RADIOMETRIC COMPARISON BETWEEN A NATIONAL LABORATORY AND AN INDUSTRIAL LABORATORY

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Abstract: One of the metrology disciplines at Fluke Calibration in American Fork, Utah is radiometric calibration. This program involves transferring radiometric temperature between liquid bath variable temperature blackbodies and a flat-plate infrared (IR) calibrator. The traceability of the blackbodies comes by contact thermometry through the National Institute of Standards and Technology (NIST). A verification of these blackbodies is a radiometric comparison NIST and Fluke. This paper discusses Fluke's blackbody traceability, and the results of these comparisons. The temperature range discussed is -15 to 500 °C.

1. INTRODUCTION

In 2005, Fluke Calibration in American Fork, Utah (formerly known as Hart Scientific and to be referred to as Fluke in this paper) began development of its radiation temperature calibration program. This program includes a series of variable temperature liquid bath blackbodies. The material discussed in this paper is the result of an effort to verify the radiometric temperature of the blackbodies.

2. FLUKE'S RADIOMETRIC CALIBRATION PROGRAM

Fluke produces a series of flat-plate infrared calibrators which receive a radiometric calibration. The Heitronics KT19 serves as the radiometric transfer standard for this calibration. The KT19 is calibrated using Fluke's liquid bath blackbodies [1].

There are three blackbodies covering a range from −15 °C to 500 °C. The LT blackbody has a range from −15 °C to 100 °C; the MT blackbody has a range from 100 °C to 200 °C; and the HT blackbody has a range from 200 °C to 500 °C. A diagram of the blackbody design is shown in Figure 1.

The temperature of the bath fluid during this calibration is monitored by a platinum resistance thermometer (PRT). This temperature is considered as the radiometric temperature of the blackbodies, as the blackbodies have emissivity greater than 0.999 [1]. This number was verified by modeling with STEEP3 [2, 3, 4]. Newer methods exist to calculate blackbody emissivity [5], but were not available for this modeling. The PRT has traceability to NIST. Fluke does not use a radiometric transfer from NIST because this method would result in larger uncertainties. This difference in uncertainties is summarized in Table 1. Thus a radiometric verification is used to validate Fluke's blackbody radiometric temperature.

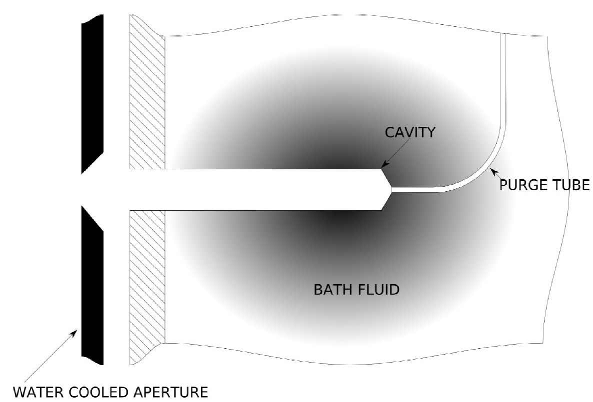

Fig. 1 *Diagram of Hart's Liquid Bath Blackbodies.*

Calibration Point (°C)	Contact Scheme Uncertainty[a] (k = 2) (K)	Radiometric Scheme Uncertainty[b] (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

[a] *The combined expanded uncertainty for KT19 calibrations*
[b] *The calculated combined expanded uncertainty for KT19 calibrations if radiometric traceability is used between Hart's blackbodies and NIST*
Table 1 *Uncertainty in Traceability Approaches.*

3. NIST CALIBRATION

The standard used for the verification was a Heitronics TRT II [6]. The NIST TRT calibration was performed using variable temperature blackbodies as the transfer standard [7, 8, 9, 10, 11, 12]. The following section discusses the results of this calibration.

3.1. Calibration Description

The NIST calibration was performed at the temperatures as shown in Table 2 [13]. These points were chosen for two reasons. First, a set of points was desired that would correspond to Fluke's KT19 calibration points [1]. Second, for the 3.9 μm spectral band, four points were desired, so that an over determined Sakuma-Hattori [14] curve fit could be performed on the points to determine self-consistency.

Spectral Band[a] (μm)	Nominal Temp.[b] (°C)	BB Temp.[c] (°C)	Signal[d] (counts)	U[e] (k=2) (°C)
8 – 14	-15	-14.99	44711	0.34
8 – 14	0	0.02	60235	0.30
8 – 14	50	50.08	133988	0.12
8 – 14	100	100.01	242965	0.11
8 – 14	200	200.00	563130	0.12
3.9	300	299.97	26816	0.13
3.9	350	349.97	44995	0.13
3.9	420	419.97	82165	0.14
3.9	500	499.98	143477	0.16

[a] The spectral band of the TRT under test adjusted by the range setting on the TRT
[b] The requested blackbody temperature for the calibration
[c] The true blackbody temperature for the calibration
[d] The TRT signal as given by 'RAD' from the readout
[e] NIST's combined expanded uncertainty

Table 2 *NIST Calibration Results.*

The aperture used for the NIST calibration is a water-cooled 35 mm aperture [13]. The distance from the aperture to the unit under test lens is based on the manufacturer's specification for focal point [15].

3.2. Calibration Results

The NIST calibration results are shown in Table 2. These results show the temperature of the blackbody as determined by a reference thermometer, the signal strength measured by the TRT, and the measurement uncertainty. The KT19 signal data are given as 'RAD' by the TRT readout [15]. It has been termed as 'counts' by NIST [13], and this term is used throughout the paper.

3.3. Self Consistency of Data

NIST performs a self-consistency check of the data using the Sakuma-Hattori curve fit. This is done independently for the data from the 8 – 14 μm and the data from the 3.9 μm spectral band. Fluke performed a curve fit as well. Fluke used a weighted curve fit [16] based on NIST's calibration uncertainties [13]. The curve-fit error is shown in Figure 2. Rather than compare calibration data points to one another, the data are checked for consistency by using the chi-squared test for goodness of fit (χ^2) [17]. The basis for the fit is taken as the Sakuma-Hattori Equation (1) [14]. Additionally, the fitting residuals are evaluated visually with attention being paid to both magnitude and sign. Unusual residuals are investigated

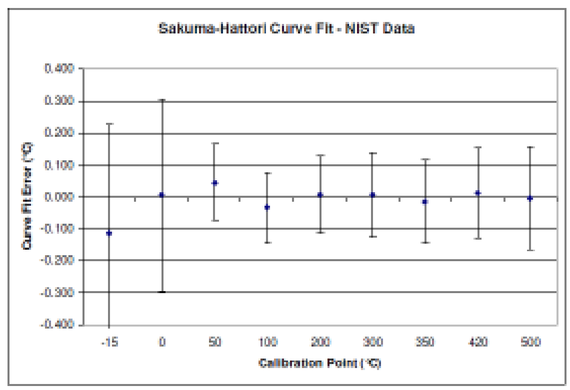

Fig. 2 *NIST Curve-fit Error.*

$$S(T) = \frac{C}{\exp\left(\frac{c_2}{AT + B}\right) - 1} \qquad (1)$$

where:
S(T): TRT signal readout
c_2: Second Radiation Constant
A, B, C: Sakuma-Hattori Parameters

4. FLUKE'S BLACKBODY VERIFICATION

Fluke's blackbody verification uses a standardized procedure which is based on Fluke's Heitronics KT19 calibration procedure. It uses many of the same quality control steps used in the KT19 calibration [18]. Data from the check are analyzed to determine self-consistency and to determine normal equivalence with the data from NIST.

4.1. Process Description

The Fluke verification procedure uses the same calibration points that were used in the NIST calibration [13]. The verification uses the same size aperture, the same aperture temperature, and the same calibration distance.

The uncertainty budgets for this process are shown in Table 5 in Appendix 1. The creation and calculation of these uncertainty budgets follows the BIPM CCT-WG5 standard [14]. The uncertainty designators match the designators given in this standard. Some uncertainties from this standard were not included. The uncertainties U_2 (impurities) and U_3 (plateau identification) are not considered in the VTBB scheme. The uncertainty U_{18} (interpolation error) is not considered; since no points between the NIST calibration points were considered in Fluke's measurement. The uncertainty U_{20} (unknown temperature) was not considered since all uncertainty should be accounted for by the other uncertainties. Much of the calculation is based on experience in calculating similar uncertainties for radiometric transfer standard uncertainties [1]. The uncertainty U_{19} (drift) was based on historical data including data from KT19 calibrations [18] and previous TRT measurement.

4.2. Verification Results

The Fluke calibration results are shown in Table 3. During the tests using the 3.9 µm spectral band, it was found that the TRT was drifting rapidly. Figure 3 shows the rate of this drift at 300 °C. As a result, data taken at Fluke before the TRT was sent to NIST was used as a comparison of normal equivalence.

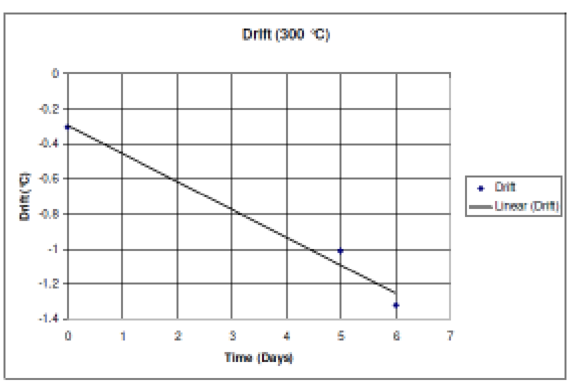

Fig. 3 *Instrumental Drift.*

BB[a]	Nominal Temp.[b] (°C)	BB Temp.[c] (°C)	Signal[d] (counts)	U[e] (k=2) (°C)
LT	-15	-14.9933	44776.8	0.128
LT	0	0.0177	60248.4	0.133
LT	50	50.0736	133882.5	0.170
LT	100	100.0003	242623.9	0.218
MT	100	99.9961	242782.6	0.218
MT	200	199.9951	562518.4	0.335
HT	200	199.9936	562670.3	0.335
HT	300	299.8796	26745.3	0.226
HT	350	349.8316	44840.4	0.260
HT	420	419.7388	81856.4	0.317
HT	500	499.6284	142872.8	0.392

[a] Blackbody used for Hart's verification
[b] The requested blackbody temperature for the calibration
[c] The true blackbody temperature for the verification
[d] The TRT signal as given by 'RAD' from the readout
[e] Hart's combined expanded uncertainty

Table 3 *Hart Verification Results.*

4.3. Self Consistency of Data

The Fluke data were also checked for self consistency. This check followed the same method used to check the NIST data. The curve-fit error is shown in Figure 4. The residuals of the curve-fit passed the chi-squared analysis [17].

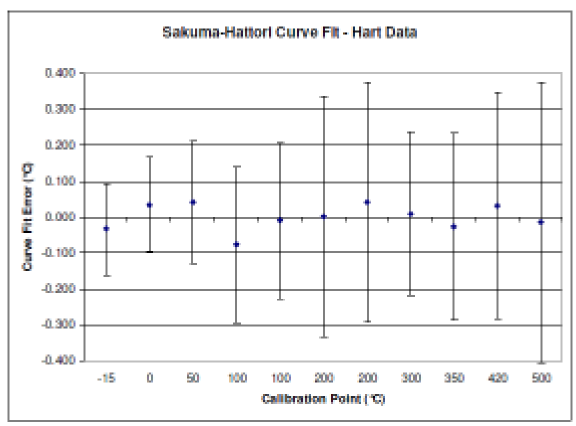

Fig. 4 *Hart Curve-fit Error.*

4.4. Normal Equivalence

The generally accepted method for comparing the results of two calibrations is through the evaluation of normalized error, denoted E_{normal} or E_n [19, 20]. The normalized error is the ratio of the difference in the measurement results relative to the combined measurement uncertainties. E_n is calculated as shown in Equation (2).

$$E_n = \frac{x_i - x_r}{\sqrt{U_i^2 - U_r^2}} \quad (2)$$

where:
E_n: normalized error
x_i: measurement result from laboratory under evaluation
x_r: measurement result from reference laboratory
U_i: expanded uncertainty of measurement under evaluation (k=2)
U_r: expanded uncertainty of reference measurement (k=2)

When |En| is less than or equal to 1, the results are considered acceptable. When |En| is greater than 1, the results are considered unacceptable. When En is close to 1, the results may be ambiguous because the magnitude of the uncertainties and correlations may convolute the results, particularly when the uncertainties are similar in magnitude [21]. Consequently, it is beneficial to target a value less than 1 and remove any correlations that may be present prior to evaluating the results [22]. When the uncertainty in the reference value is small relative to the uncertainty in the unknown value, the results are more definitive and can be taken at face value.

The data from the NIST calibration and the data from the Fluke verification were compared to determine their normal equivalence. Since the reference temperature of the Fluke blackbodies did not exactly match the reference temperature of the NIST blackbodies, the Fluke data were normalized. The results, shown in Table 4, of the normal equivalence calculation were all below 1.0.

5. CONCLUSION

All temperature points in the verification showed good normal equivalence. There are a few steps that can be taken to improve this process and to ensure continued precision of measurement using the Fluke blackbodies. First, the TRT used for this measurement showed considerable drift over a short period of time in the 3.9 µm spectral band. This unit should be repaired. Second, a program should be established to periodically perform these measurements using the TRT. Third, Fluke’s blackbody emissivity is calculated as an uncertainty. However, Fluke’s measurements are not biased due to this emissivity. Using a bias may result in more precise measurements.

BB[a]	Nominal Temp.[b] (°C)	Temp. Diff.[c] (K)	NIST Unc.[d] (K)	Hart Unc.[e] (K)	Normal Equiv.[f]
LT	-15	0.074	0.34	0.128	0.20
LT	0	0.014	0.30	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

[a] The blackbody used for the comparison.
[b] The nominal temperature for the comparison.
[c] The difference in Kelvin between the temperature of the Hart blackbody and the temperature of the NIST blackbody as measured by the Heitronics TRTII. (THART – TNIST).
[d] The combined expanded uncertainty (k = 2) of the NIST calibration based on the NIST certificate of calibration.
[e] The combined expanded uncertainty (k = 2) of the Hart verification.
[f] The normalized error is the ratio of the difference in the measurement results relative to the combined measurement uncertainties.

Table 4 *Normal Equivalence.*

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APPENDIX

Uncertainties[a]

8 – 14 µm Spectral Band	Denot.[b]	-15[c] (°C)	0[c] (°C)	50[c] (°C)	100[c] (°C)	200[c] (°C)
Blackbody						
Calibration temperature	U_1	0.013	0.010	0.013	0.013	0.013
Blackbody emissivity, isothermal	U_4	0.029	0.032	0.044	0.057	0.088
Blackbody emissivity, nonisothermal	U_5	0.003	0.001	0.002	0.006	0.014
Reflected ambient radiation	U_6	0.052	0.044	0.028	0.021	0.014
Cavity bottom heat exchange	U_7	0.000	0.000	0.002	0.007	0.015
Convection	U_8	0.006	0.004	0.004	0.012	0.027
Cavity bottom uniformity	U_9	0.005	0.003	0.004	0.011	0.023
Ambient conditions	U_{10}	0.020	0.018	0.014	0.006	0.014
Radiation Thermometer						
Size-of-source effect	U_{11}	0.008	0.008	0.009	0.012	0.018
Non-linearity	U_{12}	0.020	0.022	0.030	0.040	0.061
Reference temperature	U_{13}	0.032	0.026	0.017	0.012	0.008
Ambient temperature	U_{14}	0.022	0.025	0.034	0.044	0.068
Atmospheric absorption	U_{15}	0.010	0.011	0.015	0.020	0.030
Gain ratios	U_{16}	0.001	0.001	0.002	0.002	0.003
Noise	U_{17}	0.012	0.008	0.006	0.003	0.003
Use						
Drift	U_{19}	0.100	0.111	0.152	0.198	0.305
Combined expanded uncertainty (k=2)		**0.128**	**0.133**	**0.170**	**0.218**	**0.335**

3.9 µm Spectral Band	Denot.[b]	300[c] (°C)	350[c] (°C)	420[c] (°C)	500[c] (°C)
Blackbody					
Calibration temperature	U_1	0.019	0.019	0.020	0.029
Blackbody emissivity, isothermal	U_4	0.103	0.121	0.150	0.186
Blackbody emissivity, nonisothermal	U_5	0.020	0.025	0.031	0.042
Reflected ambient radiation	U_6	0.056	0.037	0.029	0.022
Cavity bottom heat exchange	U_7	0.024	0.028	0.034	0.041
Convection	U_8	0.042	0.050	0.060	0.073
Cavity bottom uniformity	U_9	0.037	0.043	0.052	0.063
Ambient conditions	U_{10}	0.011	0.010	0.010	0.010
Radiation Thermometer					
Size-of-source effect	U_{11}	0.011	0.013	0.016	0.019
Non-linearity	U_{12}	0.018	0.021	0.026	0.032
Reference temperature	U_{13}	0.000	0.000	0.000	0.000
Ambient temperature	U_{14}	0.003	0.004	0.005	0.006
Atmospheric absorption	U_{15}	0.018	0.021	0.026	0.032
Gain ratios	U_{16}	0.002	0.002	0.003	0.003
Noise	U_{17}	0.023	0.017	0.010	0.008
Use					
Drift	U_{19}	0.177	0.209	0.258	0.320
Combined expanded uncertainty (k=2)		**0.226**	**0.260**	**0.317**	**0.392**

[a]Uncertainties for variable temperature blackbodies as stated in CCT-WG5 standard [N]

[b]Denotations for uncertainties for variable temperature blackbodies as stated in CCT-WG5 standard [N]

[c]Uncertainties stated as expanded uncertainties (coverage factor of 2 or k=2)

Table 5 *Hart TRT Uncertainty Budget.*