Traceability and Quality Control in a Radiation Thermometry Laboratory

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Abstract

In radiation thermometry, there have been a number of steps made to improve radiation thermometer calibration quality at temperatures below 1000 °C. These steps involve work done by national metrology institutes and standards bodies. The Fluke Infrared Calibration Laboratory in American Fork, Utah has benefitted from this progress to set up its own radiation thermometry program. The calibration range of this laboratory is -15°C to 500°C. This program involves calibrating radiometric transfer standards (with pyroelectric detectors) that, in turn, are used to calibrate flat-plate radiation sources, sometimes referred to as blackbodies.

The transfer standards are calibrated by a sequence of blackbody cavity radiation sources, which cover the entire temperature range of the laboratory. The radiometric transfer takes place between the cavity sources and the flat-plate sources. The flat-plate sources' intended use is infrared thermometer calibration. Both the transfer standard calibrations and the flat-plate calibrations are accredited by the National Voluntary Accreditation Program (NVLAP).

This paper discusses the traceability involved in this radiometric calibration program. It also discusses numerous quality control measures that have been taken to improve and assure measurement accuracy in both calibrations. The paper provides description of each calibration including the details of the cavity geometry and measures taken to maximize cavity uniformity. A discussion is made about the transfer standard uncertainty budget and the steps that have been taken to make the uncertainty budget conform to the International Bureau of Weights and Measures (BPIM) Working Group 5 standard. As well, the paper briefly discusses the flat-plate radiometric calibration uncertainties. Finally, details concerning transfer standard drift management and other steps taken to assure the calibration quality are included.

Learning Objectives

The learning objectives for this paper are to list steps that should be taken to assure quality in any calibration program, especially one involving radiation thermometry; and to foster ideas on how to apply these ideas to a calibration laboratory.

1 Introduction

In 2005, Fluke – Hart Scientific (now know as Fluke Calibration in American Fork and to be referred to as American Fork or AMF in this paper) began development of flat-plate IR calibrators that are calibrated using radiometric calibration. To support calibration of this product, a series of variable temperature liquid bath blackbodies were developed. These blackbodies support the calibration of a radiometric transfer standard used to calibrate the flat-plate calibrators. There were a number of steps taken to ensure quality during the development of the radiometric temperature calibration program. There have been some additional steps taken since the initial development of this calibration program. Many of these steps are a result of research done internally. In addition, some steps are a result of development of new standards.

2 Traceability

The read-out temperature of the flat-plate IR calibrators is based on a radiometric calibration, using the Heitronics model KT19II.82 (to be referred to as a KT19 in this paper) as a transfer standard. This instrument uses a pyroelectric detector [1]. An outline of the KT19 calibration scheme is shown in Figure 4 discussed later in this paper.

The radiometric calibration was chosen over a contact calibration to account for factors such as emissivity [2] and heat exchange. The KT19 is calibrated using American Fork’s liquid bath blackbodies. A diagram of the blackbody is shown in Figure 1. The temperature of the bath fluid during this calibration is monitored by a platinum resistance thermometer (PRT). The cavities have emissivity greater than 0.999 [2]. This number was verified by modeling with STEEP3 [3, 4, and 5]. Newer methods exist to calculate blackbody emissivity [6], but were not available for this modeling. The inputs to this modeling were based on testing of blackbody uniformity [2]. One such result is shown in Figure 2. The results of this testing and modeling are used in American Fork’s uncertainty budget for the KT19 calibration.

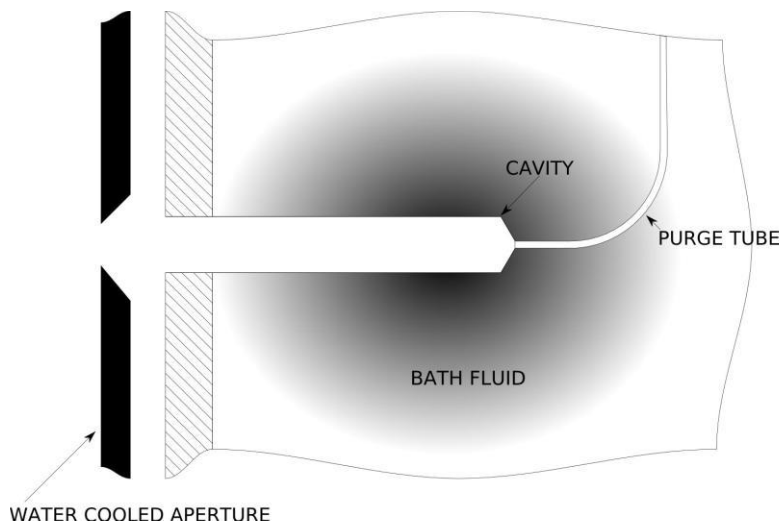

Figure 1. Liquid bath blackbodies

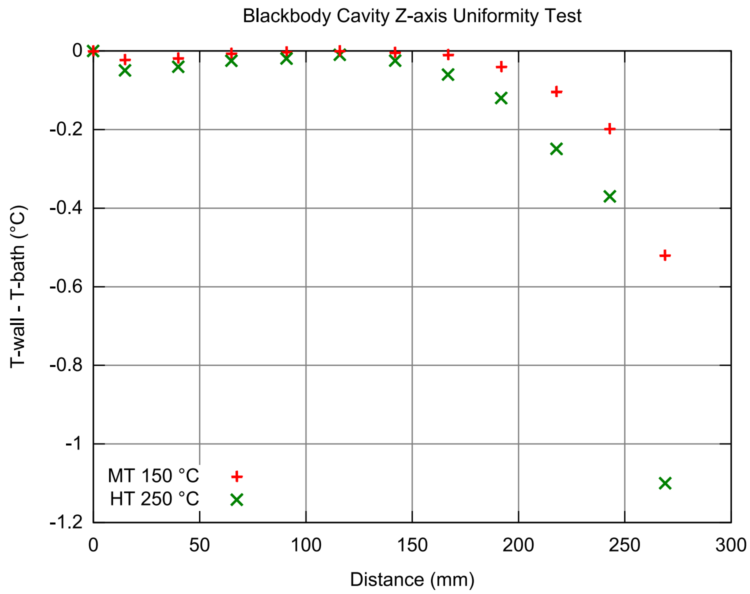

Figure 2. Blackbody uniformity test results.

2.1 Traceability Scheme

As stated above, the true temperature of the baths comes through a PRT used inside each bath. The PRTs are calibrated in American Fork's primary calibration laboratory which has traceability to the National Institute of Standards and Technology (NIST). The blackbodies' radiometric temperature is verified radiometrically by measurement with a Heitronics TRTII [7]. The TRTII is calibrated by NIST [8] Results of this test have shown normal equivalence [9]. A schematic of American Fork's radiometric traceability is shown in Figure 3.

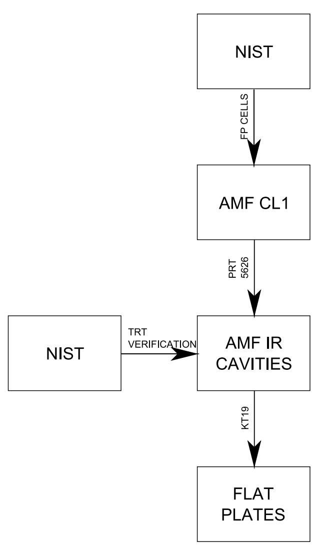

Figure 3. Radiometric traceability scheme

It would be more desirable to use the TRT transfer from NIST as a direct radiometric traceability path. However, this method would result in larger uncertainties. An example of the difference in uncertainties is summarized in Table 1.

Table 1. Differences in uncertainties between contact and radiometric traceability.

Calibration Point (°C)	**Contact Scheme Uncertainty (k = 2) (K)**	**Radiometric Scheme Uncertainty (k = 2) (K)**
-15	0.127	0.193
0	0.124	0.189
50	0.122	0.186
100	0.121	0.184
200	0.122	0.186
350	0.226	0.345
500	0.366	0.558

2.2 Uncertainty Budgets

There are four different uncertainty budgets for American Fork's radiometric calibrations. Two of these uncertainty budgets are for the two flat-plate calibrator models. The other two are for the KT19 calibration, and the blackbody verification using the TRT.

The original uncertainty budget for the KT19 calibration followed traditional uncertainty budgets used for American Fork's other contact thermometry uncertainty analysis [2]. Since this time, BIPM CCT-WG5 has released a standard for radiation thermometry uncertainty budgets [10]. American Fork has reevaluated uncertainties based on the WG5 standard. The WG5 standard places much more detail on radiometric uncertainties and less on the contact uncertainty. Regardless, there was not a significant change in the uncertainties between American Fork's original evaluation and the new evaluation following the BIPM model.

3 Quality Control - Blackbody Sources

A diagram of the KT19 calibration is shown in Figure 4. A number of steps have been taken to assure the quality of these calibrations. These steps include cross checks with a national metrology institute, determination of cavity uniformity, and use of a hot gas purge.

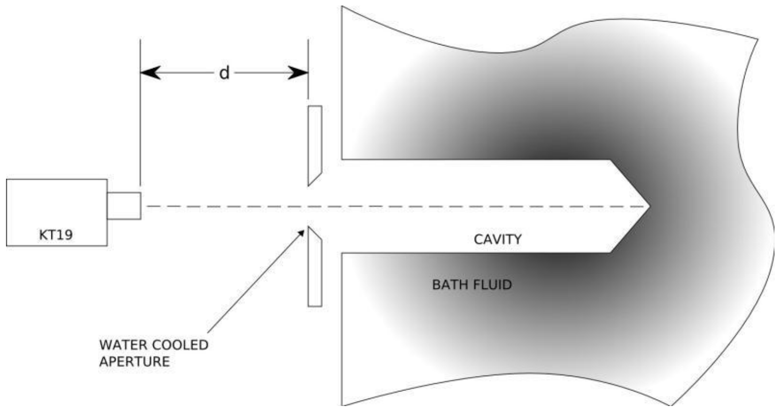

Figure 4. Transfer standard calibration geometry.

3.1 Cross-Checks – Verification

One check to verify the radiometric temperature of American Fork's cavities used a TRT calibrated at NIST [9]. A summary of these test results is shown in Table 2. This test showed normal equivalence.

Table 2. Normal equivalence results of comparison of American Fork blackbodies and NIST.

Blackbody	Nominal Temperature (°C)	Temperature Difference (K)	NIST Uncertainty (K)	AMF Uncertainty (K)	Normal Equivalence
LT	-15	0.074	0.34	0.128	0.20
LT	0	0.014	0.3	0.133	0.04
LT	50	-0.051	0.12	0.170	-0.25
LT	100	-0.125	0.11	0.218	-0.51
MT	100	-0.058	0.11	0.218	-0.24
MT	200	-0.155	0.12	0.335	-0.44
HT	200	-0.114	0.12	0.335	-0.32
HT	300	-0.144	0.13	0.226	-0.55
HT	350	-0.222	0.13	0.260	-0.76
HT	420	-0.253	0.14	0.317	-0.73
HT	500	-0.320	0.16	0.392	-0.76

3.2 Cavity Uniformity

Along with the Z-axis uniformity testing shown in Figure 2, testing has been done as well to determine cavity bottom uniformity. This is an important part of the KT19 uncertainty budget [10]. The testing was done using a Heitronics TRT 2, measuring points on the X-axis (vertical) and Y-axis (horizontal). Figure 5 is one set of data taken from this testing. The temperature map shown in this figure is created from this data. Temperature differences are referenced from the center of the cavity bottom.

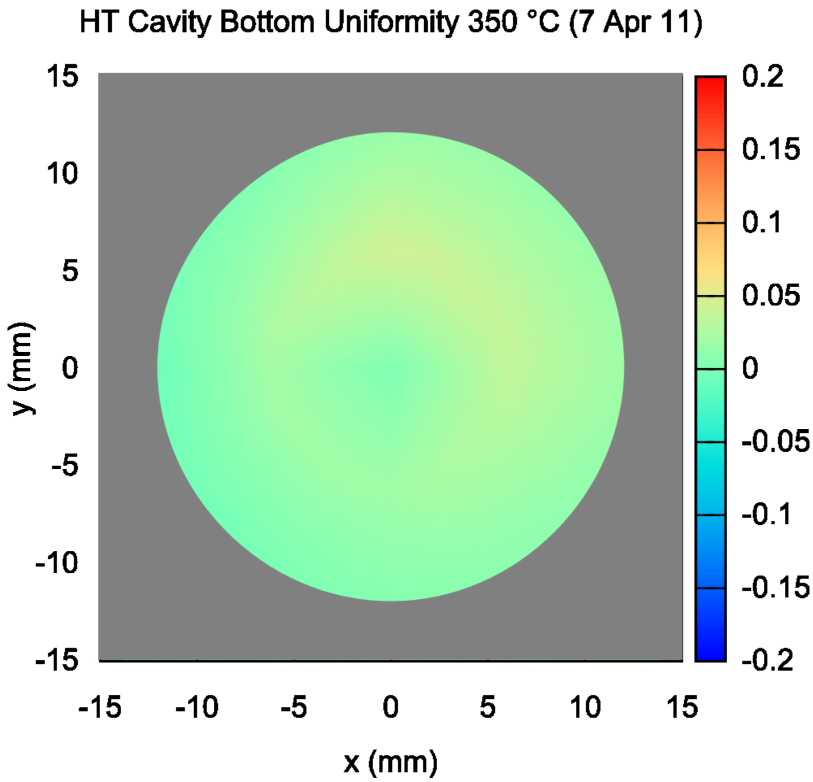

Figure 5. Cavity bottom uniformity.

3.3 Hot Gas Purge

In order to decrease the effects of temperature drop between the bath fluid and the cavity walls and to improve temperature uniformity, a hot gas purge is applied to the apex of the blackbody cone as shown in Figure 1. The air goes through tubing forming a helix inside the bath fluid. In this way it reaches the bath temperature before it exits into the blackbody. Tests have been done to observe the effects of the purge on radiometric measurement. The results of one such test is shown in Figure 6. The dashed line at 28 ℓ / min. represents the flow as indicated in American Fork's calibration procedures. The radiometric temperature of the cavity does not change significantly above half of the flow rate indicated in the procedure.

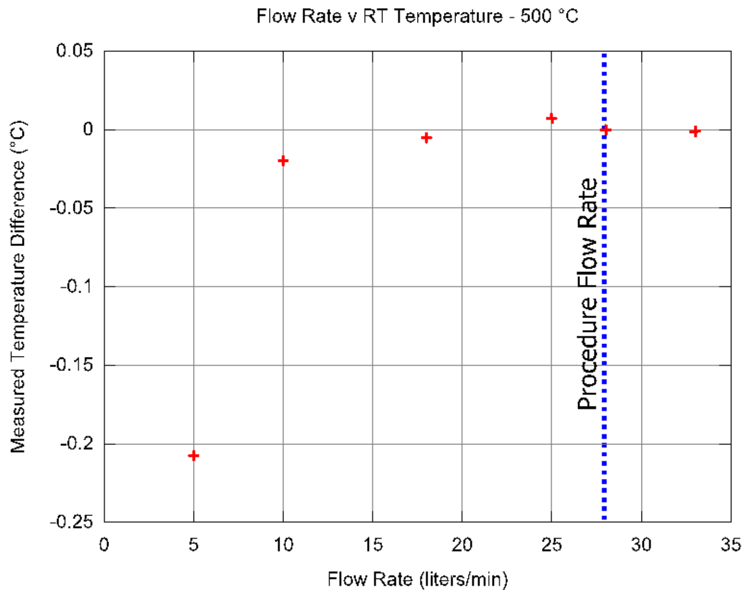

Figure 6. Blackbody purge flow rate test.

4 Quality Control Measures – Transfer Standard Calibrations

A number of steps have been taken to assure trueness of the measurements in the transfer standard calibration. Among the measures that have been taken are a self-consistency check using a chi-squared check [11] of data taken, an alignment procedure coupled with calculation of size-of-source effect uncertainty, analysis of long term stability history, use of cross-checks for verification of blackbody radiometric temperature, controlling transfer standard operating temperature, consideration of transfer standard warm-up time, and use of a hot gas purge with the blackbody. A selected set of these steps is discussed below. A diagram of the transfer standard calibration geometry is shown in Figure 4.

4.1 Size-of-Source Effect

The KT19 calibration uses a 35 mm diameter water cooled aperture. The aperture temperature is controlled near ambient and monitored during calibration as specified in American Fork's calibration procedure. Size-of-source effect testing [12] on the radiometric transfer standard was done during the development phase of the project [2]. This testing followed a standard guideline [13] for testing size of source. Results of this are shown in Figure 7 as size-of-source effect data. This data were used to determine aperture diameter and calculate aperture related uncertainties. In addition, tests were performed to test the effects of varying aperture temperature. The results of these tests were applied to the KT19 uncertainty budget.

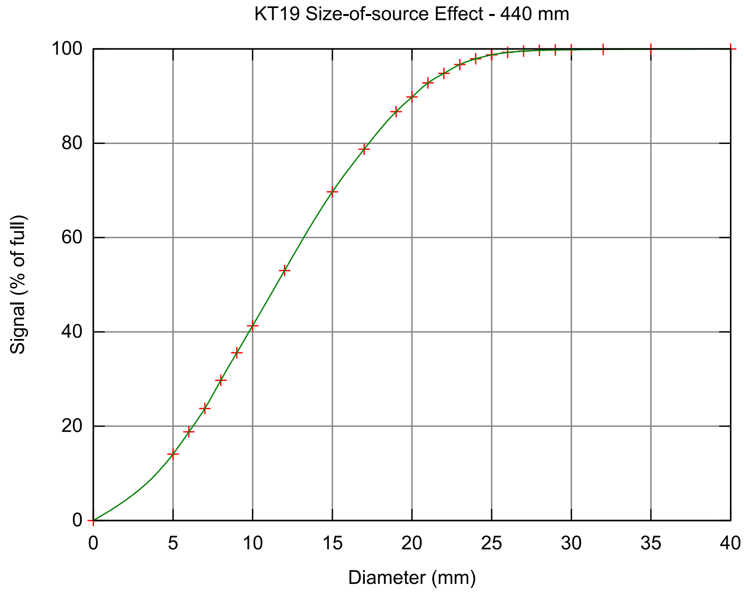

Figure 7. KT19 size-of-source testing results.

4.2 Alignment

During the KT19 calibration process the unit under test is mounted on a geared tripod head. The tripod head provides angular adjustment on two axes. The geared tripod head is mounted on an X-Y-Z carriage system which provides linear adjustment on three axes.

The angular alignment involves mounting a laser on the geared tripod head and angularly aligning the laser beam from the apex of the blackbody cone to the center of the aperture. After this, the KT19 is mounted on the tripod head. The distance is set between the aperture and the KT19 lens (Z –axis). Then the KT19 is aligned in the side-to-side direction (X-axis) and the up-and-down direction (Y-axis). For this procedure, a method from ASTM was considered [13]. However, it was found that signal received by the unit under test does not reach a definite peak during the calibration. Instead, it forms a plateau as shown in Figure 8. Taking this into account; an alternative method for alignment was devised. The KT19 is moved along one axis until the displayed temperature drops off by the 1% of displayed temperature in °C or 1 °C, whichever is greater. Then the KT19 is moved along the same axis to the other side of the aperture center until another 1% drop is observed. The KT19 is then moved to the center of these two points. This procedure is performed for both the X and Y-axes. Thus, the KT19 is centered in both directions.

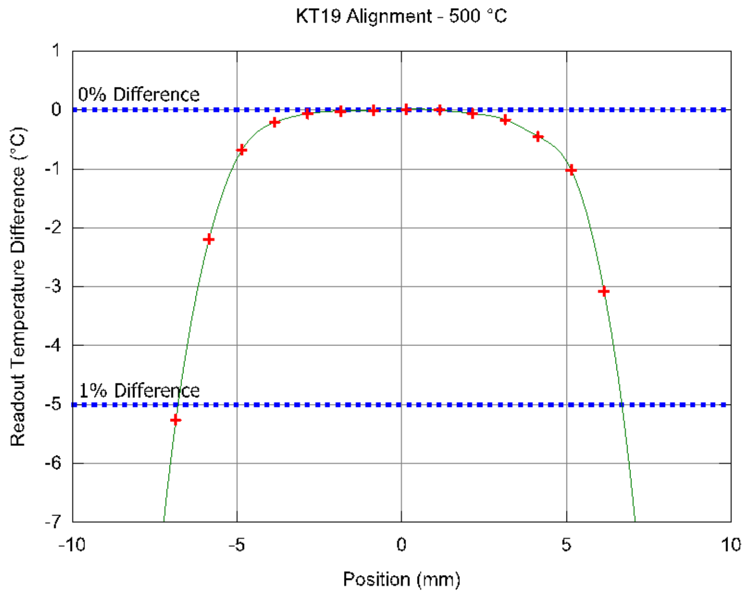

Figure 8. KT19 horizontal alignment.

A similar method has been suggested to determine size-of-source effect [14] by moving a radiation thermometer from side to side and noting its signal. This method uses a vertical slit as an aperture. American Fork uses a circular aperture, so it may be possible to use a similar method with the data shown in Figure 8 to determine size-of-source effect.

4.3 Long Term Stability History

The temporal stability of the reference standard must be considered when establishing traceability and evaluating calibration uncertainty [15]. The instrument manufacturer's specifications are frequently used as an estimate for this component. In the case of this calibration, the stability of the Heitronics KT19 is provided in the specifications [1]. However, it was found that the KT19's stability was much better than this specification. Thus, this component of uncertainty had to be determined through experimentation. A linear drift model was chosen by performing regression analysis on the calibration data obtained from 17 individual calibrations spanning 25 months.

The regression line confidence interval is a function of the number of data points and the fitting precision. The uncertainties of the data points were not considered because they are consistent from point to point and will be introduced into the uncertainty evaluation elsewhere. Thus, the uncertainties of the projected line depend on the confidence interval and expand smoothly as a function of time. The equation used to determine the confidence interval is shown below [16] in Equation (1). A graph of one such set of data is shown in Figure 9. A comparison of American Fork's findings and the manufacturer's specification is shown in Table 3. In all cases, American Fork's observed stability is much less than the manufacturer's specification. However, at the higher temperatures, the American Fork's observed stability is closer to the manufacture's specification.

$$Var\left(y_c^{'}\right) = s_{Y \bullet x}^2 \left[\frac{1}{n} + \frac{\left(X^{'} - \overline{X}\right)}{S_{xx}} \right] \tag{1}$$

where:

Var(y_c')	variance of estimate of a point on a fitted line
$s_{Y \cdot x}$	sample variance of the temperature data curve fit
n	number of data points
X'	time under consideration
X	sample mean of the time data
S_{xx}	variance of the time data

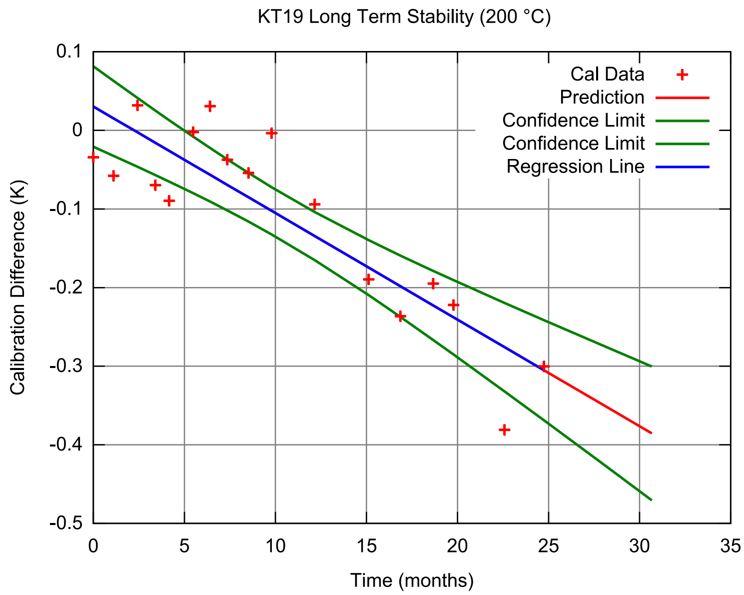

Figure 9. KT19 drift.

Table 3. KT19 stability summary.

Temperature (°C)	Stability (mK / year)	Drift / year -Specification (mK / year)
-15	6.1	310.8
0	-6.2	327.8
50	-44.9	387.8
100	-101.3	447.8
200	-84.3	567.8
350	-163.8	747.8
500	-560.0	927.8

4.4 Transfer Standard Warm-up Time

American Fork's calibration procedure specifies that the KT19 should be warmed-up for 30 minutes prior to measuring the liquid bath blackbody temperatures. The reason for this warm-up time is based on the accuracy specification from the manufacturer of 15 minutes [1]. Further testing has been done to determine the transient time constant for warm-up. The result of one of these tests is shown in Figure 10. In this test, the KT19 was enclosed in a temperature controlled water cooled jacket. The KT19's detector temperature was recorded over time. This data were fit to an exponential decay curve [17]. The time constant of the decay curve is approximately 15 minutes.

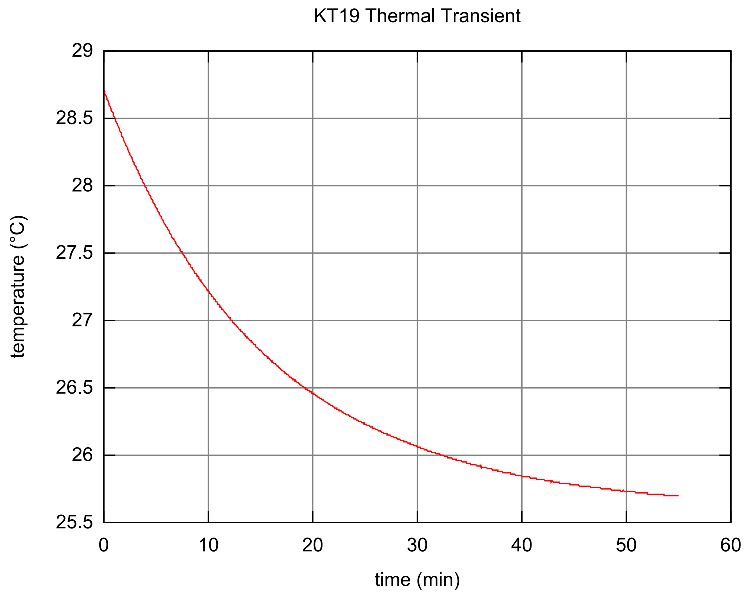

Figure 10. KT19 ambient temperature transient.

5 Quality Control Measures – Flat-Plate Calibrations

American Fork's flat-plate calibrators are the models 4180 and 4181. A diagram of the flat-plate calibration scheme is shown in Figure 11. There are a number of steps that have been taken to reduce uncertainties in the flat-plate calibration. First, the reflected radiation is controlled at near room temperature. Second, for both the KT19 calibration and the flat-plate calibration, the radiometric temperature of the optical scatter is controlled by a water cooled aperture that is controlled at a constant temperature close to room temperature. Third, the lower temperature range of the flat-plate calibrators is −15 °C. There are two calibration points below ambient, −15 °C and 0 °C. Any radiometric calibration done between −15 °C and the dew point has the risk of causing dew or ice to form on the calibrator surface which can cause variations in the radiation flux. Precautions, described below, have been taken to prevent this problem below the dew point.

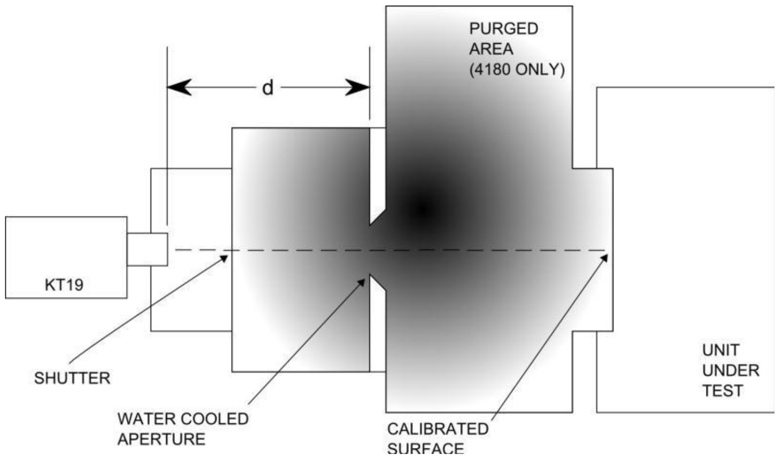

Figure 11. Flat plate calibration geometry.

5.1 Calibrations below Ambient

To prevent problems with humidity below ambient, the 4180 calibration is done inside a purged chamber [2]. This purge system involves enclosing everything between the KT19 and the flat-plate surface. This area is purged with a dry gas at a positive pressure. Humidity is monitored during these calibrations to ensure that the frostpoint inside the chamber is well below the calibration point. To ensure that no heat stacking or other thermal phenomena takes place on the IR calibrator surface, a number of tests have been run to ensure that the thermal gradient and radiometric temperature on the surface is the same with and without the chamber at calibration temperatures above ambient. The results of these tests are shown in Figure 12.

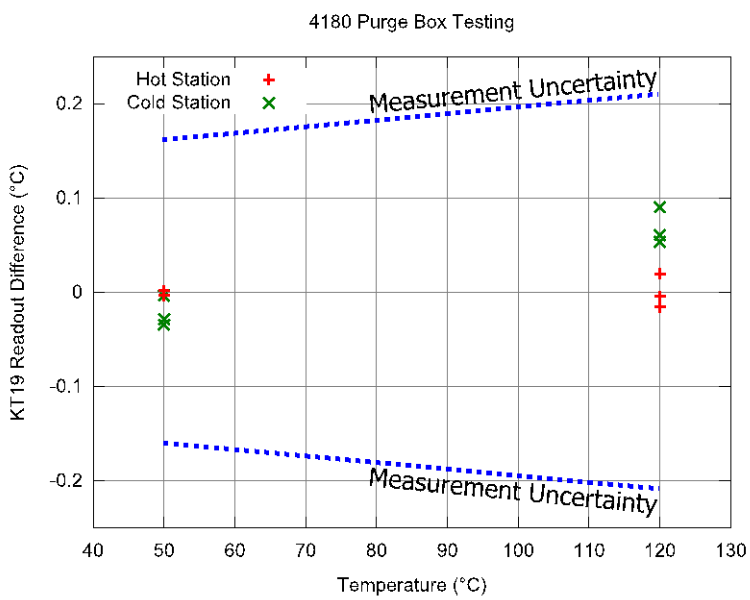

Figure 12. Radiometric measurements with and without purge chamber.

5.2 Calibration Quality Control Steps

Many of the quality control steps taken involve the calibration station. The calibration follows the same calibration geometry as the transfer standard calibration [2]. On the calibration station, the KT19 is mounted with the lens-cap removed. To ensure that foreign particles do not become incident on the lens, the area around the lens is entirely enclosed in a box with a shutter. The shutter is only opened when a measurement is being made. In addition, the lens is periodically cleaned using both a contact and a noncontact process.

6 Conclusion

By taking the steps described in this paper, American Fork has been able to establish a quality radiation thermometry program. This has involved building and qualifying a series of blackbodies. The blackbodies have provided a radiation source for calibration of radiometric transfer standards. These transfer standards have been used to calibrate a series of flat-plate infrared sources intended for the calibration of handheld infrared thermometers. In addition to using a radiometric calibration for these sources, a number of other steps have been taken to ensure the quality of these calibrations. As a result, American Fork has been able to produce a quality product with a traceable calibration.

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References

1. Operational Instructions, Infrared Radiation Pyrometer KT 19 II, Heitronics, Wiesbaden, Germany, 2005.
2. F. Liebmann, Infrared Thermometer Calibrator Development at Fluke Corporation Hart Scientific Division, Proceedings of SPIE Thermosense XXX, 6939, 5, 2008.
3. A.V. Prokhorov and L.M. Hannsen, Effective Emissivity of a Cylindrical Cavity with an Inclined Bottom, Metrologia, Vol. 41, pp. 421-431, 2004.
4. V.I. Sapritsky and A.V. Prokhorov, Spectral Effective Emissivities of Nonisothermal Cavities Calculated by the Monte Carlo Method, Applied Optics, Vol. 34, No. 25, pp. 5645-5652, 1995.
5. A.V. Prokhorov, Monte Carlo Method in Optical Radiometry, Metrologia, Vol. 35, pp. 465-471, 1998.
6. A. V. Prokhorov, S. N. Mekhontsev, L. M. Hanssen, Radiative Properties of Blackbody Calibration Sources:Recent Advances in Computer Modeling, International Journal of Thermophysics 28, 6, 2007.

7. O. Struß, “Transfer Radiation Thermometer Covering the Temperature Range from -50°C to 1000°C”, AIP Conference Proceedings, Vol. 684, pp. 565-570, 2003.
8. C. E. Gibson, B. K. Tsai, A. C. Parr, NIST Special Publication 250-43 Radiance Temperature Calibrations, National Institute of Standards and Technology, 1998, pp. 9-36, 49-52.
9. F. E. Liebmann, T. Kolat, M. J. Coleman, and T. J. Wiandt, Radiometric Comparison between a National Laboratory and an Industrial Laboratory, Memorias del Simposio Metrología de México 2010.
10. J. Fischer, P. Saunders, M. Sadli, M. Battuello, C. W. Park, Y. Zundong, H. Yoon, W. Li, E. van der Ham, F. Sakuma, Y. Yamada, M. Ballico, G. Machin, N. Fox, J. Hollandt, M. Matveyev, P. Bloembergen and S. Ugur, CCT-WG5 on Radiation Thermometry, Uncertainty Budgets for Calibration of Radiation Thermometers below the Silver Point, BIPM, Sèvres, 2008.
11. Dietrich, C.F., Uncertainty, Calibration and Probability: The Statistics of Scientific and Industrial Measurement, 2nd Ed., Adam Hilger, Philadelphia, 1991, pp. 282-283.
12. IEC 62942-1 TS, Industrial process control devices - Radiation thermometers - Part 1: Technical data for radiation thermometers, IEC, Geneva, 2007, p. 5.
13. 1256-10, Standard Test Methods for Radiation Thermometers (Single Waveband Type), Annual Book of ASTM Standards Vol. 14.03, ASTM International, West Conshohocken, PA, 2010, pp. 4-5.
14. M. Bart, E.W.M. van der Ham, P. Saunders, A New Method to Determine the Size-of-Source Effect, International Journal of Thermophysics 28, 6, 2007.
15. C.D. Ehrlich, S. D. Rasberry, Metrological Timelines in Traceability, Journal of Research of the National Institute of Standards and Technology, 103, 93, 1998, pp 93-105.
16. M. G. Natrella, in NBS Special Publication, Vol. 1, edited by H. Ku, NBS, Washington, D. C., 1969, pp. 204-227.
17. J. V. Nicholas, D. R. White, Wiley, Chichester, UK, 2001, pp. 140-143.