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A. Walter F.R.A.S.

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DISCUSSION OF THE ERRORS OF CERTAIN TYPES OF
MINIMUM SPIRIT THERMOMETERS IN USE AT
THE ROYAL ALFRED OBSERVATORY, MAURITIUS.

By A. WALTER, F.R.A.S.,
Chief Assistant.

(Read October 31, 1906.)

Since the year 1902 the corrections to the minimum spirit thermometers in use at the Royal Alfred Observatory, Mauritius, have been obtained from daily comparisons between the readings of the spirit and the corrected readings of a mercurial Standard thermometer, made near the time of minimum temperature, in accordance with the results of the "Investigation of the Degree of Accuracy of Self-registering Maximum and Minimum Thermometers" published in the "Introduction to the Mauritius Magnetical and Meteorological Observations for the year 1901" (p. xxv).

The present discussion was undertaken at the request of the Director of the Royal Alfred Observatory, in view of the occasional large differences between the minimum temperatures, as shown by a minimum spirit thermometer thus corrected, and the lowest points on the thermograms.

Table I. shows the results of the comparisons made during the month of November, 1905.

The minimum thermometer, Casella No. 1,470, was mounted in the Thermograph screen with its bulb at a distance of about 1 foot from the mercurial Standard No. 714, which is used to standardise the photographic records of the Beckley Thermograph, as follows: The observer, while reading the Standard, touches for a few moments the bulb of the Thermograph thermometer, thereby causing a slight temporary dislocation in the photographic curve, so that the exact instant at which the Standard is read is recorded. He then reads the spirit of the minimum thermometer.

TABLE I.

1905.	Lowest point on Thermogram reduced to Standard No. 714. (a).	Minimum Temperature as recorded by Casella No. 1,470. (b).	(a-b).	Time of Minimum Temperature as recorded by Thermograph.	Observed excess of the Readings of the Mercurial Standard No. 714 over those of Casella No. 1,470 used as an ordinary Thermometer at—		Adopted Correction to Casella No. 1,470 according to time of Minimum.	Corrected Minimum by Casella No. 1,470. (c).	(a-c).
					0h.	6h.			
Nov.	d.	°	°	h. m.	°	°	°	°	°
1	62.0	62.9	-0.9	5 35	-1.9	0.0	-0.2	62.7	-0.7
2	60.5	61.4	-0.9	5 40	-1.5	+1.3	+1.1	62.5	-2.0
3	63.9	64.5	-0.6	5 30	-1.3	+0.8	+0.7	65.2	-1.3
4	66.4	67.3	-0.9	5 5	-1.1	+0.2	0.0	67.3	-0.9
5	63.5	64.2	-0.7	4 40	-1.2	-0.3	-0.4	63.8	-0.3
6	62.3	63.4	-1.1	5 15	-0.9	+1.0	+0.7	64.1	-1.8
7	66.1	66.8	-0.7	4 25	-0.8	-0.2	0.0	66.8	-0.7
8	64.9	65.8	-0.9	4 25	-1.0	+0.4	+0.1	65.9	-1.0
9	68.5	69.2	-0.7	4 10	-1.2	-0.1	-0.5	68.7	-0.2
10	68.3	68.7	-0.4	23 0	-1.1	+0.5	-1.1	67.6	+0.7
11	65.5	67.0	-1.5	5 15	-1.0	+1.1	+0.8	67.8	-2.3
12	66.5	67.5	-1.0	5 30	-1.1	+0.9	+0.7	68.2	-1.7
13	66.6	67.7	-1.1	3 35	-1.2	+0.2	-0.3	67.4	-0.8
14	66.6	67.8	-1.2	5 25	-1.1	+0.1	0.0	67.8	-1.2
15	67.6	68.4	-0.8	5 25	-1.1	+0.9	+0.7	69.1	-1.5
16	66.6	67.2	-0.6	5 0	-1.1	+0.5	+0.2	67.4	-0.8
17	66.4	67.2	-0.8	5 15	-0.9	+0.7	+0.4	67.6	-1.2
18	67.7	68.9	-1.2	4 30	-1.1	+1.3	+0.7	69.6	-1.9
19	72.2	72.1	+0.1	23 55	-0.6	-0.3	-0.6	71.5	+0.7
20	71.1	71.0	+0.1	23 0	-0.3	+1.8	-0.3	70.7	+0.4
21	68.1	68.0	+0.1	20 30	-0.4	+0.3	-0.4	67.6	+0.5
22	67.9	68.0	-0.1	15 45	-0.2	+0.1	-0.2	67.8	+0.1
23	67.5	67.8	-0.3	4 20	-0.2	0.0	0.0	67.8	-0.3
24	69.9	70.2	-0.3	1 0	-0.7	+0.3	-0.5	69.7	+0.2
25	70.6	71.0	-0.4	4 45	-0.1	+0.2	+0.1	71.1	-0.5
26	70.4	70.3	+0.1	5 5	-0.2	+0.1	0.0	70.3	+0.1
27	71.0	71.2	-0.2	2 50	-0.6	+0.3	-0.1	71.1	-0.1
28	71.4	71.5	-0.1	3 15	-0.4	-1.1	-0.4	71.1	+0.3
29	72.0	72.0	0.0	6 0	-0.5	0.0	0.0	72.0	0.0
30	67.2	67.3	-0.1	21 0	-0.2	-0.3	-0.2	67.1	+0.1
Mean	—	—	Sum 17.5	—	-0.83	+0.36	—	—	Sum 24.3
Column	1	2	3	4	5	6	7	8	9

The results in Table I. are shown graphically in Fig. 1. It is very apparent that the differences (column 9) between the minimum temperatures (column 8), as recorded by Casella No. 1,470 (reduced to Standard No. 714), and the lowest points on the thermograms

(column 1), follow closely the curve of corrections (column 7) derived from simultaneous readings of the spirit and the mercurial Standard; while the sums of the residuals, irrespective of sign, given in column 9, are greater than those in column 3, whereas they should be smaller if the corrections in column 7 are real.

FIG. 1.

In order to ascertain the reason for this undoubted connection between the adopted corrections to the minimum temperatures as recorded by No. 1,470, and the excess of the minima thus corrected, over those obtained from the thermograms, the readings of the spirit at 0h. (midnight) and 12h. (noon) during the three months January to March, 1904, were compared with the corresponding readings of the Kew Standard No. 714, and the differences tabulated for steady falling and rising temperatures respectively. The results are shown in Table II., p. 422.

SUMMARY.

TEMPERATURE. EXCESS OF STANDARD NO. 714 OVER MINIMUM, CASELLA NO. 1,470.

Steady	85 observations - 0.21°
Rising	47 observations + 0.10°
Falling	48 observations - 0.51°

In forming the above tables all available observations were utilised. It will be seen that the correction to reduce the readings of No. 1,470 to the Standard No. 714 is—

- + 0.10° for rising temperatures,
- 0.51° for falling temperatures,

TABLE II.

Excess of the Readings of Kew Standard No. 714, over those of Casella No. 1,470 (minimum spirit), used as an ordinary thermometer, at—							
1904.	0h. (Midnight).			12h. (Noon).			
	Temperature.			Temperature.			
	Steady.	Rising.	Falling.	Steady.	Rising.	Falling.	
Jan.	2d. +0.5 ^o 4 0.0 6 0.0 7 0.0 8 +0.2 9 -0.2 10 +0.2 12 0.0 13 +0.2 14 0.0 15 +0.2 16 0.0 17 0.0 18 0.0 19 -0.3 20 -0.5 21 -0.2 22 +0.7 23 -0.5 25 +0.4 26 -0.2 28 -0.2 29 -0.2 31 -0.5		3d. -0.4 ^o 5 -0.9 24 -0.5 27 -0.8 30 -0.5	5d. +0.1 ^o 9 -0.1 18 -0.1 24 0.0 29 +0.1	2d. +0.3 ^o 6 +0.3 7 +0.4 8 +0.3 11 +0.7 13 +0.5 14 +0.6 16 +0.4 17 +0.5 20 +0.1 21 +0.4 22 -0.1 23 +0.1 25 +0.3 26 +0.2 27 -0.1 28 -0.2 30 0.0 31 0.0	1d. +0.1 ^o 3 -0.6 4 +0.5 10 +0.2 12 +0.3 15 +0.1 19 -0.3	
Sum	+2.4 24days -2.8			5 days -3.1	5 days 0.0	19days +5.1 19days -0.4	7 days +1.2 7 days -0.9
Feb.	1d. -0.3 ^o 2 -0.5 4 -0.7 6 -0.3 9 0.0 10 -1.2 11 -0.1 12 -0.3 13 -0.2 14 -0.3 15 0.0 16 -0.1 17 -0.4 18 -0.4 19 -0.7 20 -0.4 21 -0.5 22 -0.5 24 -0.2 25 -0.4 26 -0.5 27 -0.3	5d. -0.4 ^o 7 -0.1	3d. -0.4 ^o 8 -0.3 23 -0.9 28 -1.0 29 -0.1	4d. -0.3 ^o 5 -0.4 10 0.0 12 +0.1 17 -0.1 26 -0.7 27 -0.3	2d. +0.4 ^o 3 0.0 7 +0.1 8 -0.2 13 +0.2 14 0.0 15 +0.1 19 -0.1 20 +0.1 28 +0.4 29 +0.1	1d. -0.3 ^o 6 -0.4 9 -0.4 11 0.0 16 -0.4 18 -1.5 20 +0.1 21 -0.8 22 -0.8 23 -0.4 24 -0.9	
Sum	22days -8.3			5 days -2.7	-1.8 7 days +0.1	+1.0 11days -0.7	+0.1 11days -5.9
March	1d. 0.0 ^o 2 -0.2 3 +0.6 10 -0.6 13 -0.6 14 -0.7 16 -0.4 19 -0.4 21 -0.1 22 -0.1 23 -0.2 24 -0.4 25 -0.6 26 -0.4 27 -0.2 30 -0.0 31 -0.3	7d. -0.5 ^o 9 +0.5 17 -0.5 29 -0.3	4d. -1.4 ^o 5 -0.4 6 -0.9 8 -1.0 11 -1.0 12 -0.8 15 -1.0 18 -0.4 20 -0.3 28 -0.8	3d. -0.2 ^o 4 -0.4 5 -0.4 13 -0.4 14 -0.4 17 -0.0 22 -0.1 25 -0.5 26 -0.3 27 -0.0	6d. +0.8 ^o 7 -0.6 8 -0.1 12 -0.4 18 +0.2 23 +0.4 24 0.0 28 +0.1 29 -0.1 30 -0.1 31 +0.3	1d. 0.0 ^o 2 -0.9 9 -1.6 10 -0.7 11 0.0 15 -0.7 16 -0.2 19 -0.4 20 -0.5 21 -0.2	
Sum	-5.2 17days +0.6			10days -8.0	10days -2.7	+1.8 11days -1.3	10days -5.2
Total Mean	63 -13.3 -0.21			20 -13.8 -0.69	22 -4.4 -0.20	41 -5.5 -0.13	28 -10.7 -0.38

which become $+0.31^\circ$ and -0.30° respectively, if we consider the correction for steady temperatures (-0.21°) to be the true working correction of No. 1,470.

It will also be noticed that the results for "steady temperature" are practically identical at 0h. and 12h., showing that there is no systematic error, due to evaporation and condensation, produced by rising and falling temperatures.

The above results point to the existence of a considerable amount of "lag" in No. 1,470, and are corroborated by observations made during the rapidly changing temperatures which occur in heavy rain showers, the results of which are given below.

TABLE III.

COMPARISONS BETWEEN THE READINGS OF MINIMUM THERMOMETER
No. 1,470 AND THOSE OF THE THERMOGRAPH STANDARD No. 714
DURING A RAPID FALL OF TEMPERATURE ON JULY 10, 1906.

Time.			Standard No. 714.	Minimum Thermometer No. 1,470.	Excess of No. 714 over No. 1,470.
h.	m.	s.	°	°	°
12	59	30	72.3	72.8	-0.5
13	0	15	71.4	72.4	-1.0
	1	0	70.4	72.1	-1.7
	1	45	69.4	71.5	-2.1
	2	30	68.9	71.2	-2.3
	3	15	68.6	70.8	-2.2
	4	0	67.9	70.2	-2.3
	4	45	67.8	69.9	-2.1
	5	30	67.4	69.4	-2.0
	6	15	67.1	69.0	-1.9
	7	0	66.9	68.9	-2.0
	7	45	66.9	68.4	-1.5
	8	30	66.8	68.1	-1.3
	9	15	66.7	68.0	-1.3
	10	0	66.8	67.9	-1.1
	10	45	66.7	67.8	-1.1
	11	30	66.6	67.6	-1.0
	12	15	66.7	67.5	-0.8
	13	0	66.9	67.3	-0.4
	13	45	66.9	67.3	-0.4
	14	30	67.0	67.3	-0.3
	15	15	67.0	67.2	-0.2
	16	0	67.1	67.3	-0.2
13	39		68.9	68.2	+0.7
	40		69.5	68.6	+0.9
	41		69.8	68.9	+0.9
	45		70.4	69.5	+0.9

* Standard No. 714 has an index error of $+0.11$ which has not been applied. This makes the correction to No. 1,470 for steady temperatures -0.31° (*cf.* p. 434).

In the observations recorded in Table III. and Fig. 2 the effect of changes of temperature were eliminated by reading the thermometers as rapidly as possible in the order 714, 1,470, and 1,470, 714 alternately, and taking the mean of the observations thus obtained.

As the velocity of the wind at this time was thirty-four miles per hour, as recorded by the Dines anemometer, the thermometers were thoroughly ventilated.

Experiments were then made with the object of determining the relative coefficients of sensitiveness of three different types of

Rapid Fall of Temperature in a Rain Squall on July 10, 1906, as recorded by the Mercurial Standard No. 714, and the Minimum Spirit Thermometer No. 1,470 respectively.

FIG. 2.

minimum spirit thermometers—spherical, cylindrical, and divided bulb (see Fig. 4)—as compared with the Kew Standard No. 714.

A description of the thermometers employed, together with a history of their errors, will be found on pages 231, 232.

A bath of water was prepared at a temperature of $81^{\circ} \pm$ (Fahr.), and the thermometers completely immersed in it for five minutes: they were then rapidly removed to the comparison bath at a temperature of $66^{\circ} \pm$ (Fahr.), and the rate of decrease of temperature observed with the aid of a chronometer, care being taken to read each thermometer at the moment of immersion in the low temperature bath. The results of the experiments are given below.

TABLE IV.

Number of Thermometer.	Series.	Time Interval from Moment of Immersion in Comparison Bath.	Observed Temperature.	Temperature of Comparison Bath.
Standard (Kew) No. 714.	1	secs. 0 5.5 13.0 18.0 25.0	$80.0 = t_0$ 71.0 68.0 67.0 66.8	66.8
	2	0 3.0 7.0 12.0 22.5 30.0	$79.0 = t_0$ 74.0 70.0 68.0 67.0 66.9	66.7
Casella No. 1,470—Type I.	1	0 2.0 7.0 10.0 16.5 24.3 30.0 37.0 44.0 56.0 71.0 101.0 118.0	$80.3 = t_0$ 79.0 78.0 77.0 75.0 73.0 72.0 71.0 70.0 69.0 68.0 67.0 66.8	66.5
	2	0 5.5 10.8 15.0 19.0 23.0 28.0 35.0 44.0 56.0 74.0 80.0 90.0 96.0 112.0	$80.0 = t_0$ 78.0 76.0 75.0 74.0 73.0 72.0 71.0 70.0 69.0 68.0 67.8 67.6 67.4 67.0	66.5
Darton No. 45,535—Type I.	1	0 6.5 12.0 19.0 30.0 38.0 47.0 61.5 87.0	$81.5 = t_0$ 78.0 75.9 74.0 72.0 71.0 70.0 69.0 68.0	67.0
Darton No. 45,535—Type I.	2	0 3.5 9.0 13.0 17.0 22.0 28.0 37.0 46.0 59.0 74.0 87.0	$81.0 = t_0$ 79.0 77.0 76.0 75.0 74.0 73.0 72.0 71.0 70.0 69.0 68.5	67.0
Negretti and Zambra No. 41,178—Type I.	1	0 4.0 11.0 18.5 29.0 43.0 53.0 67.0 81.0 95.0	$81.4 = t_0$ 79.0 77.0 75.0 73.0 71.0 70.0 69.0 68.5 68.0	67.0
	2	0 3.5 9.0 13.0 17.0 22.0 28.0 37.0 46.0 59.0 74.0 87.0	$81.0 = t_0$ 79.0 77.0 76.0 75.0 74.0 73.0 72.0 71.0 70.0 69.0 68.5	67.0
Darton No. 45,535—Type I.	3	0 6.0 12.0 16.0 21.0 28.0 36.0 47.0 66.0 80.0 102.0	$79.5 = t_0$ 77.0 75.0 74.0 73.0 72.0 71.0 70.0 69.0 68.5 68.0	67.0
Darton No. 45,535—Type I.	2	0 4.0 11.0 18.5 29.0 43.0 53.0 67.0 81.0 95.0	$81.4 = t_0$ 79.0 77.0 75.0 73.0 71.0 70.0 69.0 68.5 68.0	67.0
Negretti and Zambra No. 41,178—Type I.	1	0 4.0 11.0 18.5 29.0 43.0 53.0 67.0 81.0 95.0	$81.4 = t_0$ 79.0 77.0 75.0 73.0 71.0 70.0 69.0 68.5 68.0	67.0
	2	0 3.5 9.0 13.0 17.0 22.0 28.0 37.0 46.0 59.0 74.0 87.0	$81.0 = t_0$ 79.0 77.0 76.0 75.0 74.0 73.0 72.0 71.0 70.0 69.0 68.5	67.0

TABLE IV.—*continued.*

Casella No. 115,511— Type II.	Casella No. 99,833—Type I.	Casella No. 115,511—Type I.	Negretti and Zambra No. 41,178—Type I.	Number of Thermometer.
1	2	1	3	Series.
0 5.4 12.8 26.5 46.0 61.0	0 3.0 7.0 13.0 20.0 25.0 31.0 39.0 50.0 67.0 74.0 89.0	0 4.0 11.0 17.0 22.0 26.0 30.0 37.0 47.0 61.0 78.0 90.0	secs. 0 3.0 8.0 11.0 16.0 22.0 28.0 35.0 44.0 56.0 65.0 94.0	Time Interval from Moment of Immersion in Comparison Bath.
80.0 = t_0 75.0 71.0 68.0 66.5 66.0	81.0 = t_0 80.0 78.0 76.0 74.0 73.0 72.0 71.0 70.0 69.0 68.5 68.0	82.0 = t_0 80.0 77.0 75.0 74.0 73.0 72.0 71.0 70.0 69.0 68.5 68.0	° 80.5 = t_0 79.0 77.0 76.0 75.0 74.0 73.0 72.0 71.0 70.0 69.0 68.0	Observed Temperature.
65.5	67.5	67.2	67.4	Temperature of Comparison Bath.
Hicks No. 175,616—Type III.	Casella No. 115,511—Type II.	Number of Thermometer.		
3	2	1	2	Series.
0 2.5 10.5 15.0 22.0 31.0 42.0	0 3.0 7.5 11.5 18.0 21.0 30.0 37.0 52.0	0 3.0 7.5 16.0 22.0 37.0 51.0	secs. 0 3.0 7.0 12.5 19.0 23.0 29.0 39.0	Time Interval from Moment of Immersion in Comparison Bath.
79.0 = t_0 77.0 70.0 69.0 68.0 67.5 67.0	80.0 = t_0 77.0 72.0 69.0 68.0 67.0 66.5	80.0 = t_0 75.0 72.0 70.0 69.0 68.0 67.0 66.5	° 80.5 = t_0 78.0 75.0 72.0 70.0 69.0 68.0 67.0	Observed Temperature.
66.0	66.4	66.4	66.5	Temperature of Comparison Bath.

The coefficient of sensitiveness was then computed on the assumption that the relation between the constant temperature τ of the comparison bath, the reading t of the thermometer at any time θ , and the coefficient of sensitiveness λ is represented by the equation—

$$\frac{dt}{d\theta} + \lambda(t - \tau) = 0,*$$

the solution of which gives—

$$(t - \tau) = (t_0 - \tau)e^{-\lambda\theta},$$

where t_0 is the value of t when $\theta = 0$.

Curves were drawn from the data contained in Table IV., and values of t read off at intervals $\theta = \theta_1, \theta_2 \dots \theta_n$, the unit interval being 6 seconds. Substituting the values of t and θ thus found in the expression given above, and taking t_0 and τ from Table IV., we obtain the following solutions for λ for the several thermometers.

Thermometer	No. 714.				No. 1,470.			
Series	1st and 2nd combined				1st and 2nd combined			
t_0	79.50				80.17			
τ	66.75				66.50			
θ	secs. 6	secs. 12	secs. 18		secs. 6	secs. 36	secs. 66	secs. 96
t	70.80	68.00	67.16		77.85	70.93	68.30	67.10
λ	.191	.194	.191		.031	.031	.031	.033
Mean λ	0.192				0.031			

Thermometer	No. 45,535.											
Series	1st				2nd				3rd			
t_0	81.5				81.0				79.5			
τ	67.0				67.0				67.0			
θ	secs. 6	secs. 24	secs. 42	secs. 60	secs. 6	secs. 24	secs. 42	secs. 60	secs. 6	secs. 24	secs. 42	secs. 60
t	78.3	73.0	70.5	69.1	77.9	72.8	70.4	69.2	77.0	72.5	70.4	69.2
λ	.042	.037	.034	.032	.042	.037	.034	.031	.037	.034	.031	.029
Mean λ	0.036				0.036				0.033			

* Chree's "Notes on Thermometry," Phil. Mag., 1898.

Ther- mometer	No. 41,178.														
Series	1st					2nd					3rd				
t_0 τ	$81^{\circ}\cdot4$ $67^{\circ}\cdot0$					$81^{\circ}\cdot0$ $67^{\circ}\cdot0$					$80^{\circ}\cdot5$ $67^{\circ}\cdot4$				
θ	secs. 6	secs. 24	secs. 42	secs. 60	secs. 78	secs. 6	secs. 24	secs. 42	secs. 60	secs. 78	secs. 6	secs. 24	secs. 42	secs. 60	secs. 78
t λ	$78^{\circ}\cdot3$ $\cdot040$	$73^{\circ}\cdot9$ $\cdot031$	$71^{\circ}\cdot1$ $\cdot030$	$69^{\circ}\cdot4$ $\cdot030$	$68^{\circ}\cdot5$ $\cdot029$	$78^{\circ}\cdot0$ $\cdot040$	$73^{\circ}\cdot6$ $\cdot031$	$71^{\circ}\cdot4$ $\cdot028$	$69^{\circ}\cdot9$ $\cdot026$	$68^{\circ}\cdot8$ $\cdot026$	$77^{\circ}\cdot6$ $\cdot042$	$73^{\circ}\cdot6$ $\cdot031$	$71^{\circ}\cdot2$ $\cdot029$	$69^{\circ}\cdot7$ $\cdot029$	$68^{\circ}\cdot9$ $\cdot028$
Mean λ	0·032					0·030					0·032				

Thermometer	No. 89,833.									
Series	1st					2nd				
t_0 τ	$82^{\circ}\cdot0$ $67^{\circ}\cdot2$					$81^{\circ}\cdot0$ $67^{\circ}\cdot5$				
θ	secs. 6	secs. 24	secs. 42	secs. 60	secs. 78	secs. 6	secs. 24	secs. 42	secs. 60	secs. 78
t λ	$78^{\circ}\cdot9$ $\cdot037$	$73^{\circ}\cdot3$ $\cdot037$	$70^{\circ}\cdot5$ $\cdot036$	$69^{\circ}\cdot2$ $\cdot033$	$68^{\circ}\cdot4$ $\cdot032$	$78^{\circ}\cdot4$ $\cdot036$	$73^{\circ}\cdot2$ $\cdot036$	$70^{\circ}\cdot9$ $\cdot033$	$69^{\circ}\cdot3$ $\cdot034$	$68^{\circ}\cdot4$ $\cdot035$
Mean λ	0·035					0·035				

Ther- mometer	No. 115,511.														
Series	1st					2nd					3rd				
t_0 τ	$80^{\circ}\cdot0$ $65^{\circ}\cdot5$					$80^{\circ}\cdot5$ $66^{\circ}\cdot5$					$80^{\circ}\cdot0$ $66^{\circ}\cdot3$				
θ	secs. 6	secs. 12	secs. 18	secs. 24	secs. 30	secs. 6	secs. 12	secs. 18	secs. 24	secs. 30	secs. 6	secs. 12	secs. 18	secs. 24	secs. 30
t λ	$74^{\circ}\cdot5$ $\cdot079$	$71^{\circ}\cdot2$ $\cdot078$	$69^{\circ}\cdot5$ $\cdot072$	$68^{\circ}\cdot4$ $\cdot067$	$67^{\circ}\cdot7$ $\cdot063$	$75^{\circ}\cdot5$ $\cdot074$	$72^{\circ}\cdot3$ $\cdot073$	$70^{\circ}\cdot2$ $\cdot074$	$68^{\circ}\cdot7$ $\cdot077$	$67^{\circ}\cdot9$ $\cdot077$	$75^{\circ}\cdot5$ $\cdot066$	$72^{\circ}\cdot1$ $\cdot072$	$70^{\circ}\cdot2$ $\cdot070$	$68^{\circ}\cdot8$ $\cdot071$	$67^{\circ}\cdot9$ $\cdot072$
Mean λ	0·072					0·075					0·070				

Thermometer	No. 175,616.							
Series	1st and 2nd combined				3rd			
t_0 τ	$\begin{matrix} 80\cdot0 \\ 86\cdot4 \end{matrix}$				$\begin{matrix} 79\cdot0 \\ 66\cdot0 \end{matrix}$			
θ	secs. 6	secs. 12	secs. 18	secs. 24	secs. 6	secs. 12	secs. 18	secs. 24
t λ	$\begin{matrix} 73\cdot1 \\ \cdot118 \end{matrix}$	$\begin{matrix} 69\cdot9 \\ \cdot113 \end{matrix}$	$\begin{matrix} 68\cdot5 \\ \cdot104 \end{matrix}$	$\begin{matrix} 67\cdot8 \\ \cdot095 \end{matrix}$	$\begin{matrix} 73\cdot2 \\ \cdot098 \end{matrix}$	$\begin{matrix} 69\cdot6 \\ \cdot107 \end{matrix}$	$\begin{matrix} 68\cdot5 \\ \cdot092 \end{matrix}$	$\begin{matrix} 67\cdot9 \\ \cdot080 \end{matrix}$
Mean λ	0·107				0·094			

TABLE V.

SUMMARY.

Type of Thermometer.	Maker and Number of Thermometer.	Mean λ .
Mercurial—Kew Standard	Kew 714	0·192
Minimum Spirit, Type III.	Hicks 175,616	0·101
“ “ Type II.	Casella 115,511	0·072
“ “ Type I.	Darton 45,535	0·035
“ “ “	Casella 89,833	0·035
“ “ “	Negretti and Zambra 41,178	0·031
“ “ “	Casella 1,470	0·031

TABLE VI.

RATIO OF THE COEFFICIENT OF NO. 714 TO THAT OF EACH TYPE OF MINIMUM THERMOMETER EMPLOYED.

No. 714.	No. 714. Type I.	No. 714. Type II.	No. 714. Type III.
0·192	5·82	2·67	1·90

The values of λ found above are not necessarily the actual working coefficients of these thermometers, the conditions under which they were determined differing entirely from those to which they are exposed in meteorological investigations; but they serve the purpose of this discussion in giving approximately comparative values for the different thermometers employed.

It would appear, moreover, from the persistent decrease in the computed value of λ , that for some thermometers at least, with the value of $(t - \tau)$ employed, the relation between t, τ, λ , is not correctly given by the equation—

$$\frac{dt}{d\theta} + \lambda(t - \tau) = 0;$$

but at the same time it should be remembered that the generally large value of λ found for the interval $\theta = 6$ secs., depends on a portion of the curve where t is decreasing rapidly, and where, in consequence, an error of a few tenths of a second in θ will give large errors of t .

Curves, derived from the data given in Table IV., indicating the degree of sluggishness of the several types of thermometers employed are given in Fig. 3.

FIG. 3.

In the following tables will be found the details of the construction of each thermometer, together with the errors as determined at Kew and at the Royal Alfred Observatory, Mauritius.

TABLE VII.

Type of Thermometer.	Maker and Number of Thermometer.	Date of Kew Certificate.	Bulb.		Value of 10° in millimetres.			Coefficient of Sensitiveness.
			Shape.	Length.	Diameter.	From 85° to 75°	From 75° to 65°	
Mercurial	Kew Std. No. 714	April, 1894	Cylindrical	mills. 90	mills. 7	21	21	0.192
Min. (ordinary) colourless spirit	Casella No. 1,470	April, 1859	Spherical	—	18	19.8	19.1	0.031
" " "	Darton No. 45,535	Aug., 1894	"	—	14	14.1	13.5	0.035
" " "	Negretti No. 41,178	April, 1878	"	—	16	15.0	14.7	0.031
" " red spirit	Casella No. 115,511	April, 1899	Cylindrical	27	7.7	15.9	15.9	0.072
" (grass) colourless spirit	Casella No. 89,833	April, 1893	Spherical	—	15.5	16.0	15.8	0.035
Sensitive minimum (grass) colourless spirit	Hicks No. 175,616	Oct., 1884	(Hollow) (Cylindrical)	60	(external 11.5) (internal 4)	18.2	17.4	0.101

FIG. 4.

CORRECTIONS TO THE THERMOMETERS EMPLOYED, DERIVED FROM
COMPARISONS (IN WATER) WITH THE KEW STANDARD NO. 701.

Thermometer No. 714.		Correction.
1894 at Kew	.....	0·0°
1895 at Mauritius	.....	—0·02
1898 „	.....	—0·04
1901 „	.....	—0·09
1904 „	.....	—0·11
Thermometer No. 1,470.		Correction.
1859 at Kew	.....	0·0°
1879 at Mauritius	.....	+0·1
1889 „	.....	0·0
1899 „	.....	0·0
1906 „	.....	0·0
Thermometer No. 45,535.		Correction.
1894 at Kew	.....	0·0°
1906 at Mauritius	.....	—0·7
Thermometer No. 41,178.		Correction.
1878 at Kew	.....	0·0°
1902 at Mauritius	.....	+0·3
Thermometer No. 115,511.		Correction.
1899 at Kew	.....	0·0°
1900 at Mauritius	.....	+0·1
1901 „	.....	+1·0
1902 „	.....	+0·7

Errors of Types of Minimum Spirit Thermometers. 433

Thermometer No. 89,833.		Correction.
1893 at Kew	.....	+0.1°
1895 at Mauritius	.....	+0.3
1897 ,,	.....	-0.1
1899 ,,	.....	0.0
1902 ,,	.....	-0.2
Thermometer No. 175,616.		Correction.
1884 at Kew	.....	0.0°
1888 at Mauritius	.....	+0.6
1892 ,,	.....	+0.6
1896 ,,	.....	+1.4
1902 ,,	.....	+4.0

The corrections to the minimum temperatures, recorded by No. 1,470, for the three months—1904, January to March—already dealt with, as determined from comparisons with the lowest points on the thermograms, are given in the following table—

- (1) When the minimum occurred at the apex of a sharp wave.
- (2) When either the approach to, or recovery from, the lowest point was gradual and the minimum lasted from five to ten minutes :—

1904.					
January.		February.		March.	
CORRECTION TO THE MINIMUM TEMPERATURE RECORDED BY NO. 1,470 WHEN IT OCCURRED AT—					
The Apex of a Sharp Wave.	A Period of Steady Temperature.	The Apex of a Sharp Wave.	A Period of Steady Temperature.	The Apex of a Sharp Wave.	A Period of Steady Temperature.
d. o	d. o	d. o	d. o	d. o	d. o
2 -0.2	4 +0.3	2 -3.0	1 -0.3	1 -0.5	2 +0.1
3 -2.2	5 -0.2	4 -0.6	3 -0.6	4 -0.3	3 -0.5
10 -0.2	6 0.0	5 -0.6	6 -0.4	6 -0.5	5 -0.5
11 -0.4	7 +0.2	7 -1.6	10 -0.1	8 -0.1	7 -0.4
19 -0.6	8 0.0	8 0.0	12 -0.4	11 -0.9	9 -0.3
24 -0.3	9 -0.1	9 -1.3	16 -0.3	12 -0.6	10 -0.6
25 -1.4	12 +0.2	11 -0.3	17 -0.2	18 -0.2	13 -0.3
27 -0.8	13 -0.1	15 -0.3	19 -0.7	21 -0.3	14 -0.4
	14 -0.1	21 -0.7	20 -0.6		15 -0.6
	15 +0.1	22 -0.6	24 -0.4		16 -0.2
	16 -0.3	23 -0.8	26 -0.4		17 -0.3
	17 -0.2	27 -1.5	28 +0.4		23 -0.6
	18 -0.4		29 -0.0		24 -0.4
	20 -0.5				25 -0.6
	21 -0.6				30 +0.1
	22 0.0				31 -0.1
	23 -0.1				
	26 +0.3				
	28 +0.1				
	30 +0.5				
	31 -0.3				
8d. -0.76	21d. -0.06	12d. -0.94	13d. -0.31	8d. -0.43	16d. -0.35

SUMMARY.

1904. Month.	CORRECTION TO THE MINIMUM TEMPERATURE RECORDED BY No. 1,470 WHEN IT OCCURRED AT—			
	The Apex of a Sharp Wave.		A Period of Steady Temperature.	
	Mean Correction.	Maximum Correction.	Mean Correction.	Maximum Correction.
January	—0·76	—2·2	—0·06	—0·6
February	—0·94	—3·0	—0·31	—0·7
March	—0·43	—0·9	—0·35	—0·6

The mean correction to No. 1,470 by this method is $-0\cdot22^{\circ}$, which corrected for index error of standard becomes $-0\cdot32^{\circ}$ (*cf.* pp. 423 and *infra*).

The results given in the above table are in entire agreement with those already obtained, and call for no further remark beyond pointing out the very serious nature of these errors, which all tend in the same direction, *i.e.*, to give an erroneous minimum considerably higher than the true one.

The present investigation leads us to the following conclusions* :—

1. Minimum spirit thermometers (even the so-called “sensitive”) should never be used as ordinary thermometers.

2. The corrections to the minimum temperature obtained from comparisons between the readings of the spirit and the readings of a mercurial standard, unless made at an epoch of steady temperature, are unreliable, and may, in extreme cases, be in error to the extent of 2° or more.

3. The corrections obtained at steady temperatures from comparisons made as described above, compare favourably with those obtained from comparisons with the lowest points on the Thermograms; but do not, apparently, agree with those obtained in the usual way from comparisons in water (*cf.* pp. 423, 432 *et supra*).

4. The absolute minima obtained with spherical bulb thermometers are frequently in error on account of sluggishness, the errors in extreme cases amounting to as much as $+3^{\circ}$.

5. The mean of the absolute minima obtained with spherical bulb thermometers is invariably too high, as all errors due to sluggishness tend in the same direction.

* This is only intended to apply to the types of thermometers employed in this discussion; it is quite possible that, at other stations, minimum thermometers of greater sensitiveness are in use. It should, however, be remarked that three spherical bulb thermometers made by different makers in the years 1859, 1878, and 1894 respectively give practically the same value of λ .

6. The absolute minima obtained with cylindrical, hollow-cylindrical, or bifurcated bulbs are probably but slightly affected by "lag," as the approach to or recovery from the lowest point is generally slow enough to allow them to take up the correct temperature.

Assuming that the thermometers employed are fair representatives of their respective types, it seems evident that no spirit thermometer with a spherical bulb should be allowed in the equipment of

FIG. 5.

a meteorological observatory. Hollow-cylindrical bulbs reduce the errors due to sluggishness by about $\frac{2}{3}$.

In connection with the form and dimensions of the bulb it is interesting to note that the computed values of λ appear to bear a simple relation to the radii of the bulbs, irrespective of their form.

The radii for the several types of thermometers, taken from Table VII., are—

- Spherical bulb 8 millimetres.
- Cylindrical „ 3.8 „ (radius of base).
- Hollow-cylindrical bulb, 1.85 „ $\frac{1}{2}$ (external radius—internal radius).

If we plot these values as ordinates, with the corresponding values of λ as abscissæ, we obtain a curve of the form given below, which may be represented by the formula :—

$$\lambda = a + b\rho + c\rho^2$$

where ρ is the radius of the bulb and a , b , c constants to be determined.

Substituting the values of λ and ρ , obtained from Table VII., we have—

$$\begin{aligned} \cdot 033 &= a + b \cdot 8 \cdot 0 + c \cdot 64 \cdot 00 \\ \cdot 072 &= a + b \cdot 3 \cdot 8 + c \cdot 14 \cdot 44 \\ \cdot 101 &= a + b \cdot 1 \cdot 85 + c \cdot 3 \cdot 4225 \end{aligned}$$

the solution of which gives—

$$\lambda = \cdot 135 - \cdot 020\rho + \cdot 00091\rho^2.$$