The Calibration of Contact Surface Sensors: A Manufacturers Investigation

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Abstract

Contact surface temperature measurements represent a significant portion of industrial measurements. This study explores various methods of calibrating surface sensors and attempts to better define the surface calibration process by empirical testing. True surface temperature is derived by extrapolation using two different methods. Statistical data for the testing is reported for a large group of sensors randomly sampled and tested over a two-month period. From this data the deviation from the true surface temperature as well as the sensor to sensor reproducibility is established and is correlated to the degree of surface disturbance that is dependent partially on the temperature of the sensor and its surroundings. The described calibration methods and resultant data support previously reported expected tolerances of one percent or better of reading.

1. Introduction

Nearly all temperature sensor manufacturers produce not one, but several types of surface contact temperature sensors. This fact along with the known sales volume of at least one manufacturer of such products clearly indicates a large number of industrial companies who are routinely using contact temperature surface sensors. From this fact arises the question of providing a system of traceable calibration. Some national laboratories have acknowledged the need, but a widely applicable standard has yet to be developed or adopted. In 1995, Isotech published an article written by a member of the South African Metrology Laboratory, in which the author referred to their responsibility of calibrating surface contact sensors [1]. It is interesting to note that references as recent as the seventies cite references from the early 1900's [2]. The implication of this is two fold; first illustrating the profound lack of research in this field over a long period and secondly, the long standing interest in the issue of surface temperature. Most studies have been done by National Laboratories and consortiums and provide insufficient supporting statistical calibration data for a sizable numbers of sensors. The goal of this study is to develop a traceable calibration method for surface contact thermometers and to show the results of calibration for a large number of surface sensors using the developed method.

2. Research Development

Since there exists no standardized system for calibration, a new system had to be developed that was fundamentally sound and yet simple and easy to use. Most surface calibrators are not suited for calibration and only apparently provide traceable calibration. The system developed is a true transfer standard and does provide traceable calibration. This Surface Transfer Standard (STS) was used for the calibration of a large lot of surface sensor requiring calibration. The sensor lot sizes were approximately 10 and 40; each lot represents larger production runs of 100 or 200 respectively. Data obtained from this testing are presented and support the efficacy of both the STS and the concept of surface sensor calibration.

3. STS Construction

A center core of Aluminum, Copper or Brass was used as the calibration surface. Any material having sufficient hardness at the calibration temperature and also having a thermal conductivity greater than 100 $Wm^{-1}K$ was acceptable. A vertical length large enough to dampen heat source variability was also required. A guard ring was used to reduce the external influences on the calibration block. The glass wool insulation between the guard ring and calibration block created a quasi-one dimensional heat flux in the center block, as shown in Figure 1. Due to the guard ring construction, the radial heat flux as defined by Fourier's law $q_r^{"} = -k * \frac{dT}{dr}$ [3], where k is the thermal conductivity of the material, T is temperature and r is the radial distance from the inner block, was reduced to a negligible level. The heat flux is a vectored quantity where r represents the i,j components and Z represents the k component. The i,j or (r) components of the heat flux are small in comparison to k due to the insulating material between the guard ring and block. The first boundary condition as shown in Figure 1. also reduces the r flux, as dT is small. This condition creates a Z-axis or vertical flux towards the surface. The large surface area of a well-constructed hot plate[1] reduces the likelihood of radial variability in the block. It may seem the STS would be subject to instability, however, the 200cm. Z axis length creates a thermal lag that reduces the effect of heat source variability. Block stabilities were found to be better than ±0.2 C over a ten-minute period. Surface stability was assessed but no assessment of the precise relationship between the hot plate stability and the surface temperature stability was undertaken since the surface stability was within the test requirement.

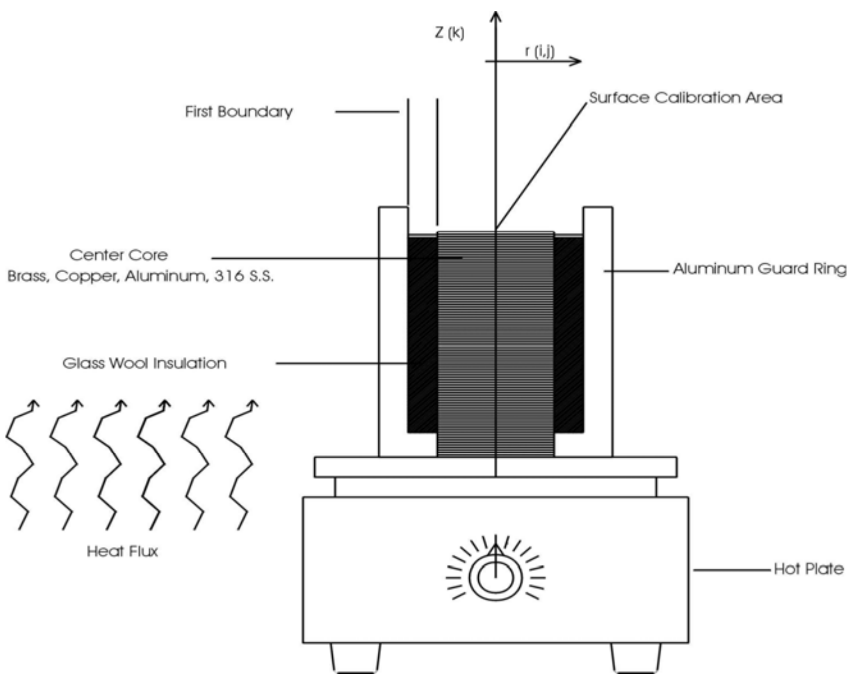


Figure1. Surface Transfer Standard (STS) Construction.

[1] A Thermolyne hot plate was used for this testing.

3.1 Alternate STS Construction

A second design for the STS was also tested and appeared to be equally accurate. The center block construction for the bath or Wet STS was identical to the center block used in the dry system. Thermocouple installation and calibration was also the same. A stirred liquid bath provided the heat source for the Wet STS. Each block was immersed into the fluid until 11.5 mm of the block was above the fluid line. (See Figure 2.) A holding system was constructed for the blocks and mounting rods were precisely installed in each block, thus reducing but not eliminating block immersion depth variability. Fluid thermal expansion and turbulent flow within the bath caused ongoing 5 to 10 mm immersion variability. The tops of the blocks were at least 10cm below the top of the bath and therefore were in a warm air environment, during testing at the 0ºC point this was not the case. Data for the Wet STS testing are presented; however, there appears to be a number of poorly quantified error contributors associated with this method. The Wet STS proved useful for testing at elevated temperature using a stirred liquid salt bath[2]. The salt bath provided a stable and uniform temperature source from 250ºC to 500ºC.

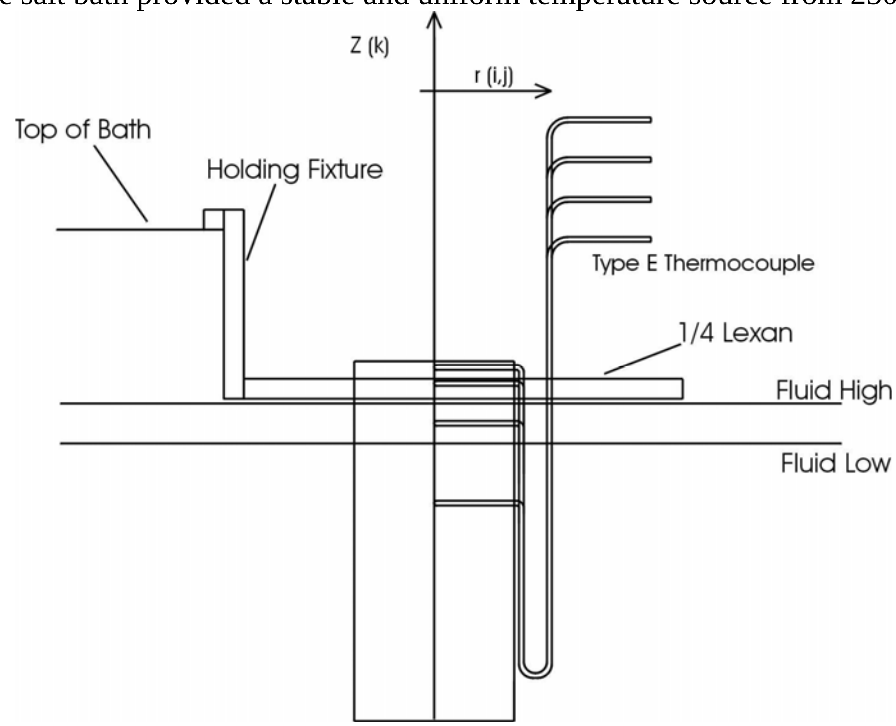


Figure 2. STS Wet Design, Thermocouple Position.

4.0 STS Traceability

In order to calibrate the STS a method to connect the device to a traceable standard was required. Simply calibrating a single RTD or thermocouple prior to insertion into the plate is unacceptable as the thermal characteristics of the sensing device will depend on the method of insertion and quality of the fit. A single sensor during calibration provides no measure of the heat flux within the block. Thermal interfaces and differences in thermal conductivity between the block and sensor prevent traceable calibration. The STS contains a series of embedded thermocouples that are placed in precisely machined bores that establish a consistent and precise fit between the

[2] A Hart Scientific stirred salt bath Mode 6055

thermocouple and block. Four grounded metal sheath .1.52 mm diameter type E thermocouples [4] were used. Each thermocouple was installed according to Figure 2. Because metal sheath thermocouples are subject to stem conduction error a system was used that created an extremely long heated region for the thermocouple. The installation method also facilitated a direct calibration of all four thermocouples in a stirred liquid bath simultaneously against a secondary PRT standard. The entire block was immersed in the bath and individual readings were taken and compared to the standard. A correction factor for each thermocouple was obtained that is directly traceable, insitu, to standard reference sensor. The difference in thermal flux within each sensor was eliminated by design in that both calibration and operation the measuring junction temperature is nearly the same as at least 10 cm of the exposed sensor. The STS was then placed on a hot plate and allowed to stabilize after which the calibration data was used to determine the precise temperature of the block at a precisely known position. A link had to now be established between the known positional temperatures and the unknown true surface temperature.

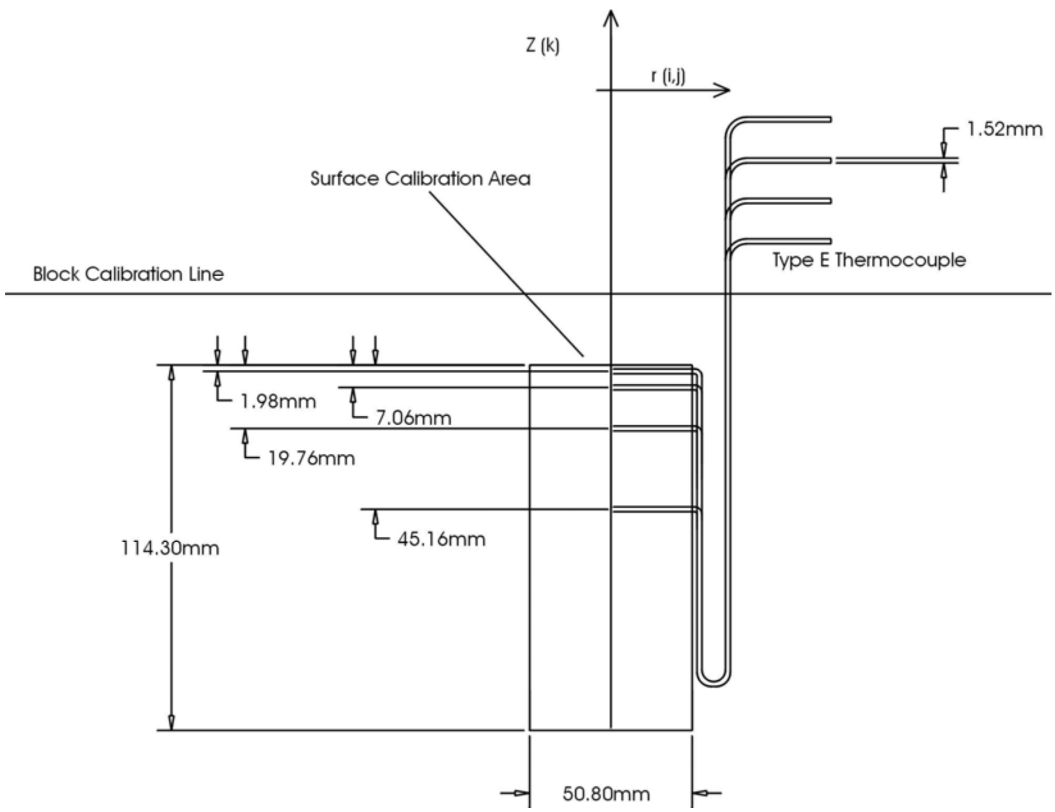


Figure 3. STS Thermocouple Installation.

4.1 Establishing the True Surface Temperature (T_s)

A true surface temperature ($T_{s)}$ was established using the extrapolation method. This technique relies on known positional temperatures within the block; that data was used to predict the surface temperature. The more recently used equation by Morice [5] was used to determine T_s. With this equation only two positional temperatures are required. However, to better assess both fit and linearity four positional temperatures were measured in each test block. The equation and positional diagram is shown in Figure 3. Positions 1 and 4 were used to determine T_s while positions 2 and 3 were used to graphically verify the fit and linearity; (See Figure 4.) The slope of each block material was dependent on the thermal conductivity (k=Wm $^{-1}$ K) of the core material. Four different materials were used as the core block in this test, Copper, Aluminum, Brass, and 316 Stainless Steel. The individual slopes for each material as tested at various temperatures as tested are shown in Figure 4. Figure 5 shows the slope versus material thermal conductivity. All of the tests produced nearly linear relationships and showed the additional positional temperatures to be within .03% or better of reading for materials having k >100Wm^{-1} K. It should be recognized that materials having k values < 100Wm^{-1} K are not suitable for a calibration device.

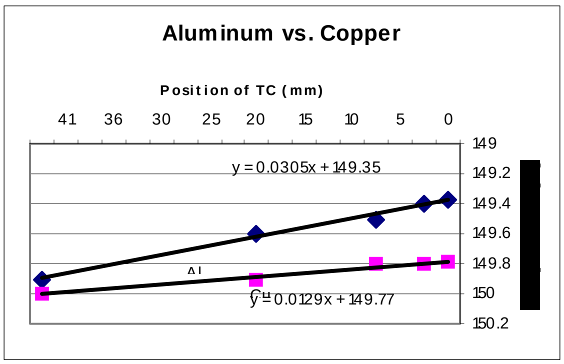


Figure 4A. Temperature Gradient in Al &Brass. & Cu.

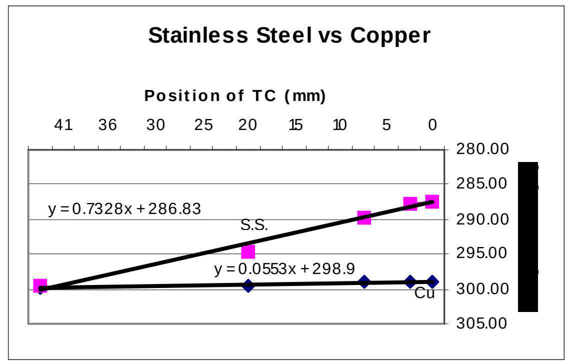


Figure 4B. Temperature Gradient in S.S.

Since equation (1) accounts only for the conductive heat transfer mode an assessment of effects of radiation and convective heat transfer from the surface was required. A basic equation accounting for these losses, given by Incropera and DeWitt [3], was used to test position four based on the extrapolated temperature $T_{s.}$ Although the equation used is referenced to Morice [5], there is documentation of both equation 1 & 2 being used in the early 1900's [2]. There were many areas of industrial interest related to surface temperatures during that period.

$$T_s = \frac{(T_2 - T_1) * (L - Z_1)}{(Z_2 - Z_1)} + T_1 \quad , \qquad (1)$$

Where L=Overall Block Length, T_1=Temperature @ Z_1, T_2=Temperature @ Z_2, Z_1=45.16 mm Position and Z2=1.98 mm Position

The only material assessed using equation 2 was brass. Agreement between the calculated value and the measured value was 0.2% at 184ºC. Equation 2 takes into account the convective heat transfer and radiation transfer losses. Emissivity (ε) and the convective heat transfer coefficient (h) were determined by table values and by calculation. The convective heat transfer coefficient was calculated using the Nusselt number for the upper surface of a horizontal plate and a Rayleigh number that was calculated using table values for quiescent air at 25ºC. These conditions approximate a laboratory environment. The emissivity value for oxidized brass was taken directly from tables [6].

$$T_1 = \frac{h*(T_2 - T_\infty) + \varepsilon * \sigma * (T_2^4 - T_{surf}^4) * L}{k} + T_2 \qquad (2)$$

Where σ= Stephan Boltzman Constant, ε=Emissivity, k=Thermal Conductivity, L=Length and h=free air convection coefficient.

Tests conducted by F. Elder of PTB [7] show good correlation between extrapolated surface temperatures and other techniques such as radiation pyrometry and Fiber Optic Fluorescence. Both techniques show T_s to be lower than the values obtained by extrapolation. Differences increased linearly from 0.3ºC deviation at 50ºC to 2.0ºC at 150.0ºC. Uncertainties for these tests were 1.0ºC to 1.5ºC for k=2. The deviations indicate the extrapolation technique overestimates T_s, by at least 1.0ºC, this assumption is deemed sensible, as the extrapolation equation does not account for free air convective and radiation losses. A detailed investigation into this area was not made because this research was limited in its scope. Values from the test equation were in agreement well within the uncertainties for this test

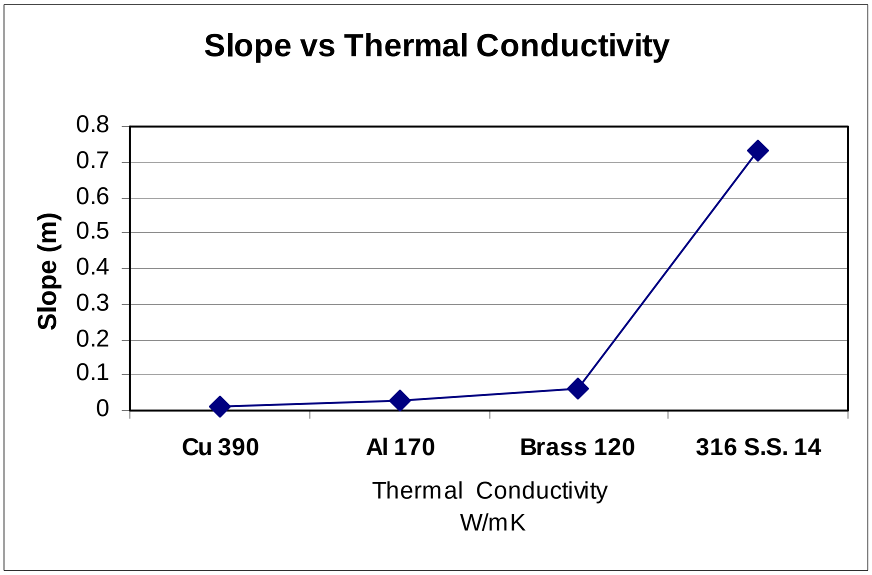


Figure 5. Slope vs. Thermal Conductivity (k).

5. Test Method

As with all calibrations, certain environmental conditions must be controlled. The ambient air temperature should be maintained at 23ºC while creating no forced air conditions in the vicinity of the test setup. Surface sensors are typically hand held test and measurement devices and should be tested as such. Figure 6. shows the design of the tested sensors. Allowing a surface sensor to remain in contact with the STS for a long period of time is unrealistic, as the sensor would never be used like this in practice. The sensor temperature should be stabilized at room temperature and was applied to the block for 30 to 60 seconds. For all first and subsequent readings the sensor temperature read between 20ºC and 30ºC prior to application to the surface. Sensor application force and alignment was considered to be a minimal problem as variances in the reading caused by inconsistencies would be included in the statistical data of the measurements taken. The large groups of sensors tested are effectively self-leveling and have some mechanical mechanism that limited the amount of force that can be applied to the surface. In the STS three readings were recorded for each sample, for T_1 the thermocouple nearest the surface in an undisturbed condition, the perturbed temperature of T_1 at the time of reading and the unit under test (UUT) value. The thermal profile within the block was recorded a two second intervals before and after each set or lot of measurements. Thermocouples T_4 and T_1 were used to calculate T_s using equation (1). The measurement error was calculated by equation (3).

$$T(UUT)-T_s = \text{measurement error.} \qquad (3)$$

The amount of surface perturbation was determined by the following equation:

$$T_{1\,(undisturbed)} - T_{1\,(disturbed)} = \text{Surface Perturbation (°C)} \qquad (4)$$

Figure 6. shows the sensors included in this test. All of the sensors are from one manufacturer. All of the statistical data presented represents conducted for 10 or 50 piece lots that were taken from standard EDL Inc. production quantities.

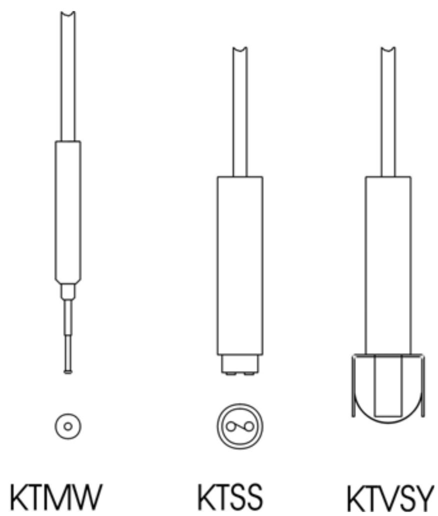


Figure 6, Surface Sensor Styles Tested.

6. Data Review

Only one set of data for tests performed using a 316S.S. block are shown. As compared to the other materials, the readings taken with the S.S. were dramatically low. And although it is likely that S.S. will be measured in the field it is not suitable as a material for calibration. Figure 7 shows the results for testing at 160°C and 300°C. The mean error for both temperatures is 5°C to 6°C. one standard deviation is from 1.0°C to 1.5°C respectively.

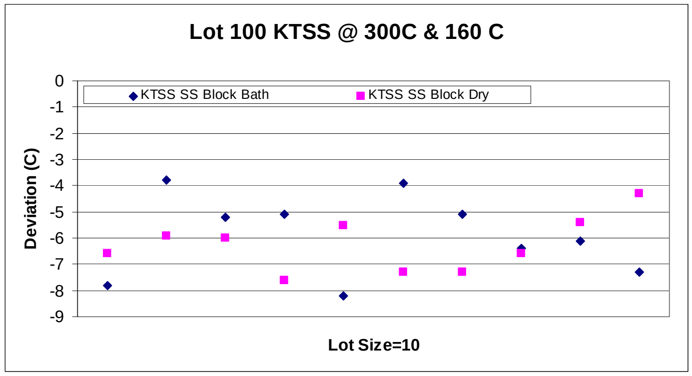


Figure 7, S.S. Test Data.

Sensor lot 100 was also tested at similar temperatures using the dry and wet STS constructed of brass copper and aluminum. (See Figure 9.) No further testing was performed using the STS constructed of Stainless Steel. Figures 8. Thru 12 show calibration data for lots of 50 sensors at various temperatures and with different core materials. The expected tolerance for each type of sensor tested was ±3.0ºC or 1% of reading whichever is greater, based on manufacturers specification. Figure 7. shows three different style sensors tested at the same temperature point. When reviewing the data one should bear in mind the relatively short time the sensor has been in contact with the surface. For all of the results shown, readings were taken between 30 and 60 seconds after contact with the surface. Applying the sensor to the surface for extended periods, e.g. 2 to 15 minutes, only marginally reduced surface versus sensor deviation. All of the data shown includes calibration corrections for each thermocouple prior to extrapolation of T_s.

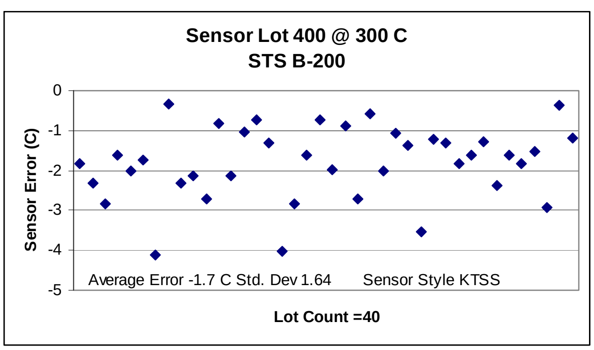


Figure 8. 300ºC Bath Method Cu.

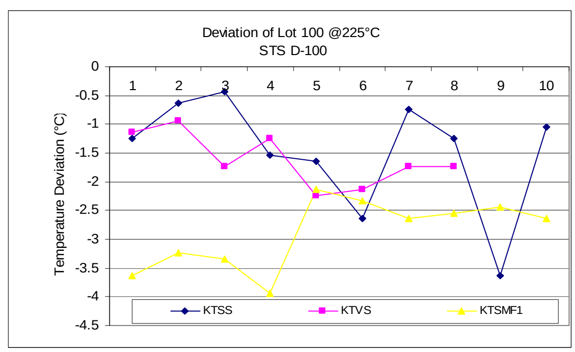
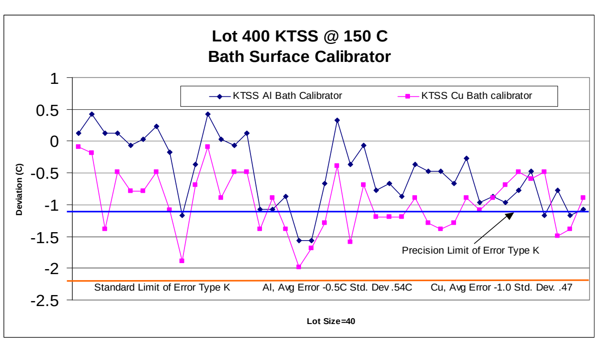


Figure 9. STS 225ºC.



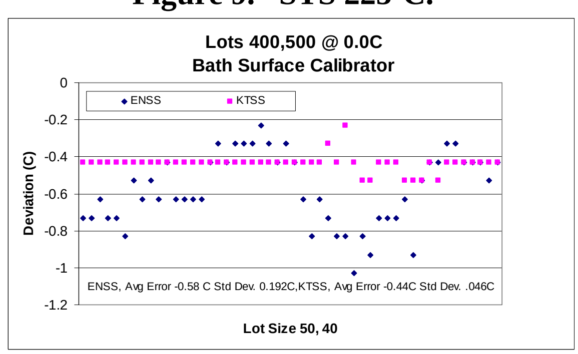


Figure 10. 150ºC Bath Method, Cu & Al. **Figure 11. 180ºC STS Dry Brass.**

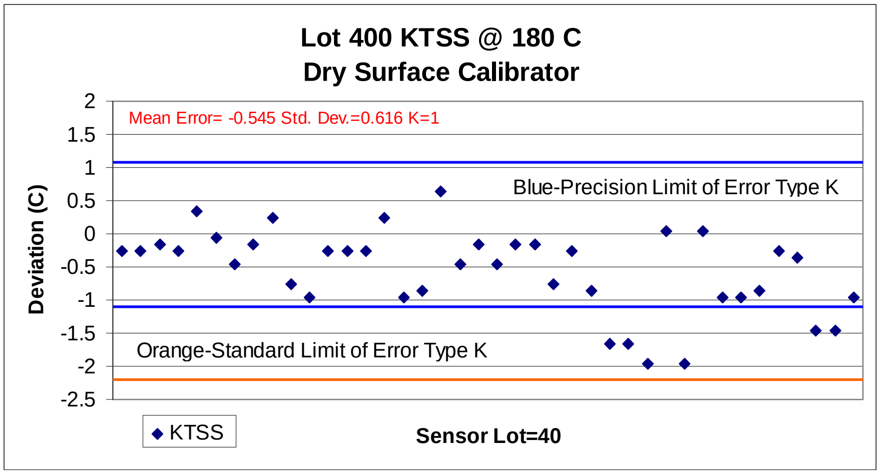


Figure 12. 180ºC STS Dry Brass.

7. Sensor Preheating

The following data are the results of a test that was performed to determine the effect of using surface sensors that have been preheated prior to the reading. It is an important consideration as the surface perturbation depends on the temperature of the sensor prior to surface contact. The sensor was tested using the previously described method; with the exception that each sensor was also reapplied to the surface as its temperature was returning to ambient. Each sensor was applied to the surface for calibration when they were at approximately 25ºC, 40ºC, 60ºC and 100ºC. The Aluminum core STS calibration system was used with a hot plate at a nominal temperature of 170.0ºC. No significant change in the sensor error was observed. Response times should improve and the surface perturbation will be decreased but the sensor accuracy will most likely only be improved by a small amount. Figure 13. shows the error for each sensor and also shows the average error for the lot of five sensors.

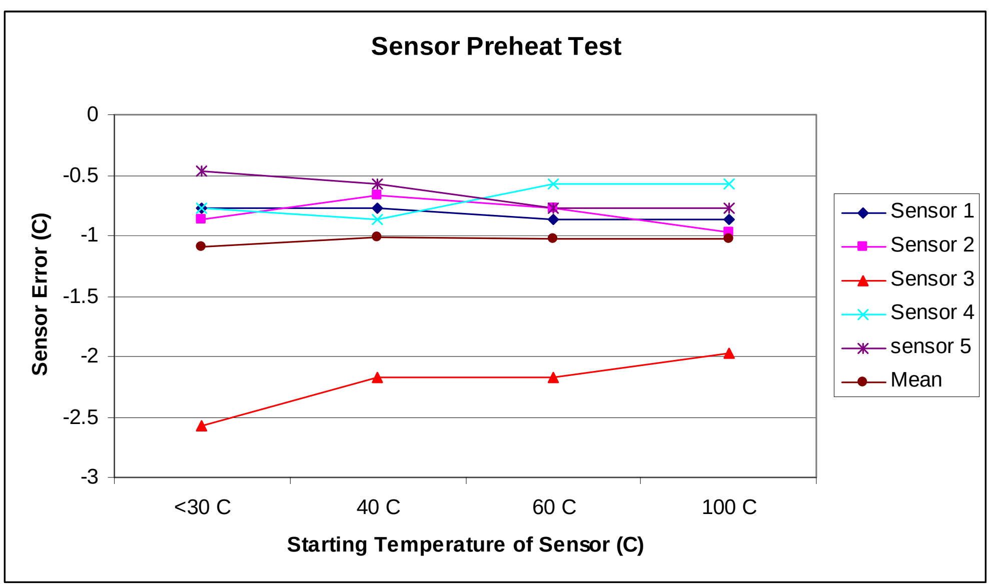


Figure 13. Sensor Pre-Heat Test.

It can be seen in Figure 13. that there is no definitive change in error; it is random and very well grouped. The average value is nearly constant from 30ºC to a 100ºC preheat. Some additional value of uncertainty must be used for an unknown sensor temperature prior to application if the sensor has not be assessed for this potential error contributor. This uncertainty contributor is not significant if the calibration procedure provides for a standardized sensor temperature prior to application to the STS surface. Preheating the sensor will be beneficial in cases where the heat flux s not in a steady state condition or where the mass of the source is low and sensitive to the influence of the sensor.

8. Uncertainty

The method used for estimating and combining uncertainties in this study follow in principal the NIST Guide to the uncertainty of Measurement. [8]. All distributions are assumed to be normal.
Lot sizes are sufficiently large to use the standard deviation to assess the sensor-to-sensor variability. Sensor starting temperature was assessed and shown to be a small contributor. Other factors affecting uncertainty such as contact pressure, angle of contact and area of contact would be included in the Type A uncertainties. The principal question is establishing the uncertainty for the True Undisturbed Surface Temperature Surface Temperature. Thermocouples are used in the STS to measure the heat flux but due to the pre-described calibration technique, their uncertainty contribution is small. Conduction error is minimized by design and all measurements were made using a Fluke Hydra Data Logger interfaced to the PC. A software program was written in basic to retrieve data from the Data logger. Channel to channel scan time was 2 seconds. The uncertainty for the measurement system is 0.1ºC K=1, this includes cold end compensation and all other device uncertainties. Although positional variability is minimized by the precise placement of the thermocouples, there is still a possibility that the sensor may move vertically up or down due to sensor and bore clearance. The sensors are approximately 2mm in diameter. For an extreme positional variation of 2 mm in materials having thermal conductivities of greater than 100 Wm^2K, T_s is changed by less than .050ºC. Extrapolating surface temperatures may overestimate T_s and the calculations from this study show that the T_s over estimated by as much as 0.5ºC. This value is in agreement with the study by PTB [7]. STS uncertainty is given in part one of Table 1, part two of the table gives the combined uncertainty for the STS and the sensors under test.

STS	Source	U_c
Stability	Measured	0.1ºC
Convective Loss	Estimated	0.25ºC
Radiation Loss	Estimated	0.25ºC
Thermocouple	±4.0 uV	0.1ºC
Positional	± 1 mm	0.05ºC
Instrument	Specification	±0.1ºC
Total	**RSS K=1**	**0.43ºC**
Sensors		
Ice Bath	Estimated	0.05ºC
Instrument	±4.0 uV	0.1ºC
Type A Uncertainties	@ 300ºC	1.6ºC
	@ 0 to 200ºC	0.6ºC
Total (150ºC)	**RSS K=1**	**0.61ºC**

Table 1. Uncertainty Assessment

9. Conclusions and Further Study

The Surface Transfer Standard (STS) provides a suitable device and method for the calibration of contact surface sensors. Obtaining the True Surface temperature using the extrapolation is relatively simple and yet the method provides uncertainties below 1.0ºC for K=2. Any variable heat source may be used and only one reference measurement is required. The study has also show that contact surface sensor can provide highly reliable reading without extended contact surface periods, less than one minute. Each sensor lot tested calibrated within standard thermocouple tolerances [9] and at some points select sensor styles calibrated within precision limits.

A further course of study should include the relationship between surface perturbation and absolute accuracy. Uncertainties should be carefully re-evaluated and tested empirically to establish a better model of the system. Computer aided modeling could also be beneficial if empirical testing can be designed to verify the computer aided modeling. If surface perturbation can be related to the thermal conductivity of the material requiring testing, for a specific type of sensor, then a correction factor for the specific sensor style could be developed to better apply the calibration information.

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