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Final Report - Summary of Thermal Testing of the Furnace Characterization Unit (FCU) for the Coast Guard

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Final Report - Summary of Thermal Testing of the Furnace Characterization Unit (FCU) for the Coast Guard

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Abstract

This report summarizes the results of a series of calibration experiments performed on the Furnace Characterization Unit (FCU). The FCU (pictured above) was developed for the Coast Guard by Hughes & Associates and Ktech Corp. This device will be used to characterize furnaces used to determine the thermal response of marine bulkheads in fires. Hughes/Ktech contracted with Sandia National Laboratories to provide the thermal environment required to simulate a fire. A series of eight (8) experiments (3 "check" tests and 5 calibration tests) using two different temperature environments – a "stair step" profile and a logarithmic profile were performed. Results of the Sandia installed instrumentation is presented. Data from the FCU instrumentation installed by Ktech is presented in a separate report due to its large volume. An uncertainty analysis of the Sandia thermocouple measurements is provided.

1.0 Introduction:

This is the final report that summarizes the tasks performed during October - December 1999 by Sandia National Laboratories in support of the Coast Guard, Hughes & Associates, and Ktech Corp. regarding thermal testing of the Furnace Characterization Unit (FCU).

Topics of discussion include the following:

2.0 Overall test setup description

3.0 Test preparation

4.0 Experiments performed

5.0 Overall description of results

6.0 Thermocouple Uncertainty Analysis

Attachment 1: Infrared Camera Results Memorandum

Figures 10-136

2.0 Overall Test Setup Description

The series of experiments to calibrate the Furnace Characterization Unit (FCU) were performed at the Radiant Heat Facility (RHF), a thermal test facility located at Sandia National Laboratories, Albuquerque, NM. The overall test setup included the heater array, "shroud," transition duct, and instrumentation; each of these items will be discussed below.

2.1 Heater array

The heater array consisted of three 12" x 46" panel modules mounted side-by-side so the total width was about 36 inches and total height was about 46 inches. Figure 1 shows a view of the heater array which was available from earlier experiments.

Figure 1: Heater Array

Each of the three (3) panel modules was partially filled with a number of quartz infrared lamps each rated at a maximum of 6,000 W at 480V. Lamps were in the form of a cylinder about 3/8 in diameter by about 12" long (10 inch heated length) and were formed by a tungsten filament surrounded by a fused quartz envelope. A module can hold a maximum of 63 lamps. Each 12 inch x 46 inch module was water cooled and electrically powered with an individual power channel, therefore, there were three power control channels. Figure 2 shows a close up of several lamps.

Figure 2: Close up of 6 kW lamps

The number of lamps in each of the three panel modules was the same and were adjusted as the testing progressed to make the shroud temperature more uniform. For all of the final tests with the FCU in place, the lamp configuration was as shown in Table 1.

Table 1: Lamp Spacing for FCU Tests	
Lamp Space	Lamp in Space?
(Top) 1, 2, 3, 4	No
5, 6, 7, 8, 9, 10, 11	Yes
12 – 50	Alternate spacing - #12 – no, #13 – yes, etc.
51, 52, 53, 54, 55, 56, 57, 58, 59	Yes
60, 61, 62, 63 (Bottom)	No

2.2 “Shroud” (Flat heated surface) and Transition Duct

Because the lamp heat flux output is somewhat specular (wavelength dependent), and a more diffuse heat source is desired, there is an interim structure located between the lamps and the FCU. The structure (called a “shroud”) is a flat inconel or stainless steel plate, in this case a 40 inch square (1 m) by 1/16 in thick inconel plate reused from earlier experiments. This “shroud” is instrumented with thermocouples and painted on both sides with a high emissivity ($\epsilon = 0.85$) black paint called Pyromark®. The shroud is mounted onto a steel transition duct and supporting frame; the duct fits around the front edge of the FCU. A photograph of the shroud being instrumented is shown in Figure 3. Figure 4 shows a side view of the lamp array and structure holding the shroud. The shroud is not visible in this photograph and the FCU is not in place.

Figure 5 shows a sketch of the shroud support and "transition duct" assembly. The transition duct was fabricated for these experiments and was made of thin mild steel insulated on the outside. The inside surface was not painted with Pyromark® on the instructions of Ktech. The inside surface emissivity can be thought of as an oxidized steel surface. Twelve (12) intrinsic TCs were mounted on the outside of the duct, three on each side, top and bottom, as shown in Figure 5.

Figure 3: Shroud being Instrumented

Figure 4: Side View of Test Setup

drawn by Jack Pantuso 11-23-99

TRANSITION DUCT ASSEMBLY for FURNACE CHARACTERIZATION TEST UNIT

Figure 5: Transition Duct Assembly for Furnace Characterization Unit

2.3 Instrumentation

The shroud was instrumented with 41 thermocouples (TCs) – Ktech asked for 21 TCs to provide a “map” of the temperature on the backside of the shroud. The “back side” is the side facing the FCU. Sandia provided 20 additional shroud TCs (at no cost to Ktech) to support internal research activities; data are provided in this report. Figure 6 shows the TC layout on the shroud.

The 21 Ktech TCs were all 10 ft long, 1/16 inch outside diameter, inconel sheathed, Type K (chromel-alumel), ungrounded junction purchased from Watlow-Gordon Co. These TCs (ungrounded junction, mineral insulated, metal sheathed [MIMS]) are very reliable with low noise and are used very often at the Radiant Heat Facility (RHF). The ungrounded junction TCs were fastened onto the shroud via thin nichrome strips spot welded to the shroud. (See Figure 7.)

Thermocouples read the temperature of their measuring junction. In ungrounded junction TCs the measuring junction is protected from the environment to increase reliability. The measuring junction is located inside an inconel sheath and the individual wires are separated from the sheath by magnesium oxide insulation. As such, the measuring junction is slightly isolated from the shroud, and therefore has a small error in reading the shroud temperature.

The ungrounded junction TCs are very reliable but have a systematic error when mounted on a flat shroud like the one used for the FCU experiments – they read a small amount lower than the actual shroud temperature. To better quantify the systematic error during the FCU experiments we installed the 20 extra intrinsic junction TCs next to the ungrounded junction TCs (see Figure 7). The intrinsic junction TCs were the same (length, diameter, etc.) as the ungrounded junction TCs except the measuring tip was an exposed junction rather than a ungrounded junction – each of the chromel and alumel wires were individually welded to the shroud. Exposed junction TCs (also called intrinsic TCs) respond faster and provide a more accurate measure of shroud temperature, but are not normally used because they are less reliable. Because we wanted to be sure to have reliable instrumentation for Ktech, we chose to use the ungrounded junction TCs as shroud temperature measurements. Sandia has provided an estimate for the systematic error of the ungrounded shroud TCs later in this report.

Figure 6: TC Layout on Shroud

Figure 7: Closeup of Ungrounded Junction and Exposed Junction TCs

Two additional TCs (ungrounded junction) were placed on the concrete below the FCU and near the heater array to provide a measure of any electrical noise induced into the TCs. These "noise TCs" were placed on the concrete because the concrete temperature was almost constant during the experiment making the noise levels easier to detect. Although these two noise TCs were not at located at the same exact location as the other TCs, they provided a measure of the noise in the area near the setup. Results are shown below.

At Ktech's request, we provided some type K TC wire that was used to fabricate 12 additional intrinsic TCs which were mounted by Ktech on the outside of the enclosure structure that held the shroud in place ("transition duct"). These TCs were used by Ktech when estimating the heat flux to the FCU directional flame thermometers (DFTs). Table 2 provides a description of the duct TCs.

Table 2: Transition Duct TCs	
Designator	Description
TL	Top of duct, left side (looking from backside)
TC	Top of duct, center
TR	Top of duct, right side
LT	Left side of duct, top
LC	Left side of duct, center
LB	Left side of duct, bottom
RT	Right side of duct, top
RC	Right side of duct, center
RB	Right side of duct, bottom
BL	Bottom of duct, left side
BC	Bottom of duct, center
BR	Bottom of duct, right side

Before the FCU was put in place, we used a (Sandia supplied) infrared camera to view the back side of the shroud during the first two calibration tests (no cost to Ktech). The first test was at a distance of 3.5 inches from the shroud to the lamp panels; the second calibration test was at a distance of 6 inches. The farther distance provided a more uniform shroud temperature, and was therefore used during the actual FCU tests.

The IR camera recorded infra-red pictures on a VHS video tape. This tape was processed into several select IR images and saved into *.bmp files and was reduced via special software. Data were provided to Ktech under separate cover (Memorandum of Record from Walt Gill and Jim Nakos, dated November 12, 1999) – see Attachment 1.

Figures 8 and 9 show digital photographs (not IR images) taken during the first and second calibration tests, both at a 1000°C nominal shroud control temperature. Careful viewing of Figures 8 and 9 shows several features. First, in Figure 8 (10/18/99 test at 3.5 inches), the lower left corner of the shroud is darker (lower temperature) than the lower right corner. This was due to several burned out lamps (replaced after the first test). The shroud uniformity during the second test (10/20/99, 6 inches) based on the red coloring was better – i.e., the shroud temperature is more uniform. This is beneficial because the more uniform the shroud temperature, the easier the setup is to model computationally.

3.0 Test Preparation

In addition to hardware fabrication, other preparation for these experiments consisted of:

- a) Checking the thermocouples
- b) Checking the extension cables
- c) "Calibrating" the data acquisition (DAQ) system
- d) Developing an "Experimental Development Plan" (EDP) to be sure the hazards were properly controlled, the environmental documentation was in place, and operating procedures were in place (called "JAWS" – job analysis work sheets).
- e) Setting up the DAQ system and control system.
- f) Performing check tests or calibration tests to ensure the equipment was functional.

a) Checking the TCs

Based on past experience, we have found that we sometimes get faulty MIMS TCs as they come from the factory. The most common problem is that the connectors are wired backwards. To check each TC, we measured the loop resistance, and resistance from each wire to the sheath on all MIMS TCs to ensure neither wire was shorted to the sheath. We also checked each connector to ensure they were wired correctly (alumel is slightly magnetic and is the negative lead, so this could be easily checked).

After checking all of the MIMS TCs we found three connectors (out of 41) were wired backwards, and one had low resistance to sheath. We replaced the one that had low resistance to sheath, and re-wired the connectors on the other three. Individual check sheets were written for each TC and are available if needed.

Figure 8: Calibration Test 2, 10-18-99, 1000°C Nominal Temperature, 3.5 inch distance from lamps to shroud

Figure 9: Calibration Test 2, 10-18-99, 1000°C Nominal Temperature, 6 inch distance from lamps to shroud

b) Checking the TC extension cable

Once fabricated and checked, we reuse TC extension cables for subsequent experiments. The extension cables for these experiments were used several times in the past, so were fully operational (almost new). Nonetheless, we checked two of the three cables and recorded resistances on individual check sheets (available if needed). No problems were found.

c) "Calibrating" the data acquisition (DAQ) system

Just before the FCU experiments, we "calibrated" the entire DAQ system without the TCs in place. This is to check the continuity and viability of all the hardware and software in the system from where the TC plugs into the extension cable, throughout the system to the output monitor or data file. We use a device called an "Ectron" calibrator (Model 1100) that provides a highly accurate input signal into the DAQ system that simulates a known temperature. Per the statement of work, we checked the system at three temperatures: 100, 500, and 1000°C (10, 50, and 100% of full scale). As can be seen from Table 2, the DAQ system had an uncertainty of less than $\pm 1.0^\circ\text{C}$ at all temperatures. This is not a statement of the uncertainty of the entire system – that will be provided later once the systematic error of the ungrounded junction TCs is analyzed – but it is a good check on the overall viability of the entire system except the TC.

d) Developing an "Experimental Development Plan" (EDP)

To be sure the hazards were properly controlled, to ensure the safety of staff and customers, to be sure any environmental concerns were addressed, and to put into place typical operational procedures (called "JAWS" – job analysis work sheets), we develop an "Experimental Development Plan" (EDP) for each test series. EDP #179 was written for this test series; suffice it to say that there were no safety or environmental concerns out of the ordinary. A copy is available if needed.

e) Setting up the DAQ system and control system.

The desired logarithmic and stair step temperature versus time profiles were programmed into the control system via a spreadsheet provided by Ktech for the logarithmic profile. The DAQ system was setup for the correct number of TCs and checked for proper operation.

f) Performing check tests or calibration tests

To ensure the equipment was functional and all of the "bugs" were found and resolved, we performed two calibration or check tests (10-18-99 and 10-20-99). We found several broken lamps, leaky water hoses, and made several small adjustments to the setup. We also took the IR camera data during those two check tests and decided the 6 inch distance was the best configuration.

Table 3: Data Acquisition System "Calibration" for FCU

Thermocouple Identification	DAQ output when Ectron Calibrator Output = 100C	DAQ Output when Ectron Calibrator Output = 500C	DAQ Output when Ectron Calibrator Output = 1000C
TC1	100.1	499.7	999.4
TC2	100.5	499.7	999.7
TC3	100.5	499.9	999.8
TC4	100.4	500.1	999.7
TC5	100.5	499.8	999.6
TC6	100.1	500	999.8
TC7	100.1	499.8	999.5
TC8	100.3	499.9	999.7
TC9	100.3	500	999.6
TC10	100	499.8	999.5
TC11	99.9	499.5	999.5
TC12	100.1	499.9	999.4
TC13	100.3	499.6	999.3
TC14	100	499.7	999.2
TC15	100.4	499.8	999.5
TC16	100	499.8	999.4
TC17	100.3	499.6	999.4
TC18	100.4	499.9	999.6
TC19	100.2	499.7	999.4
TC20	100.2	499.6	999.5
TC21	100.3	500.1	999.7
TL	100.3	500.1	999.7
TC	100.4	499.9	999.5
TR	100.5	499.8	999.8
LT	100.5	499.9	999.4
LC	100.6	500	999.5
LB	100.4	499.8	999.5
RT	100.6	500.1	999.8
RC	100.5	500.1	999.7
RB	100.4	500	999.7
BL	100.4	499.9	999.6
BC	100.2	499.9	999.5
BR	100.5	500.1	999.8
Maximum difference from Ectron output	+ 0.6°C, -0.1°C 0.2% uncertainty maximum	- 0.5, + 0.1°C 0.1% uncertainty maximum	-0.8, +0.0°C 0.1% uncertainty maximum

4.0 Experiments Performed

A summary of the experiments performed is shown in Table 4.

Table 4: Summary of Testing October - December 1999			
Test Date	Description	Purpose	Comments
10-18-99	Check test #1	Equipment check, shroud uniformity, IR camera profile	Shroud 3.5 inches from lamp panels
10-20-99	Check test #2	Equipment check, shroud uniformity, IR camera profile	Shroud 6 inches from lamp panels
10-21-99	FCU check test	FCU equipment check	Stair step profile – short hold
10-27-99	FCU Run #1	First FCU calibration test	Logarithmic profile
10-27-99	FCU Run #2	Second FCU calibration test	Stair Step profile – short hold
10-28-99	FCU Run #3	Third FCU calibration test	Stair step profile – long hold
12-13-99	FCU Run #4	Fourth FCU calibration test	Logarithmic profile
12-13-99	FCU Run #5	Fifth FCU calibration test	Logarithmic profile

a) Logarithmic Profile

The FCU was exposed to two different temperature - time profiles to provide dynamic response data. A temperature range of ambient to 1000°C was traversed. One temperature profile was defined by the International Maritime Organization (IMO) time temperature curve:

$$Temperature = [345 \cdot \log_{10}(8 \cdot t + 1)] + 20 \quad (1)$$

where: t = time (minutes)

T = Temperature is in Celsius

The IMO curve had a nominal 60 minutes of total test time. Ktech provided Sandia with an Excel spreadsheet approximating the continuous logarithmic curve with a piece-wise linear curve that was programmed into the control system computer. The piece-wise linear fit approximated the entire logarithmic curve by using 10 points. The times and temperatures for the profile used is shown in Table 5.

b) "Stair Step" Profiles

Two "stair step" profiles were used – the "short step" and the "long step" (shown later). The only significant difference between the two profiles was the length of time at the hold temperatures. The short step profile had hold temperatures every 100°C from ambient to 1000°C. Hold time was about 8 minutes at each step. Total duration for the short step experiment was about 72 minutes and went up to 900°C. The test was terminated at 900 rather than 1000°C because several FCU heat flux gages were overheating.

Table 5: Piecewise Linear Approximation for Logarithmic Profile	
Time, minutes	Temperature, C
0	20
1	349
2	445
4	544
6	603
8	645
12	705
21	789
38	877
60	945

The long step profile hold times varied from about 10 to 15 minutes depending on the temperature level. Control holds were established every 100°C from 200 to 700°C. Higher temperatures were not reached because of Ktech's desire not to overheat the heat flux gages. The experiment lasted about 168 minutes.

5.0 Overall Description of Results

5.1 Check Tests #1 and 2 (10/18 and 10/20/99)

The purposes of performing Check Tests 1 & 2 were as follows:

- 1) Checkout of equipment and instrumentation
- 2) Gather temperature data from IR cameras on backside of shroud
- 3) Determine the best distance (most uniform temperature) from the heater array to the shroud

Equipment checkout went well – there were a few burned out lamps and leaky water hoses that were replaced, and extra insulation had to be placed on vulnerable cabling to ensure there was no heat damage. Otherwise the equipment worked as intended.

Temperature data from an analog IR camera was gathered on Check Tests 1 & 2. Data were reduced and compared with thermocouple data from the three control TCs (TC9, 11, and 13). Data are summarized in Attachment 1.

From IR camera data it can be seen that the horizontal profiles are very uniform between the three panels, but drop off at the edges, as expected. There are slight drops in shroud temperature at locations corresponding to where the panel modules meet. It is also clear that the shroud temperature profiles are more uniform in Configuration 2, when the shroud is 6 inches from the heater array, rather than Configuration 1 at 3.5 inches. Therefore, we chose the 6 inch distance for the remainder of the experiments. Due to the extensive amount of data available from the remaining experiments, we will not discuss these experiments further.

5.2 FCU Check Test (10/21/99)

The FCU check test was performed on 10/21/99 to verify operation and instrumentation of the FCU and related equipment. The profile was a short stair step. The equipment worked sufficiently well to conclude that we were ready for the FCU runs scheduled for the next week.

Due to the large amount of data that will be presented on FCU Runs 1-5, data from the FCU check test will not be presented here.

5.3 FCU Run #1, Logarithmic Profile, 10/27/99

We will only present data from the Sandia instrumented shroud and transition duct. Extensive data are available from the FCU from Ktech.

Figure 10 shows the control TCs from FCU Run #1 in Figure 10. The three TCs used as feedback control were ungrounded junction TCs 9, 11, and 13. Also shown on Figure 10 is a logarithmic profile (Equation 1), and the piecewise linear approximation to the logarithmic profile, both of which begin at the same time the TCs begin to rise (1.35 minutes).

As can be seen from Figure 10, the control TCs followed the linear approximation of the logarithmic profile closely. The control TCs lagged behind the linear approximation very early in the experiment, overshoot a little at about 400°C, and undershot from about 10 minutes until the end. Overall, the control achieved shows excellent agreement with the desired linear approximation.

Figures 11-13 show plots of horizontal shroud temperature from ungrounded junction TCs 1-21. TCs 1-7 were on the top row, 8-14 on the middle row, and 15-21 on the bottom row. As can be seen, the edge TCs 1, 7, 8, 14, 15, and 21 are below the other 5 TCs on each row. This behavior is expected because the middle of the shroud is expected to be more uniform than the edges. The middle 5 TCs on each row are clustered within about 25°C of each other, indicating a uniform shroud temperature profile.

Figures 14-20 show shroud TCs (ungrounded junction) in columns. Figure 14 shows the right edge shroud TCs 1, 8, and 15, Figure 15 the next column of TCs (2, 9, and 16), etc. Except for the left and right edges (Figures 14 and 20) the TCs are clustered quite close together. The plots shown in Figures 14 and 20 show some spread due to edge effects.

Figures 21-24 show the transition duct TCs, which were made of fiberglass insulated TC wire, with each wire welded to the transition duct ("intrinsic TCs"). As can be seen, each of the transition duct TCs rose to about 800°C, less than the shroud temperature maximum of slightly less than 900°C. For the top and bottom of the duct, the center TCs were the highest while the left and right sides read almost the same. For the left and right sides of the duct, the bottom TCs were the lowest, while the center and top read almost the same.

Figures 25-27 show horizontal shroud temperature profiles at three times (10, 25, and 40 minutes) that correspond to increasing shroud temperatures (650, 800, 870°C). Figure 25 is for the top row,

Figure 26 for the middle row, and Figure 27 for the bottom row. As can be seen the horizontal shroud profiles are very uniform from 20-80 cm in the center of the shroud, dropping off at the edges. In the center 20-80 cm (middle 5 TCs), the temperature profiles were uniform to about ± 3 % for all three times and all three rows. For all 7 TC measurements the profiles were uniform to about +6 % and -12 % (all three times and all three rows).

Figures 28-34 show vertical temperature profiles from 10-90 cm on the shroud. In 6 of the 7 plots, the vertical profiles are concave downward. Figure 29 showing TCs 2, 9, and 16 is concave upward. It is not known why this occurred, but TC 9 could be slightly in error. The highest non-uniformity of all 7 cases are in Figures 29 and 33, and were no more than about +5 %, -8 %.

Figures 35-39 show the difference between intrinsic junction TCs (TC22-41) and ungrounded junction (TC1-20) TCs. In general the temperature difference quickly rises to as high as about 50°C, then drops quickly, rises slowly up to a maximum, then levels out or slowly drops until the power is turned off at about 41-42 minutes. Because we believe intrinsically mounted TCs offer the most accurate representation of the shroud temperature, the "real" shroud temperature will be assumed to be that of the intrinsic TCs. However, also because they are unreliable, the data has to be carefully scrutinized.

Because the ungrounded junction TCs are 1.6 mm (1/16 inch) diameter, the same thickness of the shroud, and the TCs are mounted on the side facing away from the lamp array, one would expect the ungrounded junction TCs should read a temperature lower than that of the shroud. This behavior may be thought of as the same as a fin, where the fin temperature is lower than the body of the object because it radiates and convects to the environment.

Because Figures 35-39 show the temperature difference intrinsic TC – exposed junction TC, the differences should be positive when the shroud is being heated. This is the case in all of the plots. However, the behavior of the individual plots varies considerably. For example, in Figure 35 all four plots show the same behavior: quick rise followed by a quick fall, followed by a slow rise to an intermediate maximum, followed by a slow drop and finally a leveling off. After the power is turned off, the plots show a quick drop to negative values then a slow rise to zero. After the power is terminated, the shroud begins to radiate from both sides with no more heat input, therefore loses heat faster than the TC. Therefore, the difference goes negative.

One plot on Figure 36 (TC28-TC7) shows a different behavior – a quick rise followed by an exponential like drop to about 5-6°C difference, much less than the other three differences. Similar behavior can be seen in Figure 38 (TC35-TC14) where the difference goes to less than zero. Additionally, the difference TC36-TC15 should also be considered suspect because it continually drops as time progresses. These behaviors are not expected and are contrary to the remaining pairs of TCs. Therefore, the three intrinsic TCs (TC28, 35 and 36) in these figures should be considered suspect and not be used.

The quick rise in temperature difference is due to the intrinsic junction TCs responding faster than the ungrounded junction TCs as they respond to the rapidly rising shroud temperature. This is especially true for the time between 2-3 minutes when the shroud temperature rapidly rises.

Just before the power is terminated at about 41-42 minutes, the temperature differences range considerably as shown in Table 6. At the same nominal temperature, the difference between the intrinsic and ungrounded junction TCs should be the same. Small differences between the viability of the intrinsic TCs (e.g., moisture penetration into the MgO) and the mounting of both the intrinsic and ungrounded junction TCs are believed to cause these differences.

The differences (i.e., systematic error between the intrinsic and ungrounded junction TCs) are largest (both absolutely and on a percentage basis) at about the 10-20 minute time (ignoring the initial spikes), rather than at the highest temperature. Based on past experiments and the results from the stair step runs, we expected the differences to rise with absolute temperature, rather than dropping as seen in Figures 35-39. In fact, data from the stair step profiles shown later do show an increasing error with nominal shroud temperature.

Table 6: Comparison of Temperature Difference Between Intrinsic and Ungrounded Junction TCs – Logarithmic Profile Run 1, 10/27/99		
TC numbers	Approximate Difference at 40 Minutes, C	Comments
TC22-TC1	6.0	
TC23-TC2	15.2	
TC24-TC3	13.7	
TC25-TC4	11.2	
TC26-TC5	20.2	
TC27-TC6	16.1	
TC28-TC7	3.9	TC28 is suspect
TC29-TC8	8.1	
TC30-TC9	16.4	
TC31-TC10	18.1	
TC32-TC11	11.8	
TC33-TC12	16.8	
TC34-TC13	15.0	
TC35-TC14	-2.2	TC35 is suspect
TC36-TC15	1.5	TC36 is suspect
TC37-TC16	10.2	
TC38-TC17	14.0	
TC39-TC18	10.7	
TC40-TC19	16.2	
TC41-TC20	23.2	
Average without 28, 35, 36	14.3	

We are in the process of trying to develop a model to qualitatively predict the systematic error of the ungrounded junction TCs mounted on the shroud. However, until that time when the model is available, an empirical method will be used to estimate the systematic error. We will assume that after the initial spike and drop, the errors are roughly constant. Taking an arithmetic average of the

differences after the fast rise in shroud temperature to about 400°C (t = 5 minutes) to the end of the experiment, the differences (i.e., systematic errors) were averaged and are shown in Table 7. They range from a maximum of about 24°C to a minimum of about 9°C. The average (bottom row of the table) is about 16.7°C – this can be used if desired to adjust the measurements of the ungrounded junction shroud TCs (1-21) to higher values.

Table 7: Comparison of Temperature Difference Between Intrinsic and Ungrounded Junction TCs – Logarithmic Profile Run 1, 10/27/99		
TC numbers	Arithmetic Average of Temperature Difference (systematic error) between 5 and 41 minutes, °C	Comments
TC22-TC1	9.2	
TC23-TC2	15.1	
TC24-TC3	17.0	
TC25-TC4	12.7	
TC26-TC5	24.0	
TC27-TC6	19.8	
TC28-TC7	NA	TC28 is suspect
TC29-TC8	12.1	
TC30-TC9	18.3	
TC31-TC10	21.8	
TC32-TC11	14.7	
TC33-TC12	20.6	
TC34-TC13	17.4	
TC35-TC14	NA	TC35 is suspect
TC36-TC15	NA	TC36 is suspect
TC37-TC16	11.0	
TC38-TC17	18.1	
TC39-TC18	11.1	
TC40-TC19	18.4	
TC41-TC20	23.0	
Average	16.7	At 5 minutes, nominal shroud temperature is about 530°C, so error is 2.1% (16.7/530+273). At 41 minutes, nominal shroud temperature is 885°C so error is 1.4%.

5.4 FCU Run #2, Short Stair Step Profile, 10/27/99

Figure 40 shows the control TCs for the short stair step profile run #2. During the 100, 200, and 300°C steps, some large overshoot can be seen. The overshoot diminishes during the higher temperature steps and is almost negligible at 700, 800, and 900°C. Overshoot is hard to eliminate

at all temperatures – the control system settings were optimized for the higher temperatures. Control at each constant temperature hold was excellent – within $\pm 4^{\circ}\text{C}$ for all three control TCs (TC9, 11, 13) (checked at 300, 500, 700, 900 $^{\circ}\text{C}$ nominal temperatures).

Figures 41-43 show horizontal row shroud temperatures. Similar to the Logarithmic Profile Run #1, the left and right edge TCs (TCs 1, 7, 8, 14, 15, 21) are lower than the center 5 TCs, but the center five TCs are close to one another.

Figures 44-50 show vertical column TCs for all 7 columns. Similar to the Logarithmic Profile Run #1, the TCs in the center 5 columns read closer than do the left and right edge TCs in Figures 44 and 50. This is due to the larger gradients towards the edges and corners of the shroud.

Figures 51-54 show the transition duct temperatures. As expected they rise with shroud temperature, however, the temperatures don't have enough time to stabilize at a constant temperature. As with the Logarithmic profile Run #1, in the top and bottom of the duct the center TCs were the highest, while on the left and right sides the bottom TCs were the lowest, followed by the middle TCs, and the top TCs were the highest.

Figures 55-57 show horizontal shroud temperature profiles at three times: 18, 43, and 69 minutes. These times correspond to three nominal shroud temperatures: 200 $^{\circ}$, 500 $^{\circ}$, and 800 $^{\circ}\text{C}$. Similar to the Logarithmic Profile Run #1, the profiles are very uniform from 20-80 cm ($\pm 4\%$ or less), but less so across the entire shroud ($+10\%$, -17%), as one would expect, due to edge effects.

Figures 58-64 show vertical shroud temperature profiles at the same three times (18, 43, and 69 minutes). The largest non-uniformities are in Figures 62 and 63 and are largest at lowest temperatures ($+8.8\%$, -12.1% at 18 minutes) and smallest at highest temperatures ($+1.1\%$, -2.7% at 69 minutes).

Figures 65-69 show plots of intrinsic/ungrounded junction TC temperature differences. Several features are evident: 1) the temperature differences (i.e., systematic errors of ungrounded junction TCs) rise with increasing shroud temperature; 2) the temperature differences at each hold temperature rise quickly, drop soon after the peak, rise again and then slowly drop (especially obvious at the lower temperatures) – the same behavior seen during the Logarithmic Profile Run #1; and 3) at higher temperatures the differences don't have enough time to stabilize. As with Run #1, TC28, 35, and 36 are thought to be faulty and should be ignored. Because the differences had not stabilized, and because similar data are available from the Long Stair Step Run #3, we will not reduce the difference data further.

5.5 FCU Run #3, Long Stair Step Profile, 10/28/99

Figures 70-99 show results from the Long Stair Step Profile, Run #3, 10/28/99. Figure 70 shows the control TCs. During the initial rise there was a considerable amount of overshoot due to improper settings on the power controllers (i.e., gain, rate, reset, etc.), but this was quickly remedied.

During the time between about 95-100 minutes there were two unplanned excursions. At about that time we were asked to hold the temperature at 500°C longer than the pre-programmed profile duration. When we turned off the automatic control to lengthen the hold time, the system "thought" it was time to increase to the next higher temperature (600°C) so increased power. By the time we realized what had occurred, the shroud temperature had already increased to about 600°C. It took several minutes to re-stabilize the shroud temperature to 500°C. Other than these two excursions, control was steady with little overshoot or undershoot. Again, control at each constant temperature hold was excellent – within $\pm 3^\circ\text{C}$.

Figures 71-73 show shroud temperatures on the top, middle, and bottom rows of TCs. As expected the 5 TCs in the middle of the shroud are clustered together, while the edge TCs are lower in temperature.

Figures 74-80 show shroud temperatures on the 7 columns. As with the other experiments, the edge TCs show more scatter than do the center 5 columns, due to edge effects.

Figures 81-84 show the transition duct TCs; the behavior is similar to the other Runs, but the temperatures have more time to stabilize and so were higher.

Figures 85-87 show the horizontal shroud temperature profiles at three times (20, 120, and 165 minutes) corresponding to shroud temperatures of 200°, 500°, and 700°C. These are similar to plots from earlier experiments with similar non-uniformities, so will not be analyzed further. Similarly, Figures 88-94 show vertical shroud temperature profiles at the same times. Behavior is similar to earlier Runs, so the data are not analyzed further.

Figures 95-99 show the intrinsic/ungrounded junction temperature differences. As with earlier runs, TCs 28, 35, and 36 should be considered erroneous. Additionally, TC39 should be considered suspect because of its behavior.

It is tempting to express the systematic error (intrinsic-ungrounded junction differences) as a constant at each shroud temperature, ignoring the spikes that occur at the beginning of each rise to a new shroud temperature. At the lower shroud temperatures this is a reasonable empirical method – e.g., see Figure 95 at 200°, 300°, 400°, and 500°C. For the higher shroud temperatures (e.g., 600 and 700°C) the differences are not as constant and so it is difficult to estimate a constant error. Nonetheless, until a model is developed, providing a constant value is a reasonable option. As result, we have estimated a constant value of the temperature difference versus nominal temperature of the ungrounded junction TC, and provided that information in Table 8.

Table 8 shows that the % errors, that is the systematic error of the ungrounded junction TCs as compared with the intrinsic junction TCs, which are assumed to be the actual shroud temperature, are only about 1% using an absolute scale (°K). This is less than originally thought based on previous data from Nakos, 1999, where errors of about 5% were observed. The data from Nakos, 1999 was based on data taken in 1980 and 1982, so perhaps TC technology has improved, and our mounting methods more consistent so the systematic errors are less. Also, the % values of the 1980-1982 data were expressed in °F, not on absolute scale (e.g., °R or °K) which would make the % errors larger than if expressed on an absolute scale.

Therefore, for data from Run #3, systematic errors of about 1% (i.e., the ungrounded junction TCs read about 1% lower than the actual shroud temperature) can be assumed if a single number is desired. This compares with a maximum error of about 2% for Run #1 (See Table 7.)

5.6 FCU Runs #4, and 5, Logarithmic Profile, 12/13/99

Subsequent to the first three runs, Ktech replaced the air flow system with a larger fan and ductwork. The last two runs were performed on 12/13/99, both being logarithmic profiles. Results for Run #4 are shown in Figures 100-114 and results from Run #5 are shown in Figures 115-129. Because the results are very similar to those from the first logarithmic profile, detailed description and analysis will not be done.

Figure 100 shows the three shroud control TCs from Run #4, which behaved as expected and very similar to the first logarithmic test.

Figures 101-103 show the top, middle, and bottom row TC responses from Run #4, also very similar to those from the first logarithmic profile run.

Figures 104-110 show the vertical profiles from Run #4, and Figures 111-114 the transition duct temperatures. All behaved similarly to the first logarithmic profile run.

Figure 115 shows the three shroud control TCs from Run #5, which behaved as expected and very similar to Runs #1 and 4.

Figures 116-118 show the top, middle, and bottom row TC responses, also very similar to those from Runs #1 and 4.

Figures 119-125 show the vertical profiles, and Figures 126-129 the transition duct temperatures. All behaved similarly to Runs #1 and 4.

6.0 Thermocouple Uncertainty Analysis

A detailed analysis of the thermocouple data acquisition (DAQ) system used during the FCU experiments has been performed in previous work (Nakos, 1999). Results of that analysis showed that the Hewlett-Packard 3852A DAQ system had a small overall uncertainty as compared with other sources. Factors taken into account were error in reading the voltage, stability, temperature coefficient, zeroing technique, reference junction uncertainty, cross-talk between channels, noise, and voltage to temperature conversion. The largest of these was noise, a random uncertainty, at about 0.10%. Because the others were at least an order of magnitude less than the noise value, and a root-sum-square method is used to find the overall uncertainty, the other uncertainty values are negligible.

Other sources of uncertainty were the TC calibration (0.75%), TC extension wire ($\pm 2.2^{\circ}\text{C}$), the systematic error due to ungrounded junction versus intrinsic junction TCs (-5.3%), and electrical

noise ($\pm 2.7^{\circ}\text{C}$). Both the systematic errors due to the junction type and the electrical noise were measured during these experiments.

a) Systematic Error – Ungrounded Junction versus Exposed Junction Sheathed (MIMS) TCs

Data from the long stair step Run #3 were used to estimate the systematic error caused by the difference in measuring junction types (ungrounded junction vs intrinsic junction) on the shroud at various shroud temperatures. Table 8 shows the results of that analysis. As noted above, at each hold temperature an average value of the temperature difference was estimated, compared with the nominal ungrounded junction TC average, then a % error was calculated using absolute temperatures ($^{\circ}\text{K}$). Lastly, the average value of the average errors ("average of averages") was estimated at each nominal shroud temperature.

Table 8: Long Stair Step Run#3, 10/28/99, Empirical Estimate of Ungrounded Junction TC Systematic Errors									
Shroud temp, C $\rightarrow$	200			300			400		
TCs – intrinsic - ungrounded	Average Difference , C	Ungrded TC avg, C	Error, %	Average Difference , C	Ungrded TC avg, C	Error, %	Average Difference , C	Ungrded TC avg, C	Error, %
TC22-TC1: average =	1.2	172.6	0.3	2.3	259.2	0.4	3.0	349.7	0.5
TC23-TC2: average =	1.8	211.1	0.4	3.2	312.9	0.5	4.6	410.2	0.7
TC24-TC3: average =	2.3	204.2	0.5	3.9	305.0	0.7	5.2	401.7	0.8
TC25-TC4: average =	1.8	208.1	0.4	2.7	309.9	0.5	3.6	407.9	0.5
TC26-TC5: average =	4.0	206.8	0.8	6.5	306.2	1.1	8.6	402.1	1.3
TC27-TC6: average =	3.5	215.7	0.7	5.5	315.4	0.9	7.2	411.5	1.0
TC29-TC8: average =	1.4	171.8	0.3	2.8	261.6	0.5	3.9	358.2	0.6
TC30-TC9: average =	2.7	201.1	0.6	4.3	301.2	0.7	5.7	401.2	0.8
TC31-TC10: average =	4.1	195.8	0.9	6.6	295.8	1.2	8.1	395.1	1.2
TC32-TC11: average =	1.8	199.2	0.4	3.4	299.8	0.6	4.9	399.8	0.7
TC33-TC12: average =	3.1	198.6	0.7	5.3	297.9	0.9	6.9	397.7	1.0
TC34-TC13: average =	2.3	200.7	0.5	4.1	300.9	0.7	5.8	400.9	0.9
TC37-TC16: average =	0.3	191.9	0.1	1.0	290.7	0.2	1.4	390.3	0.2
TC38-TC17: average =	2.7	187.2	0.6	4.4	288.1	0.8	5.9	386.4	0.9
TC40-TC19: Average =	2.3	181.6	0.5	4.7	280.1	0.9	6.1	383.2	0.9
TC41-TC20:	3.1	185.9	0.7	5.9	283.6	1.1	8.1	382.9	1.2

Table 8: Long Stair Step Run#3, 10/28/99, Empirical Estimate of Ungrounded Junction TC Systematic Errors									
Average =									
Average of averages:	2.4		0.5	4.2		0.7	5.5		0.8
Shroud temp, C →	500			600			700		
TCs – intrinsic - ungrounded	Average Difference, C	Ungrded TC avg, C	Error, %	Average Difference, C	Ungrded TC avg, C	Error, %	Average Difference, C	Ungrded TC avg, C	Error, %
TC22-TC1: Average =	2.9	440.2	0.4	4.1	531.3	0.5	4.7	626.9	0.5
TC23-TC2: Average =	5.4	504.7	0.7	7.9	601.1	0.9	10.1	697.0	1.0
TC24-TC3: Average =	5.8	496.2	0.7	8.3	592.0	1.0	9.1	687.1	0.9
TC25-TC4: Average =	4.3	502.3	0.5	6.2	599.3	0.7	7.1	694.1	0.7
TC26-TC5: Average =	8.5	497.0	1.1	12.2	591.3	1.4	13.8	685.0	1.4
TC27-TC6: Average =	7.9	504.8	1.0	10.9	599.5	1.2	11.8	693.1	1.2
TC29-TC8: Average =	3.8	455.7	0.5	5.7	553.3	0.7	5.7	652.7	0.6
TC30-TC9: Average =	6.6	500.9	0.9	9.6	600.7	1.1	11.4	701.0	1.2
TC31-TC10: Average =	9.0	495.1	1.2	12.3	594.1	1.4	13.3	695.3	1.4
TC32-TC11: Average =	5.6	499.3	0.7	8.2	599.3	0.9	9.4	699.7	1.0
TC33-TC12: Average =	6.8	499.2	0.9	10.2	598.8	1.2	11.9	699.4	1.2
TC34-TC13: Average =	6.8	500.5	0.9	9.4	600.4	1.1	10.5	700.9	1.1
TC37-TC16: Average =	2.6	494.1	0.3	4.7	596.7	0.5	5.8	697.2	0.6
TC38-TC17: Average =	7.1	485.3	0.9	9.9	585.8	1.1	10.6	687.9	1.1
TC40-TC19: Average =	6.7	482.8	0.9	9.6	585.7	1.1	9.9	686.6	1.0
TC41-TC20: Average =	11.4	477.0	1.5	15.1	581.1	1.8	16.1	679.6	1.7
Average of averages:	6.3		0.8	9.0		1.0			1.0

The "average of averages" error rises from 0.5% at 200°C shroud temperature to 0.7% at 300, 0.8% at 400, 0.8% at 500, 1.0% at 600 and 1.0% at 700°C. As a result, one can say that a reasonable value of the systematic error regarding ungrounded junction TCs mounted on the cold side of the shroud (that side facing the FCU) during Run #3 was about -1% (ungrounded junction TC read about 1% low). Results from Run #1 (Table 7) showed an error of about -1.4 to a -2.1%.

b) Electrical Noise Induced into TCs

To obtain a measure of the electrical noise during this series of experiments we installed two extra sheathed TCs (ungrounded junction) and located the measuring junction on the concrete pad. Because the concrete pad was almost at a constant temperature, fluctuations evident at the time of power on and power off would provide a measure of the magnetically induced noise into the MIMS TCs. Data from Runs #1 - 5 are shown in Figures 130-134; data from the two check tests are shown in Figures 135 and 136. Approximate times when the power was turned on and off are noted on the plots.

Noise TC1 was 10 ft long, and noise TC2 was 20 ft long. The sheaths were not connected to the HP-3852A DAQ system guard or otherwise grounded. It is difficult to see much difference between the overall noise levels before and after the power was turned on for either TC in any of the 7 plots, implying a negligible amount of noise induced into the TCs via the power system. However, the 20 ft TC had larger fluctuations than did the 10 ft long TC #1 in all tests. Both TCs were of unknown age, and so it may be that the fluctuations were due to another source than the length.

One curious behavior is seen in TC1 in Figures 130 and 131. At about 15 minutes in Figure 130 and 62 minutes in Figure 131, TC1 suddenly shows much lower fluctuations. Then, shortly after the power is turned off in both cases the fluctuations rise again. It is not known at this time why this occurred; we are studying the setup to resolve this issue.

Based on the lack of change of the signals when power is turned on and off, the electrical noise induced into the TCs via the power system is assumed to be negligible. The fluctuations in the TCs could be due to small fluctuations in the DAQ system noise levels, and the natural temperature fluctuations of the TCs.

Summary of Uncertainties

The estimation of the total uncertainty of these TC measurements, as indicated earlier, is empirical. As a result, it makes no sense to be precise in the calculation of overall uncertainty. The root-sum-square method is used to estimate the total systematic uncertainty. The same method is used to estimate the total random uncertainty. The overall method is as follows:

- 1) Generate individual uncertainty values for each of the important components of the measurement system, taking into account the entire system from the transducer to the computer used to store the data.
- 2) Use the following equations to estimate the systematic (B) and random (S) uncertainties:

$$B = [(B_1)^2 + (B_2)^2 + \dots]^{1/2}$$

$$S = [(S_1)^2 + (S_2)^2 + \dots]^{1/2}$$

The B and S values are combined by using the method provided in ASME, 1998:

$$U_{95} = \pm[(B)^2 + (2*S)^2]^{1/2} \quad (2)$$

where the individual B_i and S_i are values at 95% confidence level (2σ). Because the confidence levels of the individual uncertainty values vary, one has to be careful of how to use the above equations. For example, the TC calibration uncertainty specification is a maximum value, assumed to be 99% or 3σ . This value has to be reduced by 2/3 to provide a 2σ estimate for use in the equation (2). Therefore, after each individual uncertainty the assumed value of confidence is listed.

- 3) To obtain an uncertainty estimate for 99% confidence ASME provides the following methodology. First use the same RSS equations to determine B and S. The one difference is that the individual values are now 1σ , not 2σ . Then use equation (3) to find the total uncertainty with 99% confidence.

$$U_{99} = \pm K[B^2 + S^2]^{1/2} \quad (3)$$

Where $K = 3$ for 99% confidence.

a) Ungrounded junction MIMS TCs (TCs 1-21)

1) Systematic uncertainties:

- TC calibration: $\pm 0.75\%$ (assumed to be a 99% confidence level)
- TC connector: $\pm 1.1^\circ\text{C}$ (99%) – at 200°C this is about 0.25% and at 800°C this is about 0.1%.
Use maximum value of about 0.25%
- TC extension wire $\pm 2.2^\circ\text{C}$ (99%) – at 200°C this is about 0.5% and at 800°C this is about 0.2%.
Use maximum value of about 0.5%
- Ungrounded junction versus intrinsic junction TCs: + 0%, -2% (95%)

For 95% confidence:

$$B_+ = [(0.75 \cdot 0.67)^2 + (0.25 \cdot 0.67)^2 + (0.5 \cdot 0.67)^2 + (0)^2]^{1/2} \approx 0.6\%$$

$$B_- = [(0.75 \cdot 0.67)^2 + (0.25 \cdot 0.67)^2 + (0.5 \cdot 0.67)^2 + (2)^2]^{1/2} \approx 2.1\%$$

For 99% confidence:

$$B_+ = [(0.75 \cdot 0.33)^2 + (0.25 \cdot 0.33)^2 + (0.5 \cdot 0.33)^2 + (0)^2]^{1/2} \approx 0.3\%$$

$$B_- = [(0.75 \cdot 0.33)^2 + (0.25 \cdot 0.33)^2 + (0.5 \cdot 0.33)^2 + (2)^2]^{1/2} \approx 2.0\%$$

2) Random Uncertainties:

Noise : 0.10% (99%)

Electrical noise from power system: negligible

For 95% confidence:

$$S = [(0.10 \cdot 0.67)^2]^{1/2} \approx 0.07\%$$

For 99% confidence:

$$S = [(0.10 \cdot 0.33)^2]^{1/2} \approx 0.03\%$$

$$U_{99} = \pm [(B)^2 + (2 \cdot S)^2]^{1/2} = \pm [(2.1)^2 + (2 \cdot 0.07)^2]^{1/2} \approx 2.1\% \text{ (of the reading)}$$

$$U_{99} = \pm K[(B)^2 + (S)^2]^{1/2} = \pm 3*[(2.0)^2 + (0.03)^2]^{1/2} \approx 6.0\% \text{ (of the reading)}$$

Excluding the TC calibration uncertainty, the uncertainty due to electrical noise (negligible in this case), and the uncertainty due to the ungrounded junction systematic error, the uncertainty of the remainder of the measurement system is estimated to be about 0.6% of the reading (99% confidence, $B \approx 0.19\%$, $S \approx 0.03\%$, $K = 3$). This value is directly comparable to the results shown in Table 3: 0.2% maximum. As can be seen, the calculated value (0.6%) is three times as high as the value obtained from experimental data – a good result.

b) Exposed Junction MIMS TCs (TCs 22-41) and Intrinsic TCs (TL, TC, TR, BL, BC, BR, RT, RC, RB, LT, LC, LB)

We will assume that the exposed junction MIMS TCs and intrinsic TC wire have no systematic error due to the method by which they are mounted. This is not precisely true, but we will assume that in these experiments that the errors are negligible. Therefore, the analysis proceeds in the same manner except the error due to the ungrounded junction is eliminated.

For 95% confidence:

$$B = \pm[(0.75*0.67)^2 + (0.25*0.67)^2 + (0.5*0.67)^2]^{1/2} \approx 0.6\%$$

For 99% confidence:

$$B = [(0.75*0.33)^2 + (0.25*0.33)^2 + (0.5*0.33)^2]^{1/2} \approx 0.3\%$$

2) Random Uncertainties:

Noise : 0.10% (99%)

Electrical noise from power system: negligible

For 95% confidence:

$$S = [(0.10*0.67)^2]^{1/2} \approx 0.07\%$$

For 99% confidence:

$$S = [(0.10*0.33)^2]^{1/2} \approx 0.03\%$$

$$U_{95} = \pm[(B)^2 + (2*S)^2]^{1/2} = \pm[(0.6)^2 + (2*0.07)^2]^{1/2} \approx 0.6\%$$

$$U_{99} = \pm K[(B)^2 + (S)^2]^{1/2} = \pm 3*[(0.3)^2 + (0.03)^2]^{1/2} \approx 0.9\%$$

References

- 1) ASME PTC 19.1-1998, "Test Uncertainty, Instruments and Apparatus," American Society of Mechanical Engineers, 1998.
- 2) Nakos, J., "Uncertainty Analysis of a Thermocouple DAQ System," Working draft, April 1999.

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Attachment 1

Sandia National Laboratories

Albuquerque, New Mexico 87185-0553

date: November 12, 1999

to: Memorandum of Record

from: Walt Gill, Org 9116, MS 0553, Jim Nakos, Org 9134, MS 0555

subject: Observed temperature distributions on Radiant Heat 1m x 1m Vertical Flat Array

We recently conducted experiments at the Radiant Heat Facility with the 1m x 1m Vertical Flat Array in which we were seeking an improved (more uniform) temperature distribution over the heated shroud. We were adjusting the difference between the lamp array and the shroud, powering up the array, holding the control thermocouples on the shroud at a fixed temperature, and observing the resulting temperature distribution.

Photos of two of these experiments are shown in Figure 1. The shroud control points in both photos were being held at 1000C, and it can be seen from the shroud color that the second configuration (6" from lamps to shroud) resulted in a more uniform temperature distribution than Configuration 1 (3.5" lamps to shroud).

We also observed the shroud temperature distribution with an IR Imaging Camera. We set the camera approximately 20 ft out in front of the shroud, level with the midpoint. The camera was set to extended range, gray scale image, and emissivity equal to one. The images were recorded on VCR tape. The tape was digitized at the Area V video lab. The resulting images corresponding to the two photos are shown in Figure 2.

Figure 1. Visual comparison of the effect of distance between the lamp array and the shroud on the temperature distribution at 1000C. Lamps have burned out on the lower left corner of the Configuration 1 array.

Figure 1: Backside Digital Photographs of Shroud at 1000°C

Gray scale IR images of the same two configurations are shown in Figure 2 below. The difference in gray scale between the two images is due to auto-ranging of the camera, not to temperature differences.

Figure 2: Backside IR Camera Images of Shroud at 1000°C

The images were analyzed using SigmaScan, which allowed measuring temperature profiles along lines drawn across the shroud. Because the IR images were recorded by the camera with the emissivity set to one, the camera temperatures were corrected to an actual temperature via

$$T_{shroud} = \left(\frac{I}{\epsilon} \right)^{0.25} \cdot (T_{image} + 273) - 273 \quad C$$

The shroud emissivity was determined by comparing the image temperature to the thermocouple reading at the control points. The emissivity was found to be $\epsilon = 0.74$ for Configuration 1 and $\epsilon = 0.83$ for Configuration 2.

The results of the line scans are shown in Figures 3 and 4. Figure 3 is for Configuration 1 and Figure 4 is for Configuration 2. The second configuration has almost eliminated the "dead spots" between the lamp arrays, however, it is worth noting in both configurations, the vertical temperature variation due to the individual lamps is clearly visible.

Figure 3. Observed temperature profiles on Configuration 1.

Figure 4. Temperature profiles for Configuration 2.

Figure 10: Logarithmic Profile Run #1, 10/27/99
Control TCs, Logarithmic Profile, and Linear Approximation

Figure 11: Logarithmic Profile Run #1 of FCU, 10/27/99
Top Row Shroud TC's

**Figure 12: Logarithmic Profile Run #1 of FCU, 10/27/99
Center Row Shroud TC's**

Figure 13: Logarithmic Profile Run #1 of FCU, 10/27/99
Bottom Row Shroud TC's

Figure 14: Logarithmic Profile Run #1 of FCU, 10/27/99
Right Edge Column TCs

Figure 15: Logarithmic Profile Run #1 of FCU, 10/27/99
Center of Right Panel Column TCs

Figure 16: Logarithmic Profile Run #1 of FCU, 10/27/99
Right Side, Between Panels, Column TCs

Figure 17: Logarithmic Profile Run #1 of FCU, 10/27/99
Center Column TCs

Figure 18: Logarithmic Profile Run #1 of FCU, 10/27/99
Left Side, Between Panels, Column TCs

Figure 19: Logarithmic Profile Run #1 of FCU, 10/27/99
Center of Left Panel Column TCs

Figure 20: Logarithmic Profile Run #1 of FCU, 10/27/99
Left Edge Column TCs

Figure 21: Logarithmic Profile Run #1 of FCU, 10/27/99
Transition Duct Top TCs

Figure 22: Logarithmic Profile Run #1 of FCU, 10/27/99
Transition Duct Left Side TCs

Figure 23: Logarithmic Profile Run #1 of FCU, 10/27/99
Transition Duct Right Side TCs

Figure 24: Logarithmic Profile Run #1 of FCU, 10/27/99
Transition Duct Bottom TCs

**Figure 25: Logarithmic Profile Run #1 of FCU, 10/27/99
Top Row Shroud Profile TCs 1-7**

Figure 26: Lorgaithmic Profile Run #1 of FCU, 10/27/99
Middle Row Shroud Temperature Profile, TCS 8-14

Figure 27: Logarithmic Profile Run #1 of FCU, 10/27/99
Bottom Row Shroud Temperature Profile, TCs 15-21

Figure 28: Logarithmic Profile Run #1 of FCU, 10/27/99
Vertical Shroud Temperature Profile, TCs 1, 8, 15

Figure 29: Logarithmic Profile Run #1 of FCU, 10/27/99
Vertical Shroud Temperature Profile, TCs 2, 9, 16

Figure 30: Logarithmic Profile Run #1 of FCU, 10/27/99
Vertical Shroud Temperature Profile, TCs 3, 10, 17

Figure 31: Logarithmic Profile Run #1 of FCU, 10/27/99
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