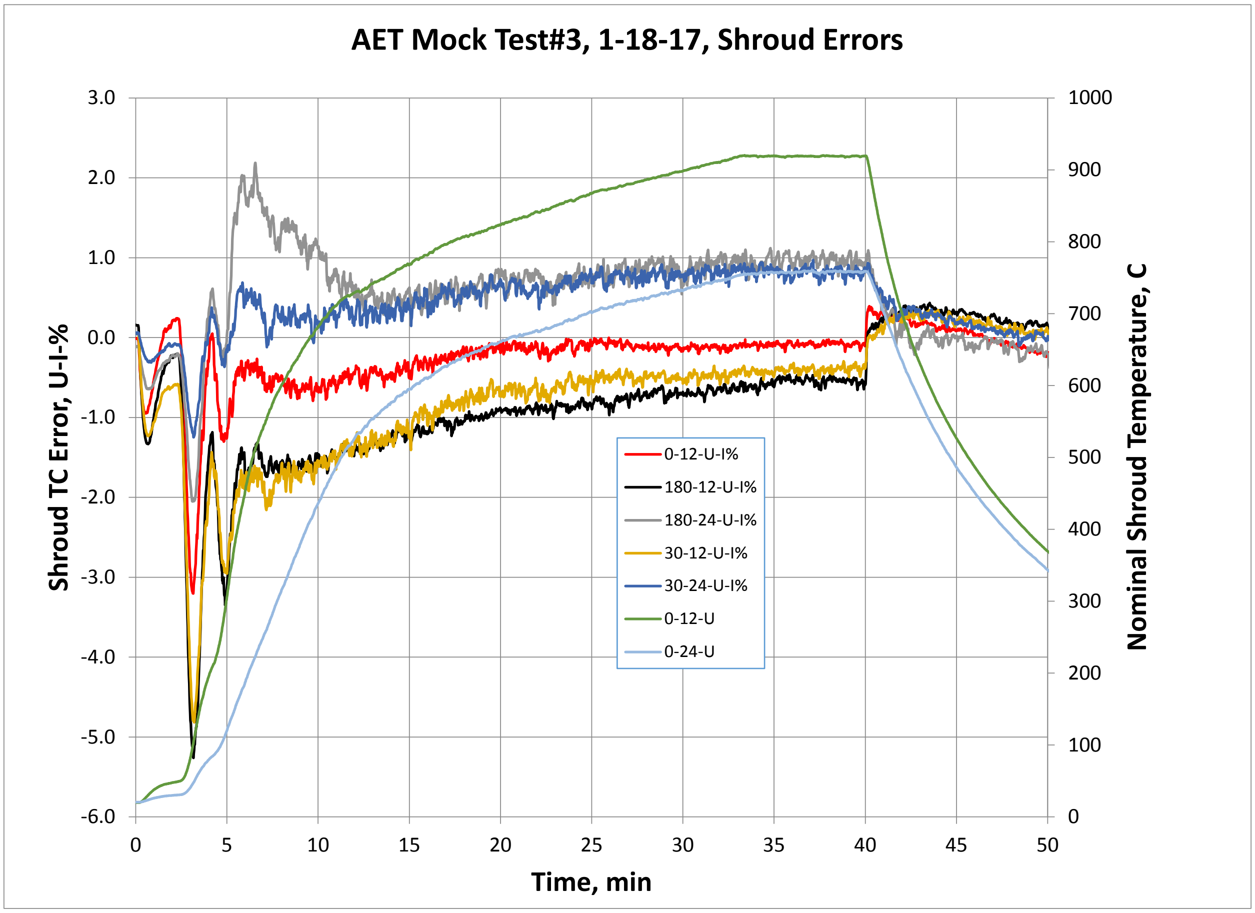


Figure 24: Test#3 Shroud Errors

Figure 24 shows shroud TC errors for Test#3. Data are similar to the first two tests in that the errors go negative early in the test, then quickly rebound to smaller absolute values. Errors at 12” are larger early in the test, but end the test lower and slightly negative (about -0.5% to 0.0%). The early time errors occur at low nominal shroud temperatures, e.g., less than 150 °C. Errors at the 24” location are smaller than at the 12” location early in the test. At the end of the test (40 minutes) all errors are within about +1.0% to -0.5%. The 180-24 location error first went negative (as expected), but then rose to about + 2% (not expected). It is not clear why this occurred.

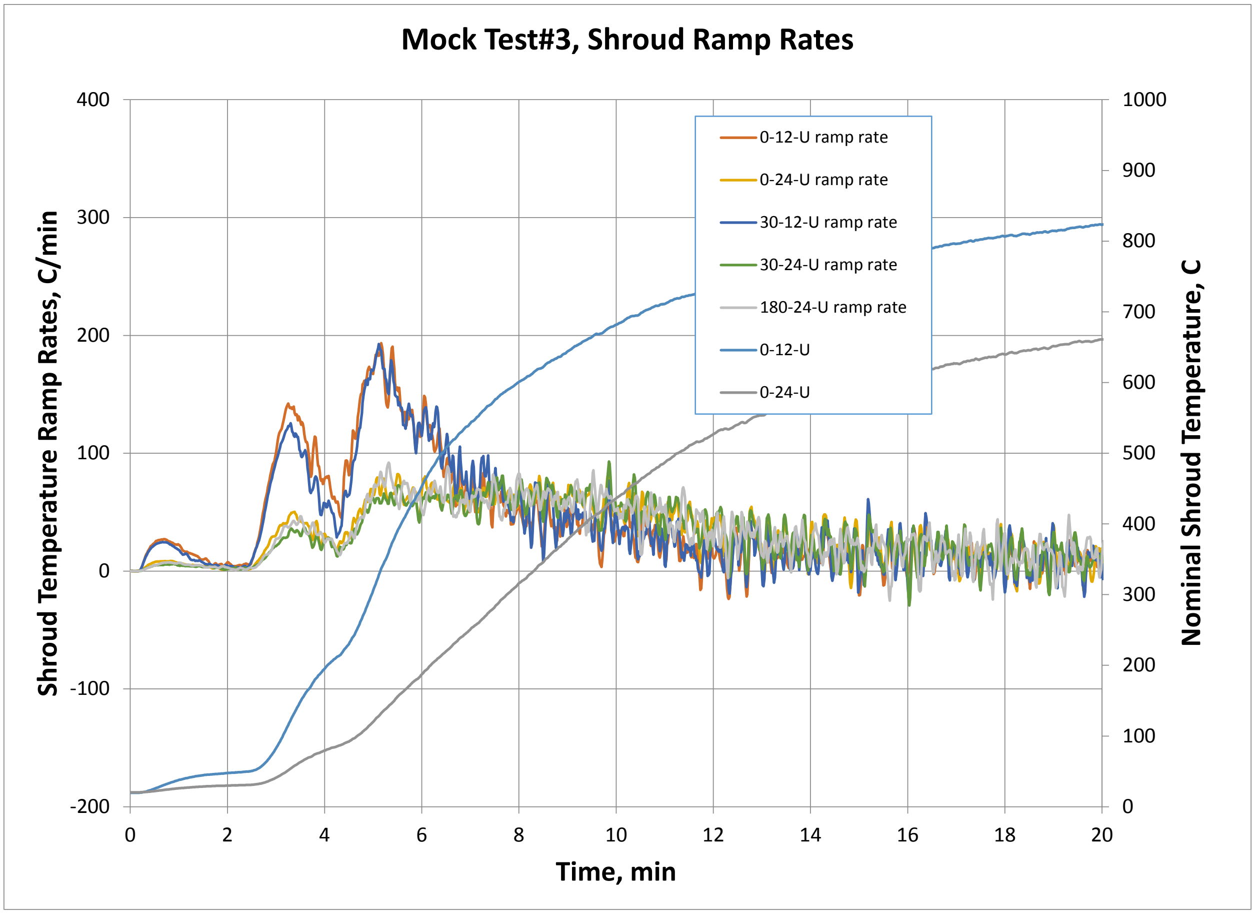


Figure 25: Mock Test#3, Shroud Temperature Ramp Rates

Figure 25 shows the ramp rates for Test #3 on the shroud. The maximum was about 185 °C/min at the 12” location and 85 °C/min at the 24” location. Maximum errors were higher for the 12” location (max of -5.2%) and lower on the 24” location (max of -2.0% in Figure 24) in an expanded scale. Again, errors early in the test were proportional to the ramp rate.

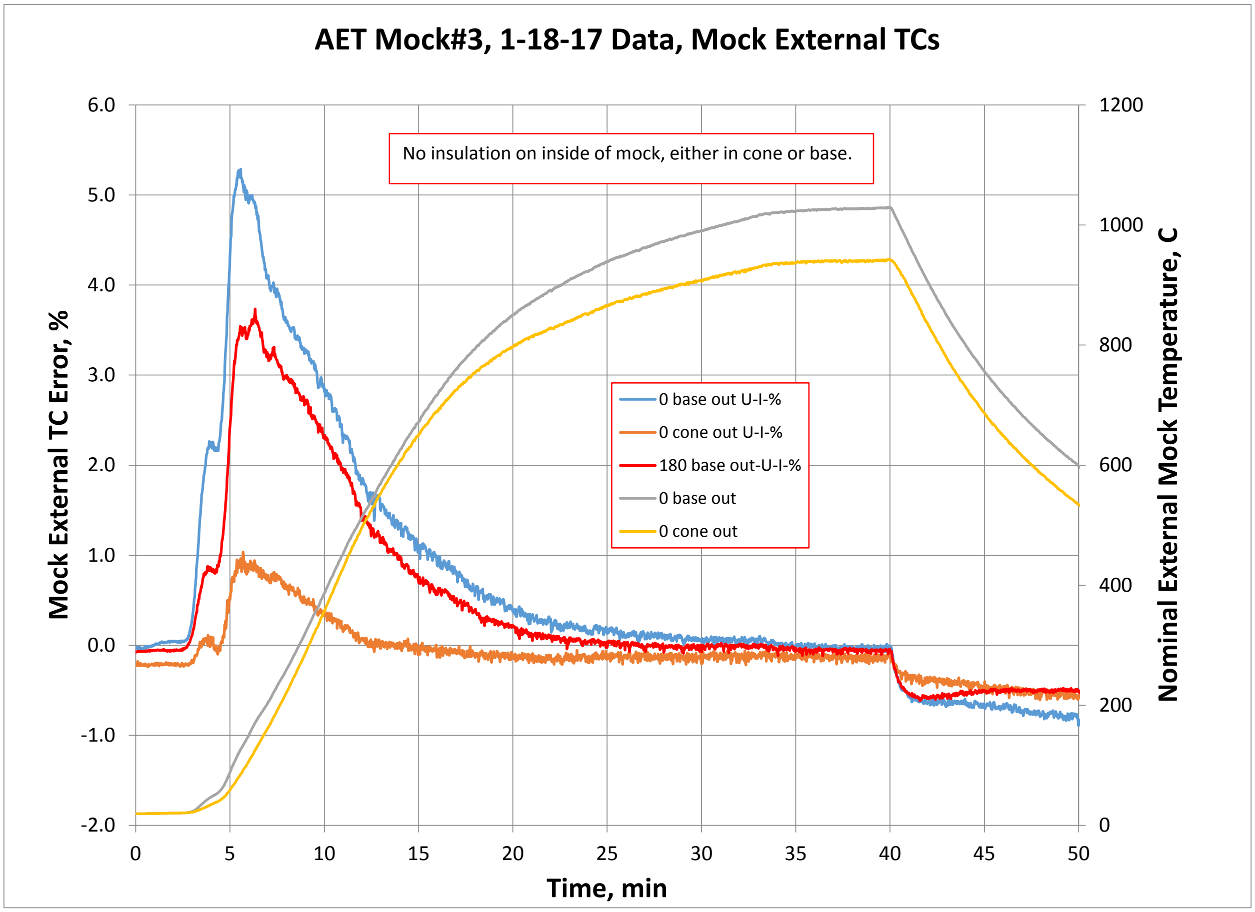


Figure 26: Test#3 External Mock TC Errors

Figure 26 shows external mock TC errors for Test#3. Data are not presented for an intrinsic TC that failed ("90 cone out"). At test start, the errors are positive, up to about 5.2%, then drop at 15 minutes to values less than 1%. The errors are positive because the UJTC has a small thermal mass as compared to the mock unit, and so it heats faster. At the end of the 40 minute test, the errors are almost zero.

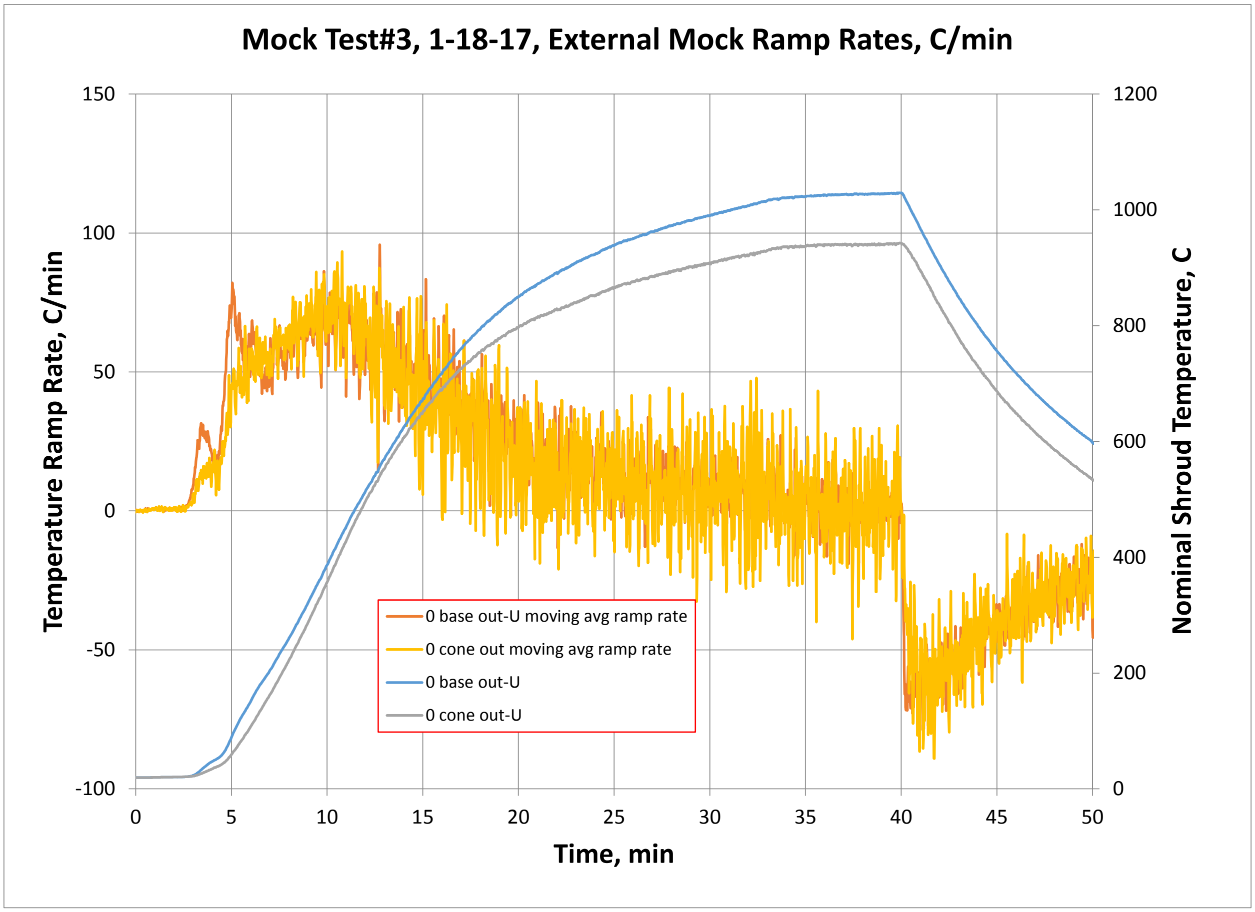


Figure 27: Mock Test#3, External Mock Ramp Rates, C/min

Figure 27 shows the ramp rates on the mock unit external TCs. The cone and base rates are noisy but are roughly equal. For the mock unit, it is more advantageous to focus on the errors as a function of wall thickness because the ramp rates were approximately equal. Recall the mock unit base was about ½” thick while the cone was ¼” thick. The errors in Figure 26 are larger for the base as compared with the cone.

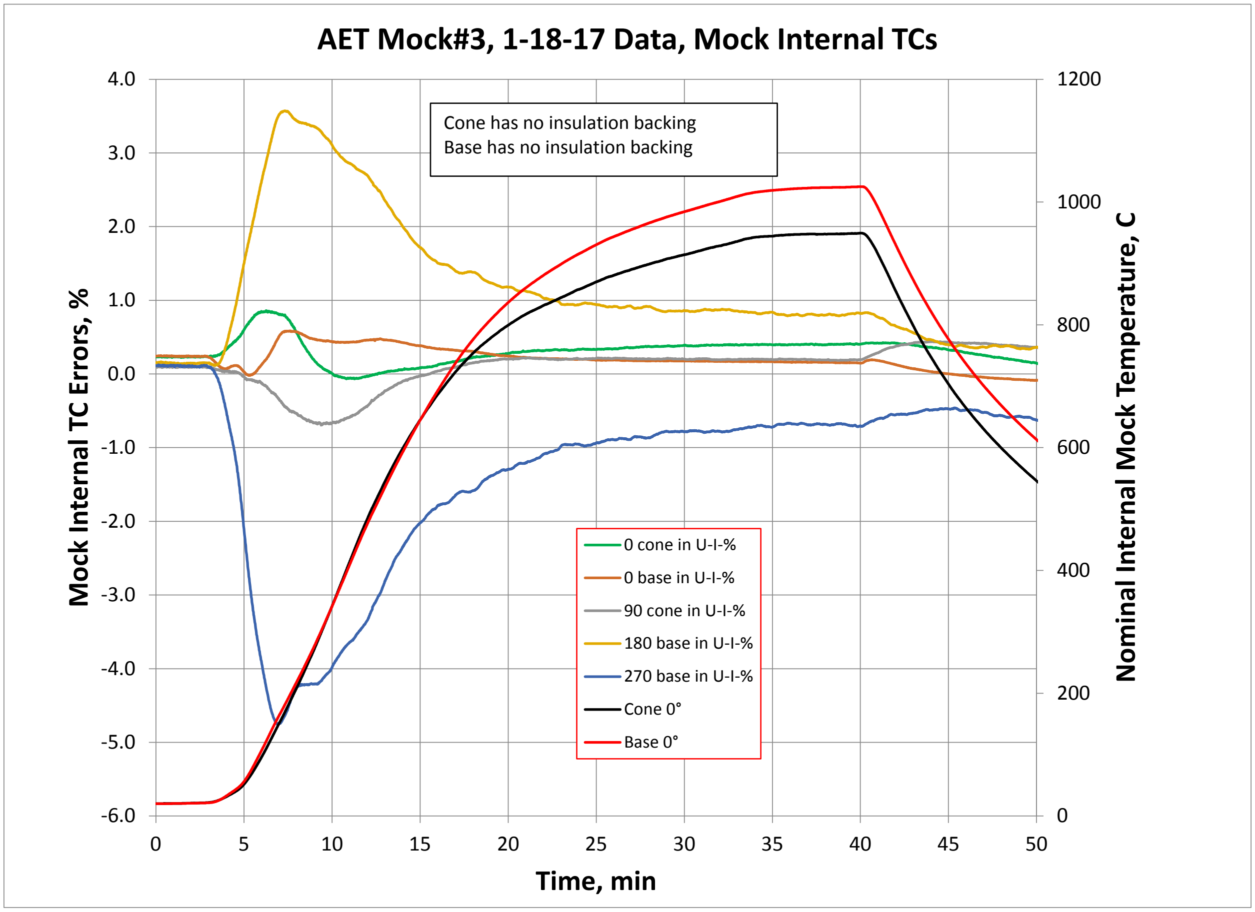


Figure 28: Test #3, Internal Mock TC Errors

Figure 28 shows the internal mock TC errors. Similar to Test#2 internal mock TCs, the "180 base in" pair and the "270 base in" pair shown in Figure 28 are questionable. Intrinsic TCs are less reliable so that may be one reason for the unexpected behavior. The IJTCs might have functioned incorrectly due to a bad junction, the wires may have touched away from the surface, etc. It was difficult to install the internal IJTCs due to a lack of space.

Being mounted on the inside surface, one would expect that the TC error would go negative initially. The "270 base in" error goes negative early, but the "180 base in" goes positive, contrary to what was expected. Both take more time to drop to lower errors than expected. The other 3 data sets seem reasonable, and are believe to be good data. Even if the questionable data are used, the end of test errors are still less than about ±1%.

Note that the behaviors of the two questionable pairs, "180 base in" and "270 base in" in Test#3 are opposite to what occurred during Test#2. In Test#2 the 180 base in pair went negative before dropping to small values, and the 270 base in pair went positive, contrary to what occurred on Test#3, adding further doubt to their validity.

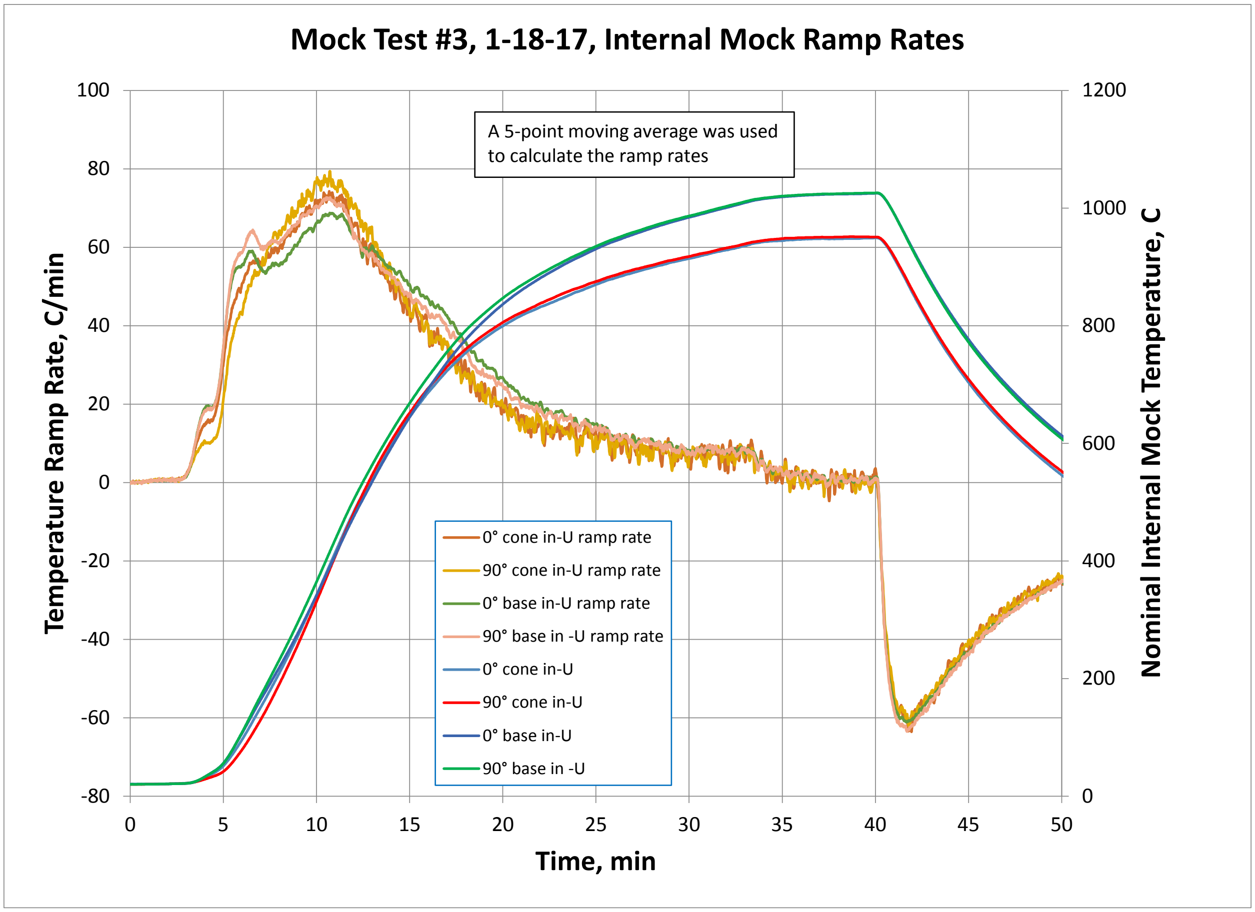


Figure 29: Mock Test#3, Internal Mock TC Ramp Rates

Figure 29 shows internal mock unit TC ramp rates for the third test. As one might expect, they are lower than for either the shroud and the external mock TCs.

Test#3 Summary

Results from Test#3 include data for shroud TCs, external and internal mock unit TCs. Shroud data are similar to the first two tests in that the errors go negative early in the test, then quickly rebound to smaller absolute values. Errors at 12" are larger than at the 24" location early in the test and end the test slightly negative, but low (about -0.5% to 0.0%). Shroud errors at 24" are smaller early in the test, and at the end of the test they are at about +0.8% to +1.0%. Early in the test the shroud errors in Test#3 are lower than for Test#2 due mainly to the faster ramp rate in Test#2.

At test start, the external mock TC errors are positive, up to about 5.2%, then drop soon thereafter to values less than 1%. The errors are positive because the UJTC has a small mass as compared to the mock unit, so it heats faster and the difference (UJTC-IJTC) is positive. At the end of the test the errors are almost zero.

Similar to Test#2 internal mock TCs, the "180 base in" pair and the "270 base in" pair in Test#3 are questionable. Mounted on the inside surface, one would expect that the TC error would go negative initially. The "270 base in" error does go negative early, but the "180 base in" goes positive, contrary to what was expected. Also, both take more time than expected to drop to lower errors. The other 3 data sets seem reasonable and are believe to be good data.

4.4 Test#4

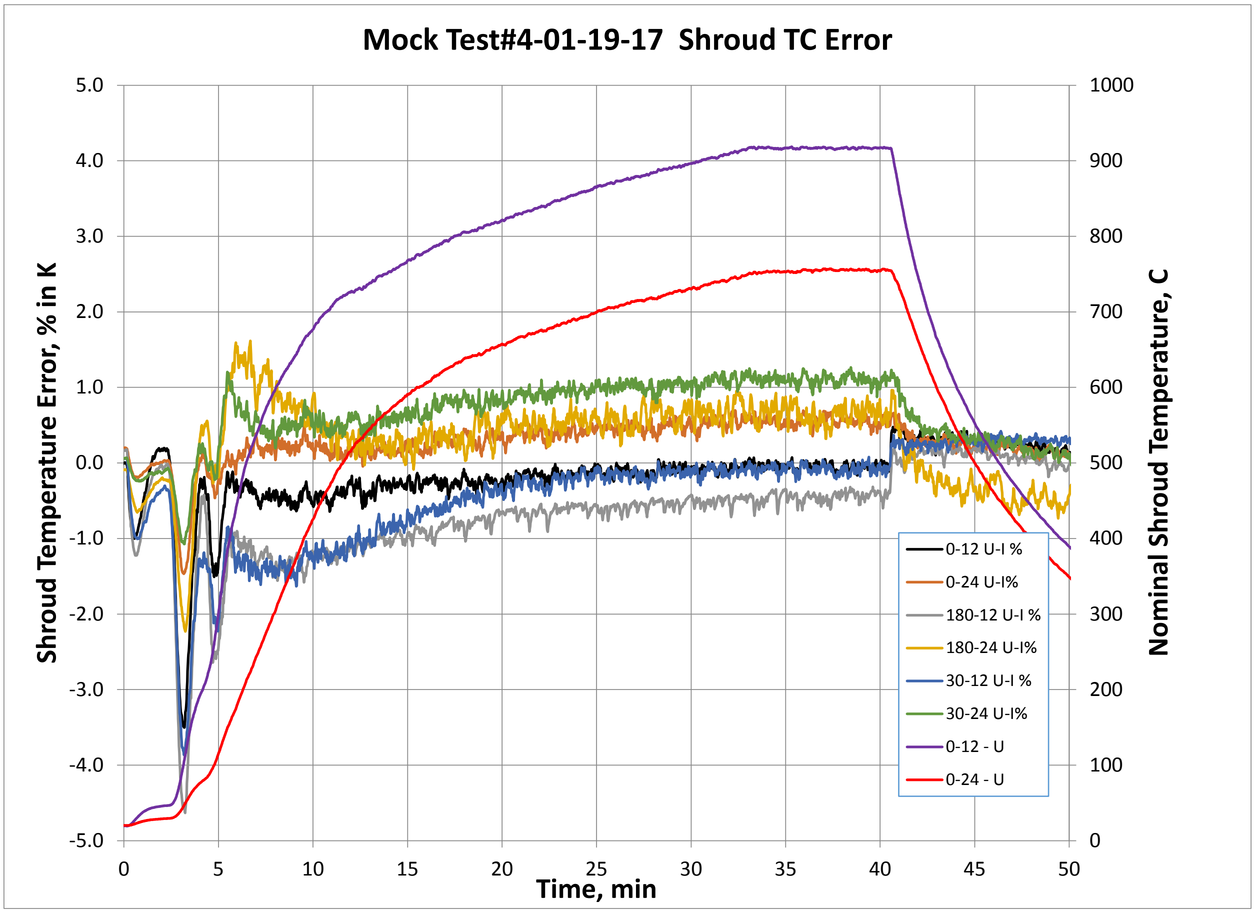


Figure 30: Test#4 Shroud TC Errors

Figure 30 shows the shroud TC errors from Test#4. Data are consistent with other tests in that the errors are negative early in the test, then drop to lower absolute values and coalesce to around ±1%. The errors at 12" are mostly below zero, while those at 24" are above zero towards the end of the test.

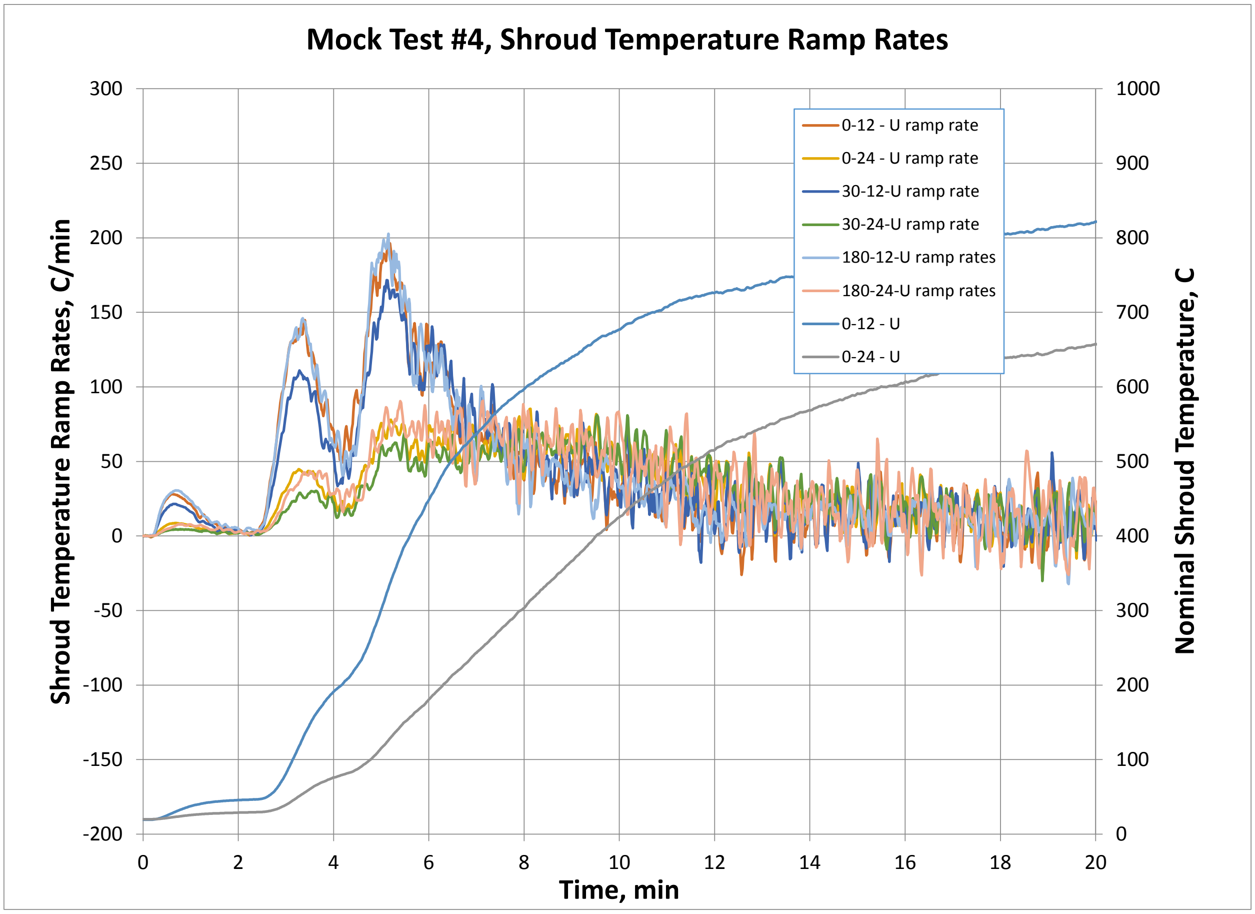


Figure 31: Test#4 Shroud Ramp Rates

Figure 31 shows the shroud ramp rates for Test#4; they are less than Test#2 but comparable to Test#3.

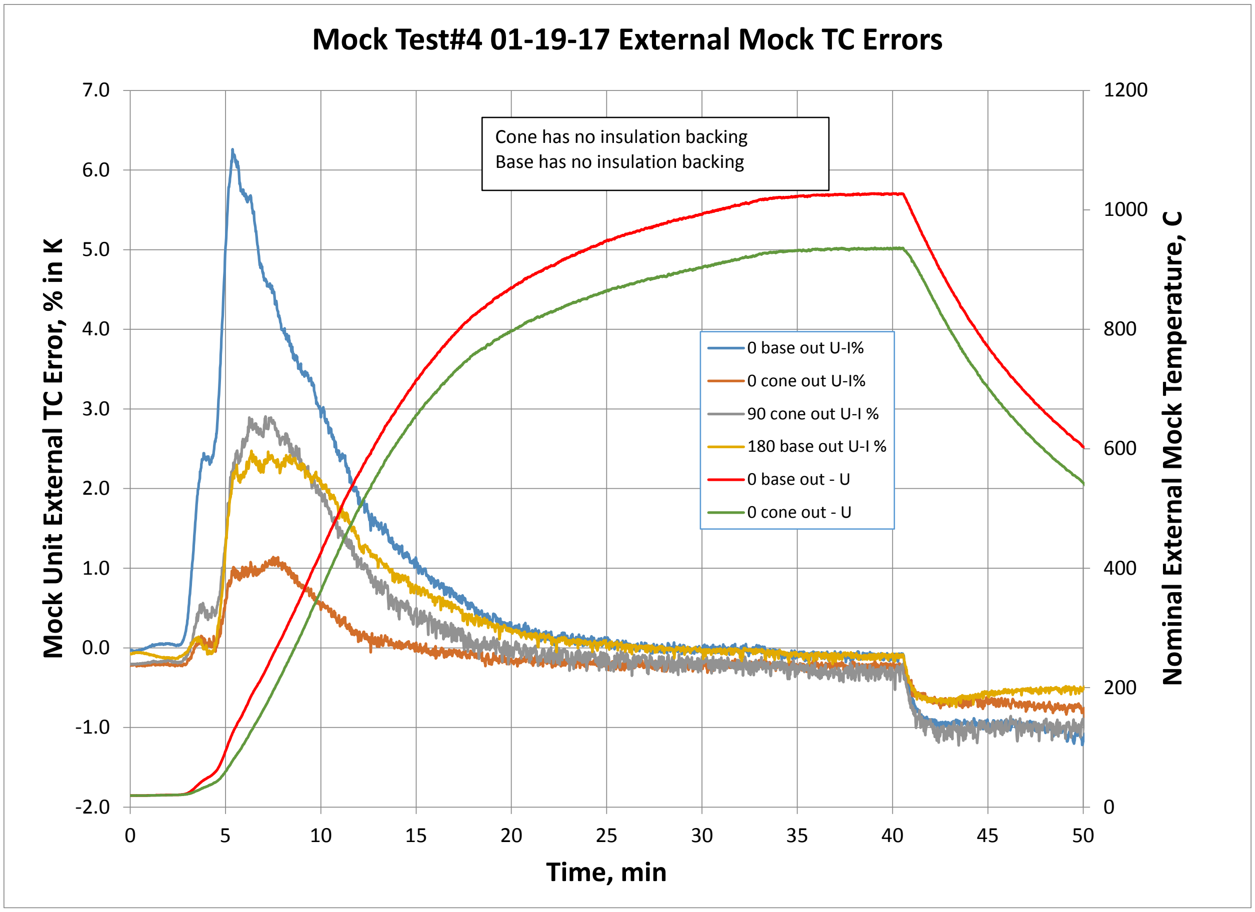


Figure 32: Test#4, External Mock TC Errors

Figure 32 shows external mock TC errors. Similar to the previous tests, the error is positive early in the test because the TCs are on the external surfaces, and the UJTC reads higher than the IJTC. The early time maximum error is about 6.2% (~ 5 minutes and ~120 °C), but the error drops to less than about +1.0% after about 15 minutes.

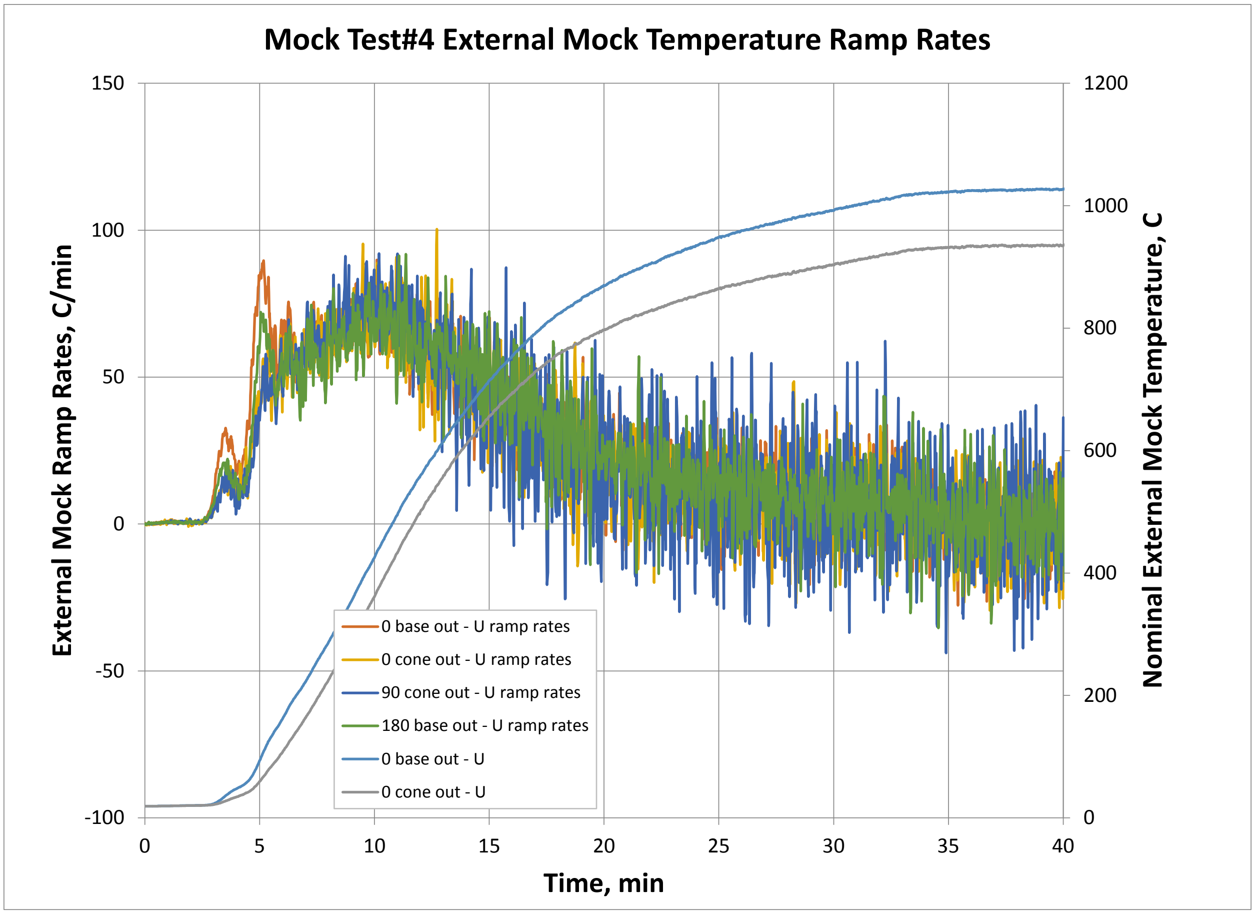


Figure 33: Test#4 External Mock Ramp Rates

Figure 33 shows external TC mock unit ramp rates; they are comparable to the other tests.

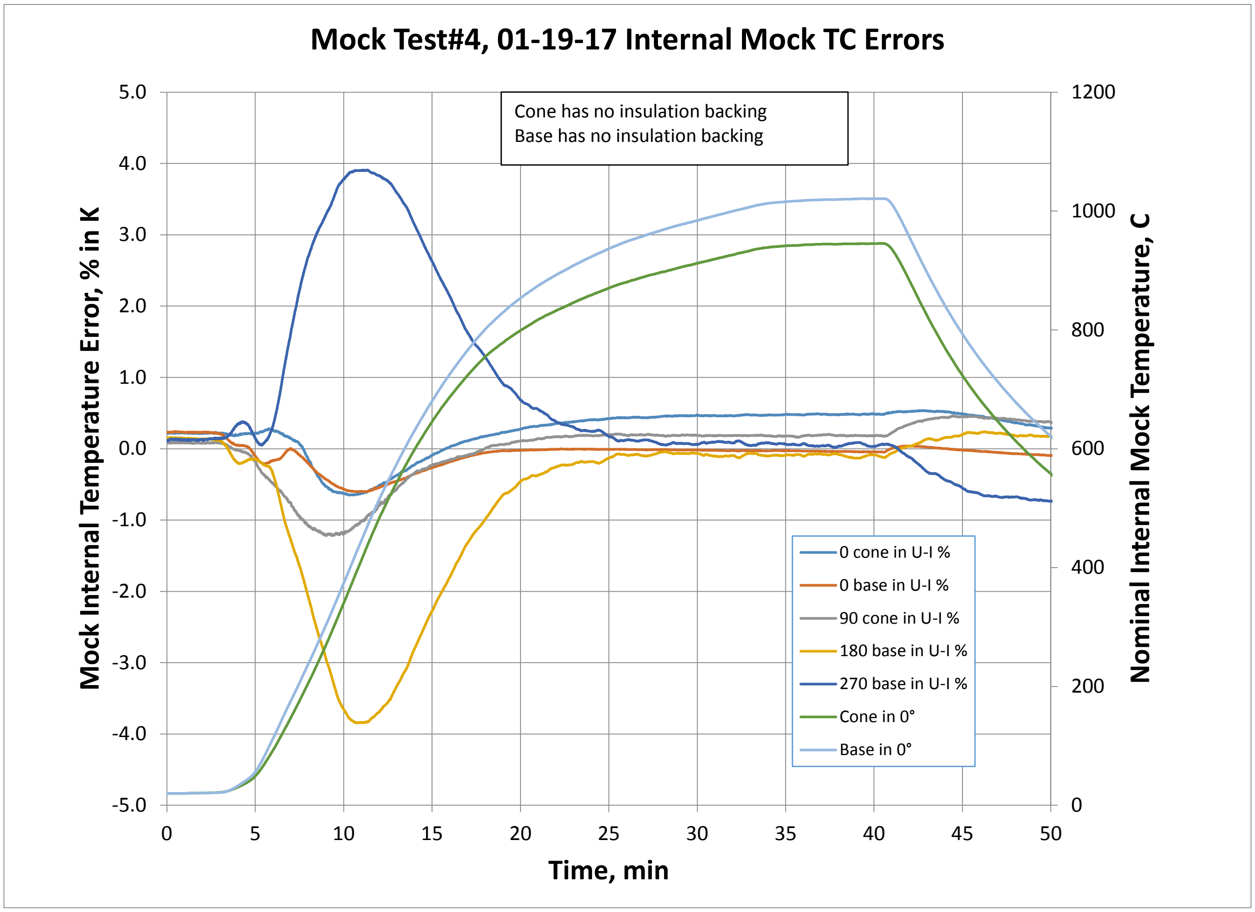


Figure 34: Test#4, Internal Mock TC Errors

Figure 34 shows TC errors on the inside of the mock unit. Similar to Tests#2 & #3, the "180 base in" and "270 base in" TCs are questionable and will not be used. The other 3 pairs begin the test by going negative, as anticipated, but only to a little more than -1%. After about 20 minutes the errors are less than ±0.5%.

Test#4 Summary

Shroud TC errors from Test#4 are consistent with other tests in that the errors are negative early in the test, then drop to lower absolute values and coalesce to around ±1%. The errors at 12" are mostly below zero, while those at 24" are above zero towards the end of the test.

Similar to the previous tests, external mock TC error are positive early in the test. The early time maximum error is about 6.2% (~ 5 minutes and ~120 °C), but the error drops fast and is about ±0.5% or less by 20 minutes.

TC errors on the inside of the mock unit are similar to Tests#2 & #3. The "180 base in" and "270 base in" TCs are questionable. The other 3 pairs begin the test by going negative, as anticipated, but only to a little more than -1%. After about 20 minutes the errors are less than ±0.5%.

4.5 Summary of General Behaviors of TC Errors for all tests

Shroud TC Errors

1) Error is negative and highest early; then it drops quickly to lower absolute error
2) Several errors rise from negative to positive during the test
3) Error is greater for TCs at 12” which had the faster temperature ramp rate and was directly opposite the mock unit
4) Maximum error occurs in first 5 minutes of test when nominal shroud temperature is less than 150 °C and ranged from +3% to -13.7%.
5) Absolute error drops quickly after 10 minutes to less than about ±1.5%
6) Late time errors are typically negative for 12” location TCs and positive for 24” location TCs, but all errors are less than ±1%.
7) Temperature ramp rates on the shroud were as high as about 550 °C/min at the 12” location, and 170 °C/min at the 24” location.
8) Note that the errors are also a function of uncalibrated TCs, each with a 0.75% of reading uncertainty. The total spread for a difference of 2 TCs could be as high as 1.5%. So much of the error seen could have been due to just normal Type-K uncertainties. This also applies to the external and internal mock TC errors.

External Mock TC Errors

1) Error is positive and highest early; then it drops quickly to lower absolute error
2) Base has larger errors than cone; partially due to different thicknesses
3) Error magnitude at test end typically +0.0%, to -1.0% or less
4) It is likely that one reason why the errors are smaller for the external mock TCs compared to the shroud TCs is because they are 0.040” diameter rather than 0.062” diameter. The smaller the TC, the smaller the error, because of a smaller thermal resistance and smaller thermal capacitance.
5) Peak errors on Test#2, with the base insulated, are lower (~3%) as compared with Tests#3 and #4 (5-6%), which had no insulation on the base. However, later in the test, the non-insulated cases had lower errors as compared with the insulated case.

Internal Mock TC Errors

1) Error expected to go negative early, then settle out to small errors
2) Several errors sets did respond as expected, going slightly negative early then settling out to small values. Two pairs did not respond as expected but even then errors were less than about ±2%.
3) Data from the two pairs that did not respond as expected were questionable.
4) Max error at all times was ±2% or less, ignoring the questionable data
5) Late-test errors were typically quite small, less than ±0.5%.
6) One reason that the errors are smaller for the internal mock TCs compared to the shroud TCs because they are 0.040” diameter rather than 0.062” diameter. The smaller the TC, the faster the thermal response, and, therefore, the smaller the error.

4.6 Presentation of Error Data

There are a number of ways to present the error data from these tests. Two ways are to estimate the maximum error in a period of time, e.g., from 0-10 minutes. All data were corrected to when the power was initiated so differences were not intended. Then any corrections can be easily made based on the time period under consideration. Another method is to present the errors as a function of the temperature ramp rates, because it is believed that early in the test the ramp rates most affect the error. (See below for why this is so.). Because we wish these data to be used as much as possible we present it in both ways and leave it to the user to choose which method is best suited for her application. First we present the error as a function of time from test start.

Table 3 provides a summary of the errors on the shroud, external mock and internal mock in 3 consecutive time periods and at test end. The time periods are somewhat arbitrary but the attempt is to capture the main behavior in select regions. The time periods were chosen to capture the largest errors ("initial transient"), when the errors are dropping ("settling time"), and when the errors have "settled" to almost constant values. There are some differences when the test was initiated. For example, on Test #2 there was a fast temperature rise in the first 5 minutes as compared with the other 3 tests.

Data in Table 3 was binned into the 3 time periods shown. Depending on one's perspective, it may be better to bind the time period such that the errors are provided at certain nominal shroud or mock temperatures or at a temperature ramp rate. For example, one might say (arbitrarily) that for nominal temperatures below 500°C the errors will be neglected because the temperature is low enough that a small error would have negligible effect. We have not done that here but it can be done.

Table 3: Summary of Reported Errors in Time Bins

Time period, minutes	Maximum shroud error range, % of nominal shroud temperature, in K	Maximum external mock error range, % of nominal external mock temperature, in K*	Maximum internal mock error range, % of nominal internal mock temperature, in K*,**	Highest temperature at end of time period, °C
0-10, initial transient	+3.0 to -13.7% Largest negative error occurs at highest ramp rate	+6.2% to -1.2% Largest positive error occurs in about first 5 minutes	+0.7% to -1.2%	Shroud: 420-760 External mock: 380-550 Internal mock: 340-550
10-25, settling	+1.1 to -1.7%	+3.0% to -1.1% +3.0% error drops fast after 10 minutes	+0.5% to -1.2%	Shroud: 700-890 External mock: 870-950 Internal mock: 860-950
25-40, settled	+1.1 to -1.0%	+0.2% to -1.1%	+0.5% to -0.1%	Shroud: 730-920 External mock: 910-1020 Internal mock:

Time period, minutes	Maximum shroud error range, % of nominal shroud temperature, in K	Maximum external mock error range, % of nominal external mock temperature, in K*	Maximum internal mock error range, % of nominal internal mock temperature, in K*,**	Highest temperature at end of time period, °C
				910-1010
At end, 40	+1.1% to -0.6%	+0.0% to -0.9%	+0.5% to -0.1%	Shroud: 730-920 External mock: 910-1020 Internal mock: 910-1020

*No mock TC data on Test#1
** Did not use questionable data from internal mock TCs.

Before we present data as a function of temperature ramp rate, an analysis based on an energy balance will be performed. If a control volume is formed around the TC sheath, one may say:

$$E_{in} - E_{out} = E_{stored} \quad [1]$$

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:

$$E_{store} = \rho * c_p * V * dT_{TC}/dt \quad [2]$$

ρ is the density of the TC, V it's volume, and c_p the specific heat. dT_{TC}/dt is the temperature ramp rate we have provided for each test (e.g., Figure 16). E_{in} is mainly from conduction into the sheath (but also from radiation). The energy in is a function of the contact resistance:

$$E_{in} = (T_s - T_{TC}) * A_{contact}/R_{contact} \quad [3]$$

where T_s is the shroud temperature (e.g., from the intrinsic junction TC), T_{TC} is the temperature read by the thermocouple bead, in this case the UJTC, $R_{contact}$ is the contact resistance and $A_{contact}$ is the contact surface area.

E_{out} may be expressed as follows:

$$E_{out} = A_{TC} * F_{TC-envt} * \epsilon * \sigma * \left(T_{TC}^4 - T_{envt}^4\right) \quad [4]$$

Where A_{TC} is the surface area of the TC sheath, $F_{TC-envt}$ is the view factor from the TC sheath to its surrounding environment, ε is the sheath surface emissivity, σ is Stefan-Boltzmann constant, and T_{envt} is the temperature of the surrounding environment. T_{envt} may be approximated as the temperature of the shroud on the opposite side (180° from where the TC is located).

Early in the test the rate-of-change ("ramp rate") dT_{TC}/dt is high. 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 [1] is reduced to:

$$E_{in} = (T_s - T_{TC}) * \frac{A_{contact}}{R_{contact}} = E_{store} = \rho * c_p * V * dT_{TC}/dt \qquad [5]$$

The temperature difference T_s-T_{TC} is the same as the error we have been plotting (except for a negative sign). T_s = surface temperature of shroud = IJTC. T_{TC} = UJTC. From equation [5] one can conclude that the error is proportional to the temperature ramp rate. Data presented above confirms this conclusion.

The following two figures (Figure 35 and 36) show plots of error vs ramp rate for a single shroud TC for Tests #1 and #2. It is obvious that the error is proportional to the ramp rate, but it is difficult to discern the type of proportionality (e.g., linear, or other). If one follows the arrows, which point to increasing time, the error goes negative as the ramp rate increases. As the ramp rate drops, the error approaches zero. This can be understood by looking at equation [6], which approximates the energy balance by noting that late in time the ramp rate drops to almost zero, so the energy storage term (eqn. [2]) is negligible.

$$E_{in} = (T_s - T_{TC}) * \frac{A_{contact}}{R_{contact}} = E_{out} = A_{TC} * F_{TC-envt} * \epsilon * \sigma * \left(T_{TC}^4 - T_{envt}^4\right) \qquad [6]$$

The term $\left(T_{TC}^4 - T_{envt}^4\right)$ drops to a low value late in the test. Therefore the error term $(T_s - T_{TC})$ also drops to a low value, as shown in the test data. This is contrary to what occurs on a flat shroud, as the energy out term remains non-negligible and the steady state error was shown to be up to about 5% depending on the temperature of the surrounding environment.

A more detailed analysis is beyond the scope of this report, but the interested reader is referred to ref. [5] for more information.

Tabular guidance on the magnitude of the error in bins of temperature ramp rate are provided in Table 4. It is obvious from Table 4 that the maximum error early in the tests is a function of the ramp rate. As with Table 3, the bins are somewhat arbitrary (0-100, 100-200, greater than 200), but were chosen to try to capture errors where data were available.

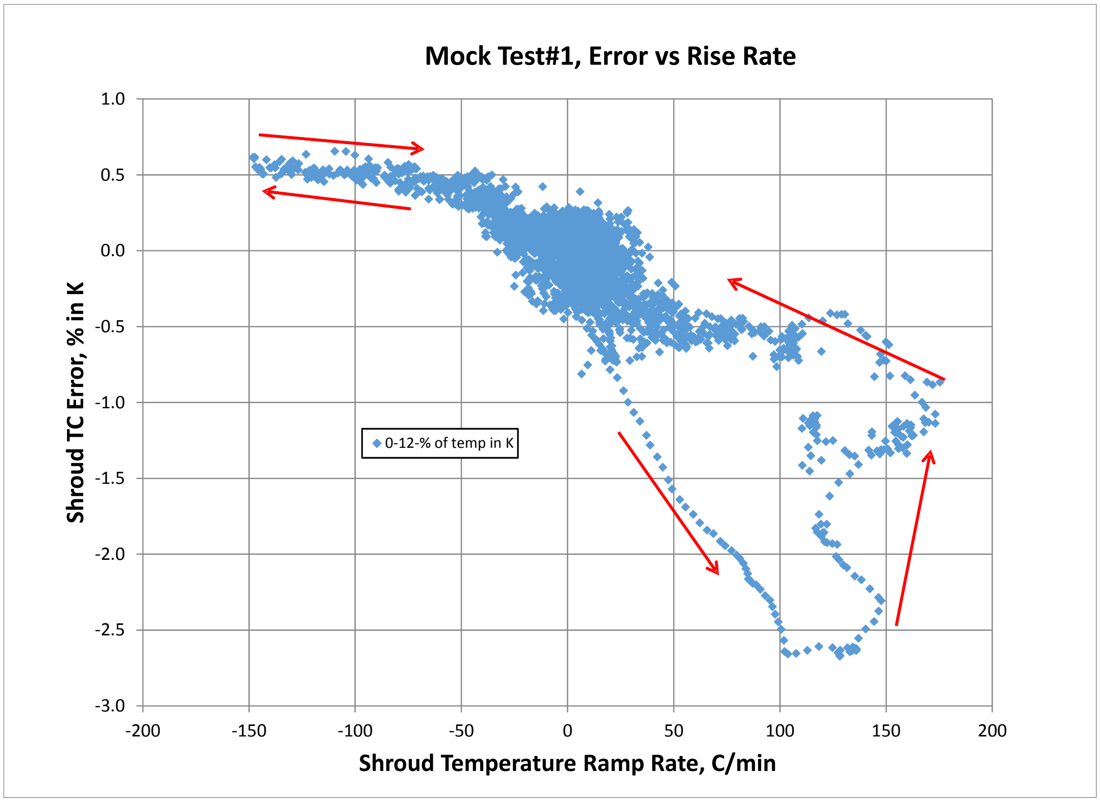


Figure 35: Mock Test#1; Shroud Error vs Shroud Temperature Ramp Rate

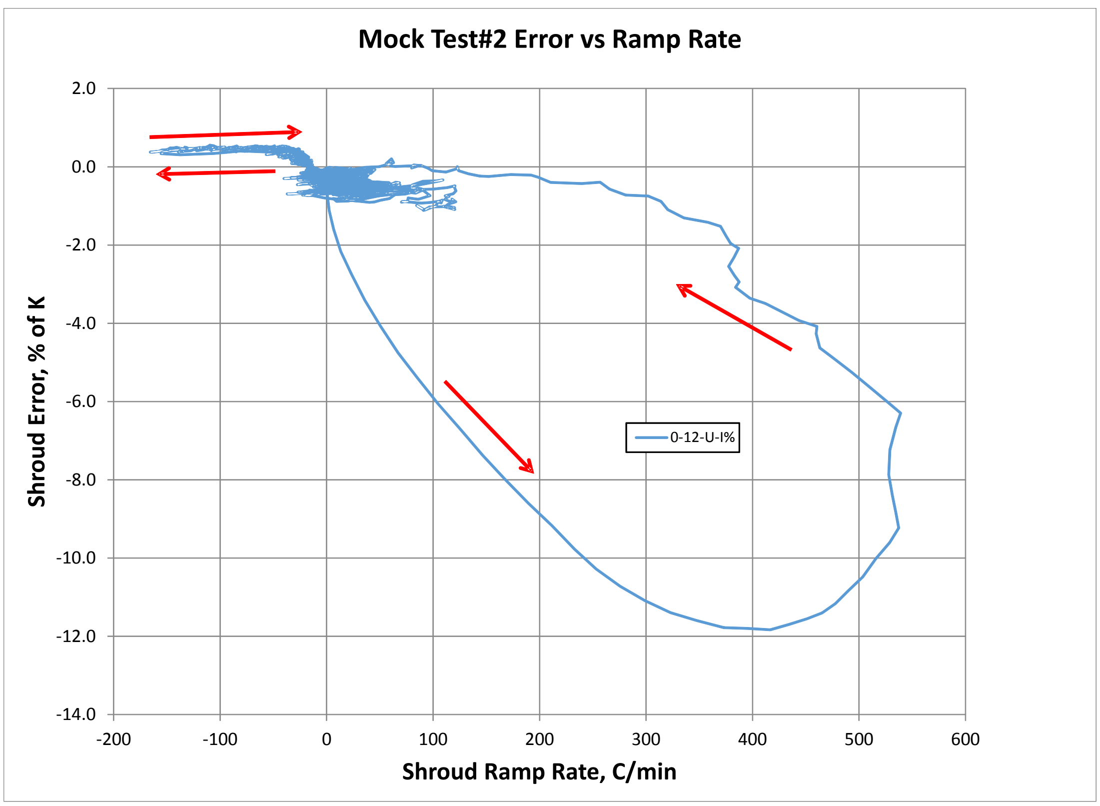


Figure 36: Mock Test#2, Error vs Shroud Temperature Ramp Rate

Table 4: Summary of Reported Errors in Ramp Rate Bins

Temperature ramp rate, C/min	Maximum shroud error, % of nominal shroud temp in K	Maximum external mock error, % of nominal external mock temperature, in K, on cone	Maximum external mock error, % of nominal external mock temp in K, on base	Maximum internal mock error range, % of nominal internal mock temperature, in K
0-100	Test#1: -1.8% Test#2: NA Test#3: -2.0% Test#4: -2.2%	Test#1: NA Test#2: +1.2% Test#3: +1.0% Test#4: +2.8%	Test#1: NA Test#2: +3.1% Test#3: +5.3% Test#4: +6.3%	Errors too small; could be just due to Type-K TC accuracy.
100-200	Test#1: -4.7% Test#2: -5.6% Test#3: -5.2% Test#4: -4.6%	Test#1: NA Test#2: NA Test#3: NA Test#4:NA	Test#1: NA Test#2: NA Test#3: NA Test#4:NA	Same
Greater than 200	Test#1: NA Test#2: -13.7% Test#3: NA Test#4: NA	Test#1: NA Test#2: NA Test#3: NA Test#4: NA	Test#1: NA Test#2: NA Test#3: NA Test#4: NA	Same

4.6 Re-visiting Overall TC Accuracy from SAND2004-1023

We now re-visit the overall error for abnormal thermal environments, but on cylindrical surfaces. Data from ref. [2] only investigated flat shrouds, and those data were used in [1], to estimate overall uncertainty of temperature measurements[1]. For abnormal thermal environments the estimate in [1] was ±2-3% in K with 95% confidence. Our goal in this study was to re-estimate the overall TC error, which includes all sources, for cylindrical setups.

For this study (cylindrical setup), we have found that, after for the initial transient (0-10 minutes), the **shroud** errors are a maximum of +1.1 to -1.7% for the remainder of the test. Errors during the initial transient were higher, +3.0 to -13.7%, but these errors occurred at relatively low nominal shroud temperatures, and occurred during periods of high ramp rates (e.g., greater than 200 °C/min.

Similar results were found on externally and internally mounted TCs on a **mock unit**. External mock errors during the initial transient were large as compared to later times, a maximum range of +6.2% to -1.2%. During the settling time period the external mock errors were in the range of 3.0% to -1.1%. The +3% value was a function of the time period chosen as the errors were dropping fast at that time. Maximum error range for external mock TCs during the settled time period was no more than about +0.2% to -1.1%. For internal mock TCs the maximum error range was no more than about +0.7% to -1.2% at all times, if one ignores the questionable data.

[1] Ref. [1] was published before ref. [2], but relevant data from [2] were available for use in [1], so [1] was published first.

We revisit the temperature uncertainty from ref. [1] and attempt to provide the results in such a way that they are easy to use. Recommendations are provided for measurements on a shroud and on the internal and external temperatures on test units in Section 6.

For shroud temperature measurements, it is recommended that in the initial transient the user just ignore the errors, even though they can be relatively large. The nominal shroud temperature is low enough that the errors likely have a negligible effect on the results. For all time periods after the initial transient, from Table 3, one can see that an approximate range of **+1.1 to -1.7%** would envelope the data.

For external mock temperature measurements, the same rationale applies to the initial transient, ignore the error because the temperature is low enough. For the settling time an approximate range would be +3.0 to -1.1%. For the settled time period the error would be **+0.2 to -1.1%.**

For internal mock temperatures, at all times, one can use an approximate range of **+0.7 to -1.2%.**

Revisiting the components of the uncertainty in SAND2004-1023 for National Instruments (NI) data acquisition systems (Table 6-9 in SAND2004-1023), we find that the random component was ±0.83 °C (random part of channel verification) and the bias components were ±2.2 °C for TC accuracy[2], ±0.80 °C for channel verification, ±0.37°C for filter step response, ±0.08 °C for long term stability, and ±0.80 °C for common mode rejection ratio. In Table 6-9 of the reference the calculation was made for normal environments, which have a negligible mounting error. For cylindrical shrouds, we have found that during any of the time periods after the initial transient, the error range is no more than about ±1.7% for the shroud or mock unit (external or internal). This specification was made symmetric for ease of calculations. Recall that it is possible that a portion of this bias error could be due to the Type-K inaccuracy, which has already been included, so we may have an overly conservative uncertainty estimate.

Using the same methodology as in SAND2004-1023 (root-sum-square combination of the uncertainty sources, we the total uncertainty is reduced to ±1.8% with 95% confidence. The 95% confidence level is assumed based on the number of tests (4), a Gaussian distribution, and number of shroud TC pairs (6), which comprised a statistically significant number of data sets.

U_{95} ≈ ±1.8% for shrouds.

A similar calculation is made for external and internal mock TCs. To account for both the settling and settled time periods, we use ±2% for external mock TCs and ±1.2% for internal mock TCs. We used ±2% rather than ±3% for external mock TCs because the +3% value came from an arbitrary selection of the duration of the initial transient (0-10 minutes). If we had chosen 15 minutes rather than 10 then the max error would have reduced from +3% to +1%.

U_{95} ≈ ±2.1% for external mock unit temperature

U_{95} ≈ ±1.4% for internal mock unit temperature

The values for cylindrical shrouds and test units are about 1/3 to 1/2 of what we have been using based on results for flat shrouds ref. [2], and they are much more symmetrical then for flat shrouds. If a single number is desired for simplicity, it is recommended that ±2.0%

[2] The ±2.2°C accuracy is for low temperatures (normal thermal environments); 0.75% of the reading in C is a larger value for abnormal thermal environments so was used in the new estimated uncertainty.

uncertainty in K be used for any of the measurements in a cylindrical setup in an abnormal thermal environment.

5. SUMMARY AND CONCLUSIONS

1) Four tests were performed to study the bias error when using 0.062" and 0.040" diameter MIMS thermocouples to measure temperatures on cylindrical metal surfaces at temperatures up to about 1000°C (1273K).
2) The errors were estimated by using multiple thermocouple pairs using 0.062" and 0.040" diameter ungrounded junction MIMS TCs (UJTC) and intrinsic junction TCs (IJTC) mounted side-by-side. Recall that the 0.062" diameter TCs were used on shrouds, and the 0.040" diameter TCs were used on the mock units.
3) IJTCs were mounted as close as possible to the end of the MIMS TC so they were measuring the temperature at the same location.
4) IJTCs are thought to be the best measurement technique available to us, but they are prone to failure and so they are not used very often.
5) Shroud TCs were mounted on the inside surface of the shroud, mock unit TCs were mounted on both the internal and external surfaces.
6) For TCs mounted on an inside surface, the UJTCs read lower than the IJTCs because the UJTCs have a higher thermal resistance and thermal capacitance than the IJTCs.
7) For locations on the outside surface of a mock unit, the UJTCs read higher early in the test because the UJTC in this case has less thermal resistance than the surface.
8) For TCs mounted on the inside surface of the mock unit, the early time errors were negative similar to the shroud TCs, and then rapidly approached small values at the end of the test.
9) Early time errors were strongly influenced by the temperature ramp rate. Late time errors were influenced by heat loss from the TC.
10) There were several questionable data sets on the inside surface of the mock. Data was difficult to explain given the expected behaviors, therefore these data should not be used.
11) For shroud TCs, the errors in the initial transient time period ranged from -3% to -13.7%, but quickly dropped to lower values during the "settling" and "settled" time periods. After the initial transient the maximum shroud errors were within +1.1 to -1.7%.
12) For external mock TCs, the errors early in the test ranged from +6.2% to -1.2% then dropped to +3.0% to -1.1% during the settling period, then +0.2% to -1.1% for the remainder of the test.
13) For internal mock unit TCs, the errors (ignoring the questionable data) had small errors throughout the test, only about +0.7 to -1.2%.
14) Errors due to uncalibrated TCs could be as high as 1.5%, so care must be used when trying to make conclusions at low errors.
15) Temperature measurements are affected by these parameters:
    a. Temperature ramp rate
    b. Diameter of MIMS TC
    c. Mock unit wall thickness
    d. What shroud TC is exposed to (e.g., a "hot" shroud or a "cold" test unit)
    e. The boundary condition on the inside of the test unit (e.g., insulated or other)

6. RECOMMENDATIONS

1) Based on the results of this study, we recommend that no adjustments be made to shroud or test unit TC data in cylindrical setups. The bias errors are small enough and symmetric enough that adjustments are not called for.
2) This is contrary to the conclusions on flat shrouds, documented in SAND2004-5080. Corrections for flat shrouds should still be made.
3) **Based on results from these tests, the uncertainty for UJTCs (0.062" diameter or 0.040" diameter) in abnormal thermal environments in test setups using cylindrical shrouds with cylindrical test units can be reduced from the ±2-3% of reading in K that is typically used, to ±2.0% of the reading in K.**

7. REFERENCES

[1] "Uncertainty Analysis of Thermocouple Measurements Used in Normal and Abnormal Thermal Environment Experiments at Sandia's Radiant Heat facility and Lurance Canyon Burn Site," Sandia National Laboratories report SAND2004-1023, by J. Nakos, April 2004.

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[4] "Ya Can't Calibrate a Thermocouple Junction, Part II – So What?," by R. Reed, Measurements and Control, October 1996.

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