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ART. XLIII.—*The Nitrogen Thermometer Scale from 300° to 630°, with a Direct Determination of the Boiling Point of Sulphur*; by ARTHUR L. DAY and ROBERT B. SOSMAN.

1. *Purpose and Plan of the Investigation.*

IN our recent investigation of the fundamental high temperature scale with the gas thermometer,* attention was chiefly directed to the temperature region above 1000°. The lower temperatures had been determined with considerable accuracy in an investigation undertaken in the Reichsanstalt† some years earlier (1900) and there was no reason to suspect any uncertainty in it of greater magnitude than the errors of observation determined at that time (2° to 3°). This does not mean that it was considered unnecessary to reduce the magnitude of the errors, which were known or suspected to exist in the Reichsanstalt instrument,—quite the contrary. All our efforts throughout an investigation which has now continued since 1904 have been put forth in the direction of reducing these errors to a minimum, but this was done more especially because of their much greater influence upon temperature determinations above 1000° than because of any specific demand which then existed for a new or better temperature scale in the region below that temperature.

The situation from our viewpoint at the time of publication

* Preliminary Publications :

- Day and Clement, *Phys. Rev.*, xxiv, 531, 1907 (Abstract).
- Day and Clement, *this Journal* (4), xxvi, 405-463, 1908.
- Day and Sosman, " (4), xxix, 93-161, 1910.
- R. B. Sosman, " (4), xxx, 1-15, 1910.

Final Publication :

- Day and Sosman, *Carnegie Institution Pub. No.* 157, 1911.

† Holborn and Day, *Ann. Physik* (4), ii, 505-545, 1900; *this Journal* (4), x, 171-206, 1900.

of our final results (1911) was accurately summed up in one of our closing paragraphs as follows:

"The chief source of present uncertainty [in high-temperature gas-thermometer measurements] is the temperature distribution over the surface of the bulb in an air bath. It would be possible to eliminate this error in the lower portion of the scale by substituting a liquid bath which could be stirred. In fact, this was done for temperatures below 500° in the earlier work of Holborn and Day, but has not, so far, been tried in the present investigation because of the relatively secondary importance of the lower temperatures to the ultimate purpose of the investigation (the study of silicates). For the higher temperatures, no satisfactory liquid bath has been found."* (Publication of the Carnegie Institution No. 157, p. 125, 1911.)

The lower temperatures upon this scale, determined in an air bath, come out about 1° lower than the corresponding temperatures of the Reichsanstalt scale (determined in a liquid bath). These temperatures are compared below:

	Holborn and Day 1900	Day and Sosman 1911
Cadmium (melting point)	321.7°	320.0°
Zinc " "	419.0	418.2
Antimony " "	630.6	629.2

This circumstance was the more conspicuous, and perhaps the more open to suspicion, because a discrepancy of precisely the same order of magnitude (1°) had appeared between air-bath and liquid-bath determinations in the neighborhood of 400° in the work of Holborn and Day in 1900, which eventually led them to reject the measurements made at that temperature in the air bath. It is, therefore, not surprising that the reappearance of this discrepancy should attract considerable attention even though this difference of 1° is within the stated and admitted limits of accuracy of the Reichsanstalt scale (2° to 3°). It is also serving a useful purpose in directing attention to an uncertainty which had remained undisturbed for so long that it probably had been forgotten, for there is abundant reason to believe that to-day, with a modern gas thermometer, adjusted to give appropriate sensitiveness, these temperatures can be determined with much greater accuracy than 1°.

That the Reichsanstalt is also of this opinion is shown by the recent publication of a new series of measurements† of these

* Prof. Holborn has directed attention to the same limitations in our results at these temperatures, in a recent paper, to which further reference will be made presently.

† Holborn and Henning, *Ann. Physik* (4), xxxv, 761-774, 1911.

temperatures. The gas thermometer measurements were made in a liquid bath, using a sensitive resistance thermometer to transfer the temperature from the bath containing the gas thermometer bulb to the (independent) sulphur boiling point apparatus. The lower temperatures were then interpolated by means of the platinum resistance thermometer. The new determinations were published so recently that there has been no opportunity for confirmation by other experimenters, but they appear to be free from any error greater than one or two tenths of a degree, and therefore indicate a very considerable increase in the accuracy of the results when compared with the earlier (1900) scale which is now in general use. Holborn and Henning's new results, on the thermodynamic scale, are in part as follows :

Benzophenone (boiling point).....	305.89°
Cadmium (melting point).....	320.92
Zinc " "	419.40
Sulphur (boiling point).....	444.51

In certain studies* now under way in this laboratory on the effect of pressure upon equilibria greater accuracy is now required in the measurement of these particular temperatures than had previously been necessary. We therefore determined to repeat these measurements, with more elaborate precautions to secure a uniform temperature about the bulb, this being, as stated above, the one factor in our measurements about which some uncertainty remained. At any rate it was important to establish the identity and the magnitude of the error in the earlier measurements which may have been due to this cause.

2. Apparatus.

No attempt will be made to describe in detail the gas thermometer and accessories used in this investigation. A full description of the apparatus, with illustrations, will be found in the publications to which reference has been made. No change whatever was made in the gas thermometer system for these measurements, except for the substitution, about the bulb, of a liquid bath, made up from potassium and sodium nitrates in eutectic proportions (55 per cent KNO_3 , 45 per cent NaNO_3). This bath was introduced into the furnace bomb described in connection with the earlier apparatus in place of the platinum wire furnace previously used. The insulating material was dried magnesia powder, as heretofore, and the bomb was water-jacketed throughout to protect the manometer. The general appearance of the furnace is shown by the accompanying diagram (fig. 1).

* Johnston and Adams, this Journal, xxxi, 501-517, 1911.

The vessel which contained the nitrates consisted of a cylindrical wrought iron tank 152^{mm} in inside diameter and of 7^{mm} wall thickness, into which the bottom plate was welded with an oxy-acetylene flame. This detail is perhaps worth some emphasis, because it was the only tank of three which were made up with various joints in the bottom which proved able to hold the nitrates up to a temperature of 630° without leaking.

FIG. 1.

FIG. 2.

FIG. 1. Nitrogen-thermometer bulb in double nitrate bath. (The two thermoelements on the outside of the bulb are not shown.)

FIG. 2. Apparatus for the determination of the melting point of zinc in the nitrogen thermometer nitrate bath.

Scale: 1 to 6.5.

As at first used this tank was merely a covered vessel without partitions into which a turbine stirrer, operated by an electric motor, was inserted. The comparatively loose lower bearing of the turbine was lubricated by the liquid itself, the upper one was water-cooled. Alongside of this stirrer, and 30^{mm} distant from it in the bath, was the bulb of the gas thermometer. Although the stirring in the tank was vigorous, temperature differences amounting to 0.4° appeared between the top and the bottom of the bulb at 400°. The current in the liquid was up-

ward in the turbine tube and downward past the bulb. With this arrangement the top of the bulb was cooler.

In an air bath it had not proved possible to reduce the variation of temperature over the surface of the bulb below 1° , so that the liquid bath, even in this form, was an improvement over the air bath. But still greater uniformity was desired. After some experimenting, which need not be described here, the arrangement shown in the diagram (fig. 1) was adopted. It amounted, briefly, to one bath within another; that is, the tube containing the stirrer was continued across the bottom of the tank and upward about the bulb, which it fitted with but little clearance (10^{mm}) in order to insure the very rapid circulation of a thin layer of liquid past the bulb, while the remainder of the bath remained at an approximately uniform temperature without. With this arrangement no systematic temperature differences greater than the errors of observation of the thermoelements (0.1°) were observed.

3. *Method of Procedure.*

In this apparatus temperatures were read simultaneously (1) upon the gas thermometer, (2) upon three thermoelements distributed at different points in the bath,—one in a re-entrant tube extending to the center of the bulb, and one each at the top and bottom of the outside wall.

For the measurements at the benzophenone boiling-point thermoelements of copper-constantan and of platinum-platinrhodium (Heraeus) were used, for the higher temperatures platinum-platinrhodium only. After a trial of the copper-constantan elements at the next higher temperature (zinc), evidence of permanent changes in their readings was obtained which was more than sufficient to offset their increased sensitivity. They were accordingly abandoned in work at the higher temperatures.

A thermoelement suggested by Geibel,* of gold against an alloy of 60 gold, 40 palladium, was also tried. This gives an electromotive force about equal to that of copper-constantan and over six times that of the platinum-platinrhodium element. But the alloy wire proved so inhomogeneous that the accuracy of the element was much less than that of the platinrhodium, and it was accordingly rejected.

Through the courteous coöperation of the Bureau of Standards, a sensitive resistance thermometer in charge of Drs. Dickinson and Mueller of the Bureau was placed alongside the bulb during a part of the measurements, and later a similar instrument ingeniously constructed for the purpose by Dr.

* *Zs. anorg. Chem.*, lxi, 38-46, 1910.

Dickinson was introduced into the re-entrant tube of the gas thermometer bulb itself. The resistance thermometer, which was easily sensitive to a few thousandths of a degree, revealed small temperature fluctuations (0.05°) in the rapidly circulating liquid outside the bulb but no systematic temperature differences. Within the re-entrant tube the fluctuations were no longer felt.

With these precautions to guard against temperature differences about the bulb, temperatures were measured (1) at the boiling-point of benzophenone, (2) at the melting-point of zinc, (3) at the melting-point of antimony.* The three thermoelements, after removal from the nitrate bath, were placed in one or the other of the following: in a vapor bath of boiling benzophenone, in an apparatus for determining the zinc melting-point, or in a similar apparatus containing antimony; after which they were returned to the gas thermometer furnace for the verification of their readings. This series of operations constituted a set of observations as carried out in the tables which follow. Inasmuch as the gas thermometer was brought as close as practicable to the temperature of the points (benzophenone, zinc, etc.) selected as standards, the intermediary role of the thermoelements was merely that of a transfer agent, in which role the individual properties of the thermoelements do not appear at all provided the wires were originally homogeneous. The danger of contamination of the elements and consequent inhomogeneity is negligible at these temperatures. Even if such contamination had crept in, it would have discovered itself in differences between the readings of the elements with each change in the gradient, of which differences no trace was found.

By way of providing a strictly rigorous test of the accuracy of the transfer of temperature from gas thermometer bulb to the reference standards and its independence of the intermediary thermoelement, a special arrangement was devised in the case of zinc as follows: A steel bulb was made up with approximately the dimensions of the gas thermometer bulb and suspended in the same position in the nitrate bath. Enclosed in this bulb was the charge of zinc in its graphite crucible (fig. 2). In this crucible the thermoelement occupied the same position which it occupied in reference to the gas thermometer bulb, and all other conditions were, of course, identical. The zinc melting-points were determined in this way, i. e., in a nitrate bath in which there were no measurable temperature differences in the region about the melting zinc and with the tem-

* The zinc and antimony were the same charges which were used in the previous investigation. The analyses may be found in Pub. 157, pp. 87 and 88; this Journal, xxix, p. 159.

perature gradient along the thermoelements identical with that surrounding the gas thermometer bulb itself.

4. *Boiling Point of Sulphur.*

Finally an attempt was made to establish one temperature in this region from which the intermediary thermoelement should be completely eliminated. The gas thermometer bulb itself was immersed in the vapor of boiling sulphur. For this determination the nitrate bath was replaced by an appropriate sulphur boiling-point apparatus, all other conditions remaining the same. In building this apparatus, which is shown in fig. 3, the experience of the Bureau of Standards was utilized for the most part. To this design certain modifications suggested by the unpublished work of Prof. G. A. Hulett of Princeton were added by way of rendering the determination, as far as practicable, independent of particular experimental conditions employed.

Heat was supplied electrically from a coil of high resistance wire about the sulphur tube, the coil ending about 2^{cm} below the level of the surface of the liquid sulphur (Bureau of Standards usage). An independent coil surrounded the vapor region, separated from it by an annular air space of about 1^{cm} (Hulett). The bulb was surrounded first by a shield of sheet aluminium (Bureau of Standards) with holes near the top and bottom to permit the free circulation of the sulphur vapor and a hole in the center of the bottom diaphragm to permit the escape of liquid sulphur which chanced to condense on the shield. The shield afforded protection against any direct interchange of radiation with the furnace or with the boiling liquid and its steep conical roof diverted the condensing liquid sulphur away from the bulb. Subsequently with the purpose of varying these conditions the aluminium shield was replaced by another of similar form but of glass (Hulett) and of somewhat smaller diameter. This was suspended from the conical aluminium roof of the first shield, which now overhung the side walls by several millimeters, with the effect that liquid sulphur condensing upon the cone could drip from the overhang instead of running down the side wall past the bulb. The radiation conditions were also radically altered by this substitution of glass for aluminium both around the bulb and below it.

Further variation was provided by changing the current in the two heating coils. Variations of some 35 per cent in the main coil about the boiling liquid were tried and the upper coil was varied from zero (Bureau of Standards usage) to over 40 per cent of the current in the main coil. Or, in other terms, the 1^{cm} air jacket about the vapor was varied in temperature

from the normal gradient (without heat in the upper coil) to a temperature equal to that of the sulphur vapor itself.

None of these changes produced any measurable change in the temperature of the sulphur vapor as recorded by the gas thermometer provided enough heat was supplied to fill the tube with vapor. During some of the measurements the vapor escaped freely between the glass tube and aluminium cover and burned there.

The remaining details and relative dimensions of the sulphur

FIG. 3. Apparatus for direct determination of the boiling point of sulphur with the nitrogen thermometer. Scale: 1 to 6.5.

vapor bath will be clear from the diagram (fig. 3), which is drawn to scale. The arrangement shown in the figure is the one with the aluminium shield.

The sulphur used was distilled to free it from a black residue which was found in both of two different preparations of C.P. sulphur. This residue, which is partly if not wholly ferrous sulphide, would probably have had no appreciable effect on the boiling point. After the close of these experiments the sulphur boiling apparatus was sent to the Bureau of Standards, where a number of measurements were made of the tempera-

ture of the vapor within the aluminium shield compared with the corresponding temperature in one of the sulphur baths which Waidner and Burgess* have standardized and described in connection with their measurements with the platinum resistance thermometer. This comparison has been described by Messrs. Dickinson and Mueller.† The differences amounted in maximum to 0.04° , which may afford some measure of the certainty with which the temperature of the sulphur vapor is reproduced in an apparatus differing considerably from the conventional form and dimensions.

At the close of the measurements the gas thermometer bulb and manometer were disconnected. In order to make certain that our calculation of the volume of the unheated space contained no unknown constant error, that portion of this space lying outside the furnace was determined directly, as follows: the mercury was brought up to the fixed point with the capillary open to the air. The connection between the two arms of the manometer was then closed, and a known volume of air (about 0.1^{cc}) was drawn in through the capillary by drawing off a weighed amount of mercury from the short arm. The open end of the capillary was then sealed, the manometer connection reopened, and the mercury again brought up to the fixed point. The pressure necessary to effect this is a measure of the volume of the space in the capillary and connections. The results were:

Direct determinations	0.159^{cc}
	0.164^{cc}
Mean	0.162^{cc}
Calculated in 1909	0.168^{cc}

The difference is negligible.

Finally, the location on the brass scale of the gas thermometer of the "fixed point" which is situated in the top of the short arm of the instrument and which defines its "constant volume," was redetermined and found to have become displaced by 0.18^{mm} since the initial determination in 1909. An appropriate correction was accordingly made to this constant in computing the results.

These various checks and verifications complete the observations. The more important constants of the instrument and the formula used in the calculations are reproduced below from the previous paper.‡

* Bull. Bur. Stds., vi, 150-230, 1909.

† J. Washington Acad., ii, 176-180, 1912.

‡ Pub. No. 157, p. 52.

Material of the bulb : pure platinum 80 per cent
pure rhodium 20 per cent

Volume of bulb: $V_0 = 205.82^{\text{cc}}$

Volume of unheated space: $v_1 = 0.309^{\text{cc}}$

$$\frac{v_1}{V_0} = 0.00150$$

Expansion coefficient of bulb material: $10^6 \beta = 8.79 + 0.00161 t$

Gas: pure nitrogen.

Initial pressure of gas (see Table I): $p_0 = \text{about } 500^{\text{mm}}$.

Pressure coefficient of gas (see Table II): $\alpha = 0.0036679$ to 0.0036681 .

Formula used in the computations:

$$t = \frac{1}{p_0 \alpha} \left[p \left(1 + \frac{3 \beta t}{1 + \frac{v_1}{V_0}} \right) - p_0 \right]$$

in which p_0 and p are the corrected pressures at 0° and t respectively.

5. *Experimental Results with Nitrate Bath.*

Table I contains the measurements of the zero-point of the instrument before and after each heating and serves to show that its variations are wholly within the accidental errors of reading of barometer and manometer. In the third column p'_0 is the measured initial pressure of the gas in millimeters of mercury at zero degrees. The application of the correction for the "unheated space" gives the pressures (p_0) of column 4.

The measurements included in Table II are introduced merely as a rough check on the pressure coefficient (α) of the gas. A much more accurate determination has been made of this constant for nitrogen by Chappuis* and his value of it (0.0036681 , corresponding to a pressure of 502^{mm}) was used in the calculations which follow. These measurements merely afford a rough confirmation of this value within the somewhat larger limits of error of our instrument. Columns 3 and 4 contain the pressures at the boiling point of water corrected as in Table I.

In Table III, columns 3 and 4 contain the pressure measurements near the three fixed temperatures of reference, reduced as before; t (column 5) is the gas thermometer temperature in the nitrate bath and e (column 6) the corresponding electromotive force of the thermoelement in microvolts; e (column 7) is the electromotive force of the same elements in benzophenone, zinc and antimony respectively and the final column contains the corresponding gas thermometer temperatures.

* Trav. Mem. Bur. Int., vol. xiii, 1907.

TABLE I. Measurements of p_0 .

Date	Serial No.	p'_0	p_0
1911	<i>First Gas Filling.</i>		
17 Oct.	1	486.03	485.98
19 "	4	486.05	486.00
21 "	7	486.06	486.01
21 "	8	486.05	486.00
	<i>Second Gas Filling.</i>		
26 "	9	501.91	501.86
27 "	10	501.91	501.86
31 "	12	501.87	501.82
31 "	13	501.88	501.83
2 Nov.	15	501.94*	501.89*
6 "	17	501.89	501.84
6 "	18	501.91	501.86
11 "	22	501.84	501.79
15 "	24	501.81	501.76
18 "	26	501.87	501.82
20 "	29	501.81	501.76
6 Dec.	30	501.79	501.74
8 "	35	501.84	501.79
11 "	38	501.82	501.77
22 "	43	501.83	501.78
27 "	48	501.77	501.72
1912			
2 Feb.	54	501.86	501.81
15 "	61	501.88	501.83

TABLE II. Measurements of p_{100} .

Date	Serial No.	p'	p	Barom.	t	a
1912						
15 Feb.	58	683.51	683.69	754.3	99.790	0.0036684
"	59	683.49	683.67	753.7	99.768	0.0036685
"	60	683.46	683.64	753.4	99.757	0.0036686
					Mean	0.0036685

* High wind, both mercury columns varying.

TABLE III. Gas Thermometer Measurements in Nitrate Bath.

Date	Serial No.	p'	p	t	e	e at fixed point	Temp. of fixed point
<i>Benzophenone, boiling point.</i>							
1911							
18 Oct.	2	1023·36	1024·47	306·97	2379·8	2369·2	305·82
20 “	6	1020·60	1021·69	305·37	2364·7	2369·2	305·86
30 “	11	1053·07	1054·18	304·91	14944*	14996	305·82
1 Nov.	14	1054·84	1055·97	305·91	15002*	15005	305·96
						Mean	305·87
<i>Zinc, melting point.</i>							
18 Oct.	3	1216·27	1218·05	418·78	3429·4	3433·7	419·24
20 “	5	1215·85	1217·61	418·53	3427·1	3433·7	419·24
4 Nov.	16	1256·96	1258·76	419·32	3432·2	3433·7	419·48†
17 “	25	1256·54	1258·35	419·18	3432·9	3433·7	419·27
18 “	27	1255·85	1257·69	418·80	3429·0	3433·7	419·31
18 “	28	1254·96	1256·80	418·29	3423·8	3433·7	419·36
						Mean	419·28
<i>Antimony, melting point.</i>							
10 Nov.	19	1627·10	1630·58	629·66	5525·8	5527·7	629·84
10 “	20	1627·09	1630·57	629·66	5525·2	5527·7	629·90
10 “	21	1626·96	1630·44	629·58	5524·2	5527·7	629·92
14 “	23	1625·08	1628·59	628·54	5515·5	5527·7	629·73
						Mean	629·85

* Copper-constantan thermoelement.

† Wide temperature variation on manometer. This value is omitted from the mean.

6. *Interpolation Formula.*

For convenient interpolation with thermoelements in this temperature region, the following equation is accurate within 0·3° as far as the melting point of copper, but may not be used beyond that temperature or below the boiling point of benzophenone:

$$e = -308 + 8·2294 t + 0·001649 t^2$$

In terms of the standard element used in our recent publication upon this subject,* this equation gives the following electromotive forces:

* Publication No. 157, Carnegie Institution of Washington, pp. 109 *et seq.* For the measurement and interpolation of temperatures above 1082·6°, the reader is referred to the same pages; for temperatures below 305·9° to page 536, following (Adams and Johnston).

Fixed point	Temperature (Nitrogen Thermometer)	Standard thermo- element (in microvolts)	E. M. F. calculated (in microvolts)	Difference Obs. — Cal.	
				Mv.	Degr.
Benzophenone (boiling point)	305.9°	2365	2364	+1	+0.1
Cadmium (melting point)	320.8	2502	2502	0	0.0
Zinc (melting point)	419.3	3429	3432	—3	—0.3
Antimony (melting point)	629.8	5530	5529	+	+0.1
Silver (melting point)	960.0	9113	9112	+1	+0.1
Gold (melting point)	1062.4	10295	10296	—1	—0.1
Copper (melting point)	1082.6	10534	10534	0	0.0

7. *Experimental Results on Sulphur.*

Table IV contains the measurements made in the sulphur vapor bath. p' and p represent the gas thermometer pressures corrected as before, t the resulting temperature, followed by the barometer reading reduced to sea level at lat. 45°, and the boiling temperature reduced to 760^{mm} pressure.

TABLE IV. Direct Measurement of Boiling Point of Sulphur.

Date.	Serial No.	p'	p	t	Barom.	t at 760 ^{mm}
1912.						
31 Jan.	49	1298.77	1301.07	443.21	746.3	444.45
"	50	1298.83	1301.16	443.26	747.0	444.43
"	51	1298.84	1301.17	443.27	747.0	444.44
1 Feb.	52	1299.14	1301.44	443.42	748.4	444.47
"	53	1299.14	1301.44	443.42	748.2	444.48
3 Feb.	55	1299.70	1302.00	443.73	752.0	444.45
"	56	1299.50	1301.81	443.62	751.4	444.40
"	57	1299.55	1301.87	443.66	751.0	444.47
Mean						444.45

TABLE V. Gas Thermometer Determinations of the Boiling Point of Sulphur since 1890.

Date	Author	Thermometer	Gas	Pressure mm.	Original figure	Corrected figure	Const. vol. nitrogen scale			Thermodynamic scale	Notes
							$p_0 = 1000$	$p_0 = 760$	$p_0 = 500$		
1890	Callendar and Griffiths	Const. pr.	Air	760	444.53*	----	444.71	444.76	444.81	444.91	{ Indirect through Pt. res. therm.
1902	Chappuis and Harker	Const. vol.	Nitrogen	530	445.2†	444.7‡	444.60	444.65	444.70	444.80	{ Indirect through Pt. res. therm.
1908	Eumorfopoulos	Const. pr.	Air	760	443.58§	444.55	444.73	444.78	444.83	444.93	Direct.
1911	Holborn and Henning	Const. vol.	Hydrogen Helium Nitrogen	623 } 612 } 625 }	444.51 ¶ (444.39)	----	443.31	444.36	444.41	444.51	{ Indirect through Pt. res. therm.
1912	Day and Sosman	Const. vol.	Nitrogen	502	444.45	----	441.35	444.40	444.45	444.55	Direct

* Phil. Trans., clxxxii, A, 119-157, 1891.

† Trav. Mem. Bur. Int., xii, 1902.

‡ Ibid., p. 90.

§ Proc. Roy. Soc., lxxxi, A, 339-362, 1908.

|| Proc. Roy. Soc., lxxxiii, A, 106-108, 1910.

¶ Ann. Physik, xxxv, 761-774, 1911. The value given for "Nitrogen" is calculated from the authors' table of experimental results. They give in their paper only the final mean value on the thermodynamic scale.

In Table V are brought together all the gas thermometer determinations of the boiling point of sulphur since 1890 with the necessary information for an intelligent comparison of the determinations. Column 5 contains the initial pressure of the gas used, and column 6 the original value published by the author with a reference to the place of publication. Two of these determinations were subsequently corrected by the authors themselves. These corrections (with the reference) are given in column 7.

Inasmuch as these various determinations were made under somewhat different gas conditions, the results are not directly comparable without reduction to some common unit. The four columns which follow contain such reductions for purposes of convenient comparison. Our own observations are directly comparable with the numbers contained in the column "Const. vol. nitrogen scale, $p_0 = 500$." The fairest comparison is afforded by reduction to the thermodynamic scale, in view of the fact that the different gases used by the various observers depart in varying degree from the behavior of a perfect gas expanding at constant volume from the same initial pressure. It should be noted that the small differences between the four columns are really arithmetical and not experimental, since none of the original determinations can claim an accuracy closer than 0.05° .

The Callendar and Griffiths determination above, which is often quoted as direct, is in reality indirect. In his first investigation (Phil. Trans. 1887) Callendar showed that his parabolic formula represented within 1° the variation of the resistance of platinum with the temperature as determined by the constant pressure air thermometer as far as 600° . In this later work (Phil. Trans. 1891) he showed by a comparison of two resistance thermometers with the air thermometer, using sulphur merely as a constant temperature bath, that his original value of $\delta = 1.57$ would still represent the results for these thermometers within the limits of error. This value of δ was then used to calculate the sulphur boiling point determined with several platinum thermometers in the usual (Meyer) form of sulphur boiling tube.*

* The air thermometer observations of Callendar and Griffiths in sulphur vapor comprise fourteen readings, made between 4:52 and 5:30 p. m. on Friday, September 12, 1890, and between 8:25 and 9:07 the following morning, as follows (Phil. Trans., 182 A, 1891, p. 139):

Friday, Sept. 12, 1890.		Saturday, Sept. 13, 1890.	
Time	Temperature	Time	Temperature
4:52	444.52°	8:25	444.51°
5:02	444.90	8:28	444.51
5:06	444.68	8:38	444.52
5:18	444.77	8:42	444.53
5:21	444.79	8:48	444.54
5:26	444.94	8:50	444.52
5:30	444.98	9:07	444.61

8. *Summary.*

The new gas thermometer temperatures which this investigation has given us are brought together in Table VI, expressed (column 2) in terms of nitrogen expanding at con-

Concerning the sulphur used with the air thermometer, the following information is offered (p. 140):

"The sulphur used on the Friday was poured out of the apparatus before it solidified. It was found to be much discoloured, owing to the presence of various impurities due to residues of oil, red lead, etc., used in fitting the iron tubes together. Fresh sulphur was used on the Saturday, and this, on examination, appeared to have suffered hardly any change."

Notwithstanding the fact that the conditions surrounding the observations of Saturday appear the more favorable, these are rejected, with this statement (p. 140):

"The mean values of t deduced from the observations with the platinum thermometers M_1 and M_2 , by assuming the value $\delta=1.570$ in formula (d), are:

On Friday, $t = 444.78^\circ \text{C.}$

On Saturday, $t = 444.84^\circ \text{C.}$

"The mean values of t deduced from the simultaneous observations with the air thermometer are:

On Friday, $t = 444.80^\circ \text{C.}$

On Saturday, $t = 444.52^\circ \text{C.}$

"The value found on Friday is seen to agree perfectly with that deduced from the observations with the platinum thermometers. The value of t deduced from Saturday's observations is 0.32° too low; but it is probable that the value of mk , used in reducing the observations taken on that day, is a little too great."

" We may, therefore, conclude that these experiments, so far as they go, are a complete verification of the value of δ found in 1887, and show that the platinum wire has not altered appreciably in the interval."

Of the apparatus used, the following details are taken from another part of the paper (p. 120):

"Two new thermometers, M_1 and M_2 , were therefore constructed out of the remainder of the old spiral [1887], and were very carefully compared with the air thermometer at a temperature very near the boiling-point of sulphur. . . . The result agrees perfectly with that found in 1887, and shows that the value of the δ -coefficient has not altered appreciably in the interval.

"The apparatus used for this comparison [the sulphur bath used with the air thermometer], although useful as a constant high-temperature bath, was not very well suited for determining the actual temperature of the sulphur vapour. Another series of experiments was therefore undertaken in a Meyer tube, which proved to be more convenient for the purpose."

On page 145 occurs the following statement of the final result (obtained in the Meyer tube with resistance thermometers only):

"Assuming $\delta = 1.570$ for thermometers L , M_1 and M_2 , we find for the corresponding air-temperature the value

$$t = 444.53^\circ \text{C.}$$

We believe this to be within 0.1° of the true temperature of the vapour of sulphur boiling freely under a pressure of 760^{mm} ."

The value assumed for δ is entirely dependent upon the temperature determined with the air thermometer, and can not be more accurate than this determination. From the air thermometer measurements above quoted, 0.5° would appear to be a fairer measure of the uncertainty of the final sulphur point.

stant volume from an initial pressure of 760^{mm} and (column 3) in terms of the thermodynamic scale. These values replace the corresponding temperatures published in our papers to which reference has been made.

TABLE VI.—SUMMARIZED TABLE.

Point	Temperature		Notes
	Const. vol. $p_0=1$ at.	Thermo- dynamic	
Benzophenone (Kahlbaum) boiling pt. at 760 ^{mm}	305·85	305·9	Transferred by platinum-rhodium and copper-constantan thermoelements.
Cadmium, melting pt.	320·8	320·9	Interpolated.
Zinc, melting pt.	419·3	419·4	Transferred by thermoelements.
Sulphur, boiling pt. at 760 ^{mm}	444·40	444·55	Direct.
Antimony (Kahlbaum), melting pt.	629·8	630·0	Transferred by thermoelements.
Aluminum, melting point	658·5	658·7	Interpolated.

Finally a comparative table is added showing in terms of the same (thermodynamic) scale a comparison of our results with those obtained by Holborn and Henning in the latest work published from the Reichsanstalt.

TABLE VII.—COMPARATIVE TABLE.
Thermodynamic Scale.

Point	Holborn and Henning 1911	Day and Sosman 1912
Benzophenone	305·9	305·9
Cadmium	320·9	320·9
Zinc	419·4	419·5
Sulphur	444·51	444·55
Antimony	Holborn and Day 630·6	630·0

Geophysical Laboratory,
Carnegie Institution of Washington,
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