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ESTABLISHMENT OF A TEMPERATURE SCALE FOR THE CALIBRATION OF THERMOMETERS BETWEEN 14° AND 83° K

By Harold J. Hoge and Ferdinand G. Brickwedde

ABSTRACT

Seven resistance thermometers (six Pt; one 90Pt:10Rh alloy) have been calibrated on the thermodynamic scale by comparison with a helium gas thermometer. The boiling point of oxygen was taken to be 90.19° K, and computations were made in such a way as to secure continuity between the International Temperature Scale and the scale being established. On the latter scale the triple point of normal hydrogen was found to be 13.96° K and the boiling point 20.39° K. Tables have been prepared by means of which temperatures corresponding to observed resistances may be obtained by linear interpolation.

CONTENTS

I. INTRODUCTION

There are in the United States at the present time 13 laboratories equipped or being equipped to produce liquid hydrogen, liquid helium, or both, and the number is growing steadily. Many of the investigations being carried on in these laboratories require the precise measurement of temperatures in the region below 83° K (−190° C), and the National Bureau of Standards has received a number of requests for calibrations in this temperature range. The International Temperature Scale[1] defines no standard procedure for the measurement of temperatures below −190° C, and as a consequence it has been customary for cryogenic laboratories to calibrate their temperature-measuring instruments by direct comparison with a gas thermometer. The difficulties inherent in gas thermometry make it highly desirable that some simpler procedure be found, which may be used in all investigations where the measurement of temperature is not itself the primary object. Since from 660° C down to −190° C the International Temperature Scale is based on the resistance of platinum, a desirable solution of the problem would be to extend the useful range of the platinum resistance thermometer to lower temperatures. The

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[1] George K. Burgess, BS J. Research **1**, 635 (1928) RP22.

provisional temperature scale described in this paper represents such an extension. Apparatus is now being set up to make this scale available to other laboratories by the calibration of thermometers which may be submitted for test. The purpose of this paper is to describe the establishment of this scale, which is to serve (1) as the basis for calibrations made by the National Bureau of Standards between 14° and 83° K and (2) as the scale to be used by this Bureau in reporting the results of its own investigations.

Since the National Bureau of Standards, in common with other standardizing laboratories, makes all calibrations above −190° C on the International Temperature Scale, it is important that the scale extending to lower temperatures should join smoothly with it at its lowest point. This continuity can be obtained by using the oxygen point as the primary fixed point in determining the constant of the gas thermometer, rather than the ice point, which is the more usual procedure, and by assigning to it the same temperature on both scales. The scale described in this paper is based on seven resistance thermometers (six Pt; one 90Pt:10Rh alloy) whose resistances have been determined as a function of temperature by comparison with the gas thermometer.

The resistances of these thermometers will be checked from time to time at the triple point and boiling point of hydrogen, at the boiling point of oxygen, and at the ice point. It is planned in subsequent investigations to determine a number of other fixed points on the scale described. With a sufficient number of such points established, the maintenance of the scale will not be dependent on the preservation of the seven original thermometers.

It is hoped that the scale will be found to be in agreement with the thermodynamic scale to within ±0.02°. When a program for thermometry was laid out it was considered advisable to establish first a provisional scale of reasonable accuracy without waiting for the construction of more elaborate apparatus with which somewhat greater accuracy might have been attained. The continuation of this program includes, however, the construction of a new and more accurate gas thermometer with which not only to improve the present provisional scale but also to determine fixed points throughout the region below the ice point.

II. APPARATUS

There was available the low temperature adiabatic calorimeter used by Southard [2] and his collaborators in their calorimetric investigations. This calorimeter had been used by Southard and Milner [3] as a cryostat for the gas thermometer with which they calibrated their resistance thermometers. After some changes, designed to improve its accuracy, this apparatus was used in the present work.

The thermometer bulb and cryostat are shown schematically in figure 1. Surrounding the heavy cylindrical copper bulb was a thermal shield with independent heaters in top, side, and bottom, and outside the shield in turn was a vacuum-tight brass container. Outside this container was a dewar flask which was filled with liquid hydrogen (in some cases with liquid air). This dewar flask was entirely enclosed by a metal jacket (not shown). By reducing the

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[2] J. C. Southard and F. G. Brickwedde, J. Am. Chem. Soc. **55**, 4378 (1933).

[3] J. C. Southard and R. T. Milner, J. Am. Chem .Soc. **55**, 4384 (1933).

pressure inside this jacket with a vacuum pump, temperatures down to 55° K could be obtained with liquid air and temperatures down to

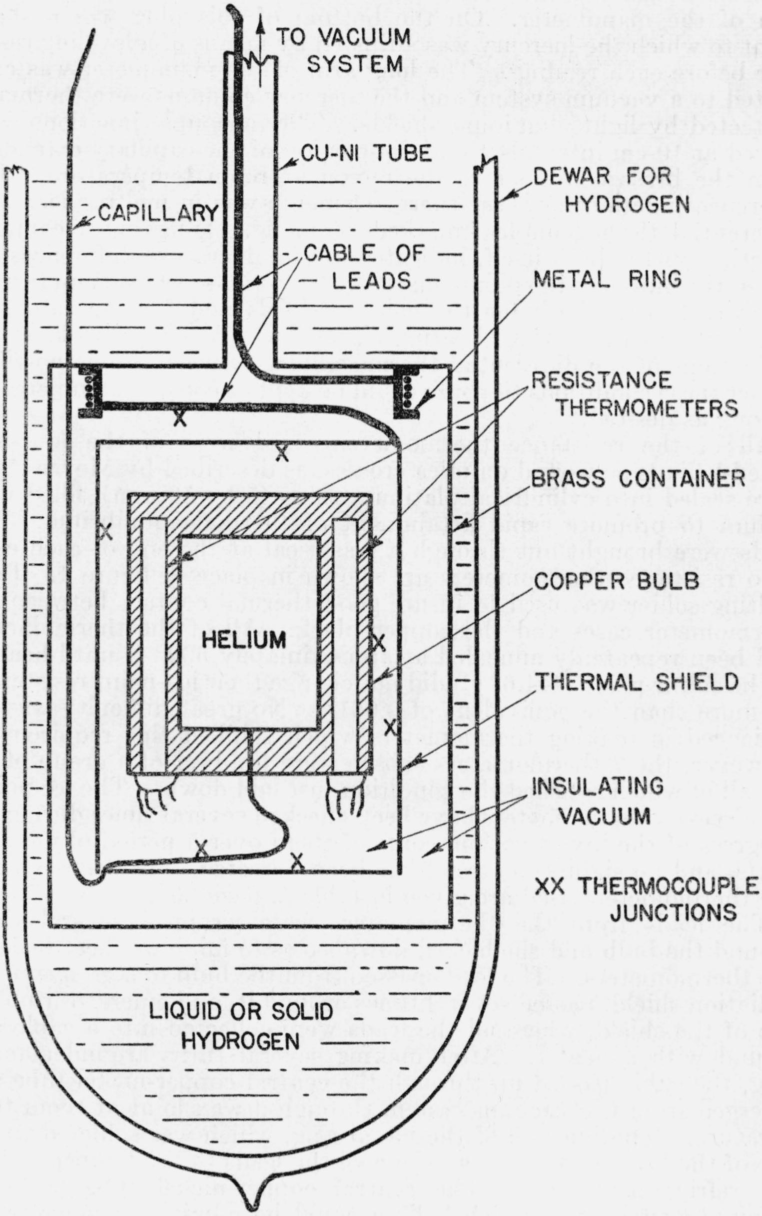

Figure 1.—*Thermometer bulb and cryostat.*

10.5° with (solid) hydrogen. The metal jacket was always surrounded by liquid air before filling the inner dewar with liquid hydrogen.

The copper-nickel capillary led to a mercury manometer where the pressures were read on a glass mirror scale. The end of the capillary passed through a turned-brass plug which was waxed into the short arm of the manometer. On the bottom of this plug was a sharp point to which the mercury was adjusted by means of a leveling reservoir before each reading. The long arm of the manometer was connected to a vacuum system and the mercury columns were thermally protected by light aluminum shields. Thermocouple junctions were placed at 10-cm intervals along the portion of the capillary extending from the brass container to the region at room temperature. The reference junction for these thermoelements was in melting ice. Six differential thermocouples (marked × in fig. 1), having a common junction on the bulb itself, indicated any temperature differences between the bulb and the points marked ×. It was necessary to furnish separate heaters both for the cable of leads and for the capillary. The input to the various heating circuits was regulated to keep the indications of the differential thermocouples as near zero as possible. Under these conditions the bulb could be kept at constant temperature as long as desired.

All of the resistance thermometers used were of the four-lead coiled-helix type wound on mica crosses, as described by Meyers,[4] but were sealed into cylindrical platinum cases (5 by 50 mm), filled with helium to promote rapid attainment of thermal equilibrium. The leads were brought out through a glass seal at the end of each case. Two resistance thermometers are shown in place in figure 1. Low-melting solder was used to insure good thermal contact between the thermometer cases and the copper block. All of the thermometers had been repeatedly annealed at approximately 500° C until heating to the sulfur point (444.6° C) did not change their ice-point resistances by more than the equivalent of 0.001°. No great difficulty was experienced in making thermometers which fulfilled this requirement. However, the 7 thermometers chosen were the best of a group of 12, not all of which satisfied the condition just laid down. The ice points of the seven thermometers have been checked several times during the progress of the investigation, some of them over a period of nearly 3 years, and no significant trend has been detected. The constants of the thermometers used are given in table 4, page 362.

The leads from the thermometers were wrapped several times around the bulb and shellacked down, so as to minimize heat leaks to the thermometers. The leads passed from the bulb to a groove in the radiation shield, passed several times around it, and emerged from the top of the shield, where all the leads were collected into a cable and wound with a heater. After making several turns around a metal ring, the cable passed up through the central copper-nickel tube and emerged from the vacuum system through a wax joint at room temperature. The purpose of the metal ring, which was soldered to the top of the brass container, was to cool the leads to the temperature of the refrigerating bath. The central copper-nickel tube led to a vacuum system into which helium could be admitted whenever the gas thermometer was to be brought rapidly to the temperature of the bath. This vacuum system was entirely independent of the one to which the manometer was connected.

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[4] C. H. Meyers, BS J. Research **9**, 807 (1932) RP 508.

Resistances were measured on a thermostated Wheatstone bridge of the type designed by Mueller.[5] The thermocouples on the capillary were read with a potentiometer; those on the temperature-controlling system were arranged for direct connection to a galvanometer.

III. THEORY

A real gas, confined in a volume which is strictly constant and at uniform temperature throughout, exerts a pressure which is a single-valued function of the temperature. This pressure may be used to define a scale of temperatures according to the equation

$$p=cT_g, \qquad (V \text{ const}), \tag{1}$$

where the subscript g indicates that the scale depends on the kind of gas and on its density, and does not necessarily agree with the thermodynamic scale. The constant c is fixed by the condition that T_g increase by 100° in passing from the ice point to the steam point.

To realize a definite gas scale of temperatures it is necessary to take into account the fact that no actual gas thermometer quite fulfills the conditions laid down above. The volume always changes somewhat with changing temperature and pressure, and there is always some gas in the capillary and other pressure-transmitting volume[6] that is not in general at the same temperature as the gas in the thermometer bulb. These facts make it necessary to work with the product pV in place of the single variable p of eq 1. Referring to unit mass of gas, consider the equation

$$pv=aT_g \tag{2}$$

For any given value of v this may be made identical with eq 1 by making $a/v=c$, so that there are exactly 100° between the ice and steam points. If a is kept fixed while v is allowed to vary, the T_g corresponding to a given thermal state is no longer uniquely defined by eq 2, but may range over a narrow band of values whose width is proportional to the deviation of the gas from Boyle's law. Evidently the ice-to-steam interval will in general be 100° only for one particular gas density. Let a be so chosen that the particular density for which this occurs is the same as the density[7] of the gas in the bulb of a constant-volume gas thermometer. Then, if the total volume of the gas thermometer is V and the mass of gas contained is m, we have

$$pV=maT_g \tag{3}$$

if the entire thermometer is at uniform temperature. If it is not at uniform temperature, imagine it subdivided into smaller volumes, each of which may be considered to be at uniform temperature. For the gas in each we may write

$$pV_i=m_iaT_{gi}, \tag{4}$$

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[5] E. F. Mueller, J. Research NBS. (Publication pending.)

[6] Other expressions used for this volume are "obnoxious volume", "noxious volume", "dead space", "nuisance volume", "unheated space", "schädlicher Raum", and "espace nuisible". The expression "pressure-transmitting volume" was adopted as being more descriptive of the actual function of this part of the apparatus.

[7] This density will change slightly as the thermometer bulb expands and as the temperature of the pressure-transmitting volume changes. Within the experimental error, however, a constant value of a may be used, since the density variations are small,

and summing over all the volumes

$$p\sum_i \frac{V_i}{T_{gi}} = a\sum_i m_i = A = \text{constant}.$$

Separating out and dropping subscripts on the important term which refers to the gas-thermometer bulb,

$$p\left\{\frac{V}{T_g}+\sum_i{}'\frac{V_i}{T_{gi}}\right\}=A, \tag{5}$$

the prime indicating that one of the terms has been taken outside the summation. Variations in the bulb volume may be taken into account by writing

$$\begin{aligned} V &= V_0(1+\alpha T+\beta T^2+ \;.\;.\;.\;.\; +\gamma p+\epsilon p^2+ \;.\;.\;.\;.) \\ &= V_0[1+f(T,p)], \end{aligned}$$

the constants being determined by preliminary investigations. Substituting this expression in eq 5 and multiplying by T_g/V_0, we obtain

$$p\left\{1+f(T,p)+\frac{T_g}{V_0}\sum_i{}'\frac{V_i}{T_{gi}}\right\}=\frac{A}{V_0}T_g$$

and putting $V_0/A=C$,

$$T_g=C\left\{1+f(T,p)+\frac{T_g}{V_0}\sum_i{}'\frac{V_i}{T_{gi}}\right\}p. \tag{6}$$

From this equation, T_g may readily be found by successive approximations since only the first term in the braces is large. In the calculations it is generally permissible to use T_g for T in finding the change in bulb volume with temperature. The change in bulb volume with pressure is in many cases negligible. The pressure-transmitting volumes, V_i, must be found by actual measurement, but their change with temperature and pressure may ordinarily be neglected. The temperatures T_{gi} which should be assigned to the transmitting volumes are really defined by eq 4. However, they are ordinarily measured with thermometers or thermocouples calibrated to give temperatures in approximate agreement with the thermodynamic scale. With data on the deviation of the gas from Boyle's law one may calculate how the value of T_{gi} corresponding to a given thermal state will vary as the gas density is changed. For most gases this variation is small, seldom more than a few hundredths of a degree throughout the range of densities likely to occur in a gas-thermometer system. Hence, since the T_{gi}'s occur only in small correction terms, it is generally permissible to replace them directly with the thermometer and thermocouple indications of T.

Experimental determination of the constant C requires in principle that p be measured at both the ice and steam points. In many instances it is better to determine C from measurements made at a single point, employing the results of earlier investigations to insure the preservation of the 100° ice-to-steam interval. With the apparatus used in the present work, for example, determination of C at the oxygen point rather than at the ice and steam points permitted the helium density to be increased by a factor of 373/90, with a proportional increase in sensitivity. It is worth-while to emphasize that when C is determined without measuring the ice-to-steam interval, the gas-scale temperature, T_g, rather than the thermodynamic temperature, T, of the calibration point must be inserted in eq 6.

To obtain centigrade gas-scale temperatures from temperatures on the corresponding absolute gas scale, the temperature of the ice point on the latter scale must be subtracted,

$$t_g = T_g - T_{g0}.$$

Since many investigators employ the pressure coefficient β and compute temperatures directly on a centigrade gas scale it should be pointed out that in eq 1

$$c = \beta p_0$$

IV. REDUCTION TO THE THERMODYNAMIC SCALE

The most common method of reducing gas-scale temperatures to the thermodynamic scale is based on the assumption that when a gas is used at lower and lower densities, the corresponding gas scale approaches the thermodynamic. Data for helium which permit this extrapolation to zero density have been obtained both at the Reichsanstalt and at Leiden for the temperature range in which we are interested, and tables of corrections [8], [9] based on these data have been published. These corrections are for a centigrade gas scale and are consequently zero at the ice and steam points. To permit a more direct comparison of the results of the two laboratories, the corrections which they would obtain for the absolute scale of the same gas were computed. The Kelvin and Celsius thermodynamic scales satisfy the relation $T = T_0 + t$, while two corresponding gas scales satisfy the relation $T_g = T_{g0} + t_g$. Hence

$$T - T_g = (T_0 - T_{g0}) + (t - t_g). \qquad (7)$$

The published tables referred to give values of $t - t_g$.

From the Reichsanstalt data we have computed $T - T_g$ directly, following the procedure of Henning [10] on page 174. In place of his equation for $t - t_v$ ($t - t_g$ in our notation) the corresponding equation

$$T - T_g = -\frac{T}{A_0}\left[(B_t - B_0) - \frac{T_0 + 100}{100}(B_{100} - B_0) \right] p_0$$

was used, where A_0, B_t, etc., are taken from equations of isotherms of the form

$$\frac{(pV)_t}{(pV)_s} = A_t + B_t p + C_t p^2 \; . \; . \; . \; . \; .$$

The B values used were computed from the equation used by Henning.[11] The value found for $T_0 - T_{g0}$ was $-0.021°$. As a check,

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[8] F. Henning, Z.ges. Kälte-Ind. **37,** 169 (1930).

[9] W. H. Keesom and W. Tuyn, Leiden Commun. Supp. No. 78, table on p. 49. (Reprinted from Travaux et Mémoires du Bureau International des Poids et Mesures **20** (1936).)

[10] Footnote 8.

[11] F. Henning, Z. ges. Kälte-Ind. **37**, 169 (1930); the entire set of constants is given by J. Otto, Hand. Exp. Physik **8**, part 2, 191 (1929).

$t-t_g$ was computed from eq 7, using this value, and the values found were identical with those of the Reichsanstalt table.

Keesom and Tuyn plotted the corrections computed from several sets of isotherm data, and based their table on a smooth curve drawn through these points. In the heading of their table it is stated that their corrections are based on a value of -0.361×10^{-6} for $\alpha_A-\alpha_{nH_2}$ ($=\gamma-\beta$ in our notation).

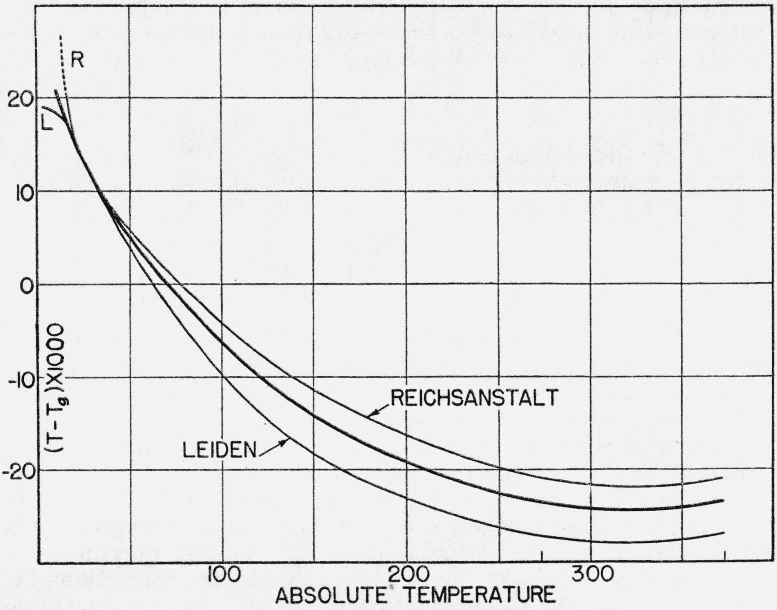

FIGURE 2.—*Corrections for reducing to the thermodynamic scale, computed from data of the Kamerlingh Onnes Laboratory at Leiden and the Physikalisch-Technische Reichsanstalt.*

The heavy line represents corrections adopted for use in this paper.

Since $T_0=1/\gamma$ and $T_{g0}=1/\beta$, we have

$$(T_0-T_{g0})=1/\gamma-1/\beta=\frac{\beta-\gamma}{\beta\gamma}\doteq T_0^2(\beta-\gamma).$$

Substituting their value for $\beta-\gamma$, we find $T_0-T_{g0}=-0.027°$. This quantity was used with eq 7 to compute $T-T_g$ from the Leiden table.

In table 1 the original values of the two laboratories are reproduced, together with the derived values of $T-T_g$. In figure 2 the corrections $T-T_g$ have been plotted against the absolute temperature. The heavy line on this graph is a weighted mean of the two sets, and represents the corrections adopted for use in the present work. The numerical values are given in table 2. Since the computed ice point pressure of our thermometer was 2.46 m Hg, the corrections actually used were 2.46 times those given in the table.

TABLE 1.—*Deviation of the constant-volume helium gas scale* (p_0=*1 m* Hg) *from the thermodynamic scale, according to the Kamerlingh Onnes Laboratory at Leiden and the Physikalisch-Technische Reichsanstalt*

t	$T=t+$ 273.16	$t-t_g$		$T-T_g$	
		L[a]	PTR[b]	L	PTR
100	37.16	0.000	0.000	−0.027	−0.021
50	323.16	−.001	(−.001)	−.028	−.022
0	273.16	.000	.000	−.027	−.021
−50	223.16	.002	.003	−.025	−.018
−100	173.16	.006	.007	−.021	−.014
−150	123.16	.013	.013	−.014	−.008
−180	93.16	.019	-------	−.008	---------
−183	90.16	-------	.019	-------	−.002
−200	73.16	.024	.022	−.003	.001
−220	53.16	.030	(.026)	.003	.005
−240	33.16	.037	(.031)	.010	.010
−250	23.16	.041	.035	.014	.014
−260	13.16	.045	(.045)	.018	.024
−270	3.16	.046	-------	.019	-------

[a] W. H. Keesom and W. Tuyn, Leiden Commun. Supp. No. 78, table on p. 49 (Reprinted from Travaux et Mémoires du Bureau International des Poids et Mesures **20** (1936).

[b] F. Henning, Z. ges. Kälte-Ind. **37**, 169 (1930). Values in parentheses were computed by the authors from Henning's formula.

TABLE 2.—*Deviations used in this paper for correcting from the helium gas scale* (T_g) *to the thermodynamic* (T)

[For p_0=1 m Hg.]

T	$T-T_g$	T	$T-T_g$	T	$T-T_g$	T	T_g
10	+0.021	60	+0.002	120	−0.010	220	−0.021
15	+.018	65	+.001	130	−.012	230	−.021
20	+.016	70	+.000	140	−.013	240	−.022
25	+.013	75	−.001	150	−.014	250	−.022
30	+.011	80	−.002	160	−.015	260	−.023
35	+0.009	85	−0.003	170	−0.016	273.16	−0.023
40	+.008	90	−.004	180	−.017	373.16	−.023
45	+.006	95	−.005	190	−.018	----------	----------
50	+.005	100	−.006	200	−.019	----------	----------
55	+.004	110	−.008	210	−.020	----------	----------

V. PROCEDURE AND CALCULATIONS

The thermometer was filled to approximately atmospheric pressure at liquid-air temperature. The gas was admitted through the manometer after evacuating the system for several days. During the filling the helium was purified by slow passage over charcoal cooled by liquid air and through a cotton-filled tube immersed in liquid hydrogen. Mercury was brought up into the manometer and the manometer tube evacuated. The cryostat was filled with liquid hydrogen and the bulb cooled to the temperature of the hydrogen bath. Measurements were then made at intervals of a few degrees, one operator being required to control the bulb temperature, a second to measure resistances, and a third to observe the pressure. Pressure readings were alternated with resistance-thermometer readings, and the temperature computed from the mean observed pressure. Two thermometers on the mercury column and the thermocouples on the capillary were also read at each temperature. Readings at the very lowest temperatures were obtained with helium in the space surrounding the bulb.

The pressure readings were corrected for capillarity and reduced to mm Hg at 0° C and standard gravity. Values of R and of $w(=R/R_0)$ for each thermometer were computed. Thermal expansion of the copper thermometer bulb was calculated from the data of Keesom, Van Agt, and Jansen.[12] The equation $V=V_0(0.991171+3.267\times10^{-6}T+1.064\times10^{-7}T^2)$ was found to fit these data satisfactorily below 90° K.[13] A rough calculation showed that pressure changes should have a negligible effect on the volume of the bulb.

The temperatures of the pressure-transmitting volumes were deduced from the thermocouple and thermometer readings. The transmitting volumes were determined by substituting for the gas-thermometer bulb a calibrated glass tube sealed to the capillary and arranged to be filled with mercury to any desired height. After admitting a small amount of gas to the system its volume was varied by changing the height of the mercury in the glass tube. The effect of volume change on the pressure was noted, and the transmitting volume computed from Boyle's law. This process was repeated after cutting off all except a small section of the capillary. Volumes found were 0.180 cm³ for the space where the capillary joined the manometer, and 0.000942 cm³/cm length for the capillary. The length of the capillary was 146.7 cm, making the total transmitting volume[14] 0.318 cm³, or 1.6 percent of the volume of the thermometer bulb, which was 19.69 cm³. In calculating the quantity

$$\sum_i{}' \frac{V_i}{T_{gi}},$$

a linear change in temperature between one thermocouple and the next was assumed. The section of the capillary between the bulb and the first thermocouple was wound with a heater extending about half its length, by means of which the flow of heat away from the bulb was prevented. A parabolic temperature distribution in the heated section and a linear distribution beyond it were assumed.

To determine the gas-thermometer constant, C, of eq 6 several observations in the neighborhood of the oxygen point were made at the end of each run. All of the thermometers used were intercompared before the final calculations were made, and all had had their oxygen-point resistances determined on the International Temperature Scale. By utilizing the results of the intercomparisons, the error in the oxygen-point resistance assigned to any particular thermometer was considerably reduced. From resistance measurements, the temperatures of all experimental points above 86° K were computed on the International Temperature Scale, on which the boiling point of oxygen is −182.97° C. These were converted to absolute thermodynamic temperatures by using the value of 273.16° K for the thermodynamic temperature of the ice point. Each value of T thus found was converted to the corresponding T_g on the gas

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[12] W. H. Keesom, F. P. G. A. J. van Agt, and Miss A. F. J. Jansen, Leiden Commun. 182a (1926).

[13] Southard and Milner (J. Am. Chem. Soc. **55**, 4384 (1933)) used a different equation based on these same data. Dr. Southard has informed us that an error was made in the derivation of their equation.

[14] Earlier estimates of the transmitting volume based on filling a section of the capillary with water and weighing, and computing the volume at the manometer from dimensions gave somewhat smaller values. The possibility that this might be the case was brought to our attention by J. A. Beattie of the Massachusetts Institute of Technology, who also suggested the method finally adopted.

scale by use of table 2 and substituted in eq 6 to determine C. Determined in this way the constant C is presumably the same as would have been obtained by making actual measurements at the ice and steam points. On one occasion during an interruption of measurements the thermometer bulb was kept at liquid-air temperature for more than a month. In this interval the gas in the thermometer was lost at the rate of about 11 parts in 10^6 per day. During a single run such a loss would be entirely negligible, but for each run the value of C was independently determined. Having found C, temperatures were computed from eq 6 and corrected from the gas scale to the thermodynamic by means of table 2. The corrected temperatures and the corresponding resistance values are given in table 3.

TABLE 3.—*Experimental data: p is corrected pressure ($=T_g/C$ in eq 6); T is temperature corrected from the gas scale to the thermodynamic, $w=R/R_0$*

Point Number	p	T	w_{L8}	w_{L11}	w_{M1}
	mm Hg	° *K*			
55	96.16	10.754	0.00 2890	0.00 2952	
18	97.38	10.833	2899	2963	0.55 3710
49	97.68	10.923	2911	2975	
50	100.73	11.262	2963	3026	
56	101.01	11.293	2968	3034	
51	104.91	11.726	0.00 3045	0.00 3110	
52	111.65	12.475	3183	3250	
66	125.48	14.013	3554	3624	
53	125.50	14.015	3561	3630	
67	128.47	14.344	3654	3726	
54	132.18	14.756	0.00 3786	0.00 3860	
68	133.44	14.897	3833	3907	
69	142.69	15.925	4215	4296	
70	153.39	17.115	4751	4827	
57	162.07	18.080	5257		
19	165.07	18.317	0.00 5392		
58	178.10	19.862	6413		
20	182.01	20.191	6656		
11	183.90	20.399	6820	0.00 6917	0.55 5783
71	189.77	21.159	7443	7545	
59	195.82	21.832	0.00 8048	0.00 8154	
21	207.46	23.004	9199	9311	
29	209.63	23.246	9452		
72	235.19	26.209	0.01 3173	.01 3306	
12	245.95	27.261	.01 4731	.01 4870	0.56 0052
22	255.39	28.305	0.01 6464		
30	259.35	28.742	.01 7196	0.01 7350	0.56 1343
13	300.49	33.293	.02 6275		
60	310.12	34.540	.02 9302	.02 9482	
31	315.83	34.990	.03 0330		
23	341.45	37.825	0.03 7719	0.03 7918	.57 1665
14	350.92	38.873	.04 0656	.04 0859	.57 3094
32	360.42	39.925	.04 3731		
73	384.41	42.804	.05 2674	.05 2894	
33	409.93	45.401	.06 1177	.06 1400	.58 2912
24	422.69	46.813	0.06 6058		
34	444.94	49.274	.07 4875		
25	492.10	54.494	.09 4634	0.09 4875	.59 8528
15	499.15	55.274	.09 7631		
35	501.94	55.582	.09 8819		
36	545.03	60.349	0.11 7946	0.11 8188	.60 9276
3	552.65	61.192	.12 1407		
26	575.85	63.759	.13 2076		
A	585.30	64.757	.13 6290		
61	589.95	65.666	.14 0019	.14 0268	
4	595.93	65.982	0.14 1363		
37	623.18	68.997	.15 4157		
B	625.85	69.242	.15 5179		
5	634.51	70.251	.15 9402		
16	640.70	70.936	.16 2422		
42	642.17	71.442	0.16 4606		
C	663.56	73.413	.17 2996		
27	668.81	74.047	.17 5691		
6	690.46	76.443	.18 5968		
D	703.23	77.799	.19 1822		

TABLE 3.—*Experimental data: p is corrected pressure* ($=T_g/C$ *in eq 6*); *T is temperature corrected from the gas scale to the thermodynamic,* $w=R/R_0$—Continued

Point Number	p	T	w_{L8}	w_{L11}	w_{M1}
	mm Hg	° K			
38	708. 31	78. 418	0. 19 4514	0. 19 4754	0. 64 4313
7	713. 11	78. 949	. 19 6776	----------	----------
65	711. 44	79. 182	. 19 7745	. 19 7988	----------
E	740. 89	81. 963	. 20 9845	----------	----------
8	751. 93	83. 245	. 21 5384	----------	----------
I	764. 94	84. 623	0. 22 1438	----------	----------
44	761. 59	84. 722	. 22 1820	----------	----------
46	766. 03	85. 216	. 22 3866	----------	----------
F	778. 92	86. 169	. 22 8058	----------	----------
1	785. 20	86. 927	. 23 1366	0. 23 1608	0. 66 1101
J	791. 41	87. 549	0. 23 4078	----------	----------
9	791. 14	87. 584	. 23 4294	----------	----------
17	802. 95	88. 891	. 23 9819	0. 24 0049	----------
62	804. 91	89. 581	. 24 2940	. 24 3173	----------
74	809. 30	90. 069	. 24 4956	. 24 5187	----------
40	814. 46	90. 165	0. 24 5425	0. 24 5658	0. 66 7512
10	815. 08	90. 233	. 24 5762	----------	----------
41	815. 33	90. 261	. 24 5943	. 24 6176	. 66 7748
47	812. 68	90. 403	. 24 6420	. 24 6651	----------
G	817. 59	90. 445	. 24 6544	----------	----------
63	813. 70	90. 559	0. 24 7128	0. 24 7358	----------
28	818. 48	90. 610	. 24 7330	. 24 7560	----------
48	816. 44	90. 821	. 24 8287	. 24 8518	----------
2	823. 01	91. 111	. 24 9465	. 24 9696	0. 66 9351
64	820. 82	91. 350	. 25 0600	. 25 0831	----------
45	821. 56	91. 390	0. 25 0793	0. 25 1025	----------
39	825. 77	91. 416	. 25 0772	. 25 1004	0. 66 9946

VI. DATA AND RESULTS

The constants of the seven resistance thermometers are given in table 4. All except two had previously received complete calibrations on the International Temperature Scale. The constants δ and β are those appearing in the modification of Callendar's equation proposed by Van Dusen [15]

$$t=\frac{1}{\alpha}(w-1)+\delta\left(\frac{t}{100}-1\right)\frac{t}{100}+\beta\left(\frac{t}{100}-1\right)\left(\frac{t}{100}\right)^3,$$

which is equivalent to the International Temperature Scale equation and somewhat easier to use.

TABLE 4.—*Constants of the seven calibrated resistance thermometers*

Thermometer	Material	R_0	δ	β	R/R_0 at various fixed points				
					n-H$_2$, triple (13.96° K)	n-H$_2$, nbp (20.39° K)	O$_2$, nbp (90.19° K)	Steam (373.16° K)	Sulfur (717.76° K)
		Ohms							
L8	Pt	29. 11355	1. 4951	0. 11294	0.00 3665	0.00 6993	0.24 6325	1.39 1177	2.64 9570
L5	Pt	23. 10284	1. 4974	. 11142	3669	6990	6114	1316	2.65 0018
L6	Pt	28. 83022	----------	----------	3543	6811	5540	----------	----------
L9	Pt	27. 54587	1. 4963	. 10840	3607	6901	5780	1607	1312
L10	Pt	24. 93025	1. 4945	. 11235	3628	6935	5936	1406	0568
L11	Pt	27. 52747	1. 4952	. 10895	3613	6909	5771	1604	1364
M1	90Pt: 10Rh	59. 47388	----------	----------	----------	----------	----------	----------	----------

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[15] M. S. Van Dusen, J. Am. Chem. Soc. 47, 326 (1925).

Of the seven resistance thermometers, three (*L6*, *L11*, *M1*) were compared directly with the gas thermometer, and the data given in table 3 obtained. After this the capillary was removed and thermometers *L3*, *L5*, *L9*, and *L10* placed with *L6* in the copper thermometer bulb, which now served as a comparison block. Resistance readings on all the thermometers were then made at 1- or 2-degree intervals throughout the range 10° to 90° K, without making use of the apparatus as a gas thermometer.

No satisfactory simple formula connecting the resistance of platinum and the temperature in this range has yet been proposed. The formula of Henning and Otto [16] based on the sum of two Debye functions can be used, but since it does not avoid the use of a tabulated function it was decided to construct directly a table which gave the resistance-temperature relation for one of the thermometers used (*L6*), and to use this table for the other thermometers by tabulating the deviations of each from this table. A previously published table [17] was taken as a starting point and values of $w(=R/R_0)$ corresponding to the observed temperatures computed from it. These were subtracted from the observed values of W_{L6} and the quantities $(W_{L6}-W_{table})$ plotted. A deviation curve was drawn and used to improve the original table. This process was repeated several times until a table was obtained from which the deviations were random. This table was next smoothed by Spencer's method.[18] The smoothed values are given in table 5, page 364. In figure 3 the deviations of the observed values from this smoothed table are plotted. The curved lines in this graph correspond to ±0.01° and allow the scattering to be estimated in degrees. They also show how very rapidly dw/dT falls off below 25° K. It is this rapid decrease which makes it more convenient to plot Δw, which approaches zero, than ΔT, which becomes large. However, the actual scattering is chiefly due to errors in the determination of T rather than w.

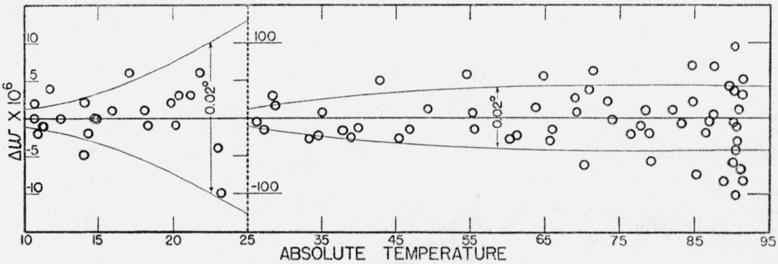

Figure 3.—*Scattering of the experimental points.*

Zero deviation represents agreement with table 5.

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[16] F. Henning and J. Otto, Phys. Z. **37**, 601 (1936) and earlier papers.

[17] J. C. Southard and R. T. Milner, J. Am. Chem. Soc. **55**, 4384 (1933).

[18] E. T. Whittaker and G. Robinson, The Calculus of Observations, 2d ed. p. 290 (Blackie and Son, Ltd., London and Glasgow, 1929).

TABLE 5.—*Smoothed temperature-resistance table for platinum, based on thermometer L6*

[$w=R/R_0$. Differences are for use in Bessel's interpolation formula. Example: $w_{55.800}=10^{-6}\left[96552+0.8\times 3931+\frac{0.8(0.8-1)}{4}\times 75\right]=0.099694$]

T	*w*			*T*	*w*			*T*	*w*		
10	0.002789			39	0.041046			67	0.145672		
		135	59			2921	186			4230	25
11	2924			40	.043967			68	.149902		
		166	73			3011	176			4242	22
12	3090			41	.046978			69	.154144		
		208	91			3097	169			3252	20
13	3298			42	.050075			70	.158396		
		257	105			3180	162			4262	18
14	3555			43	.053255			71	.162658		
		313	119			3259	154			4270	16
15	3868			44	.056514			72	.166928		
		376	132			3334	147			4278	16
16	4244			45	.059848			73	.171206		
		445	146			3406	141			4286	14
17	4689			46	.063254			74	.175492		
		522	160			3475	133			4292	14
18	5211			47	.066729			75	.179784		
		605	175			3539	125			4300	13
19	5816			48	.070268			76	.184084		
		697	187			3600	118			4305	11
20	6513			49	.073868			77	.188389		
		792	197			3657	112			4311	12
21	7305			50	.077525			78	.192700		
		894	208			3712	104			4317	10
22	8199			51	.081237			79	.197017		
		1000	219			3761	97			4321	10
23	9199			52	.084998			80	.201338		
		1113	227			3809	91			4327	9
24	0.010312			53	.088807			81	.205665		
		1227	231			3852	84			4330	--
25	.011539			54	.092659			82	.209995		
		1344	235			3893	79			4334	--
26	.012883			55	.096552			83	.214329		
		1462	239			3931	75			4337	--
27	.014345			56	.100483			84	.218666		
		1583	241			3968	70			4339	--
28	.015928			57	.104451			85	.223005		
		1703	240			4001	66			4342	--
29	.017631			58	.108452			86	.227347		
		1823	241			4034	63			4344	--
30	.019454			59	.112486			87	.231691		
		1944	240			4064	58			4344	--
31	.021398			60	.116550			88	.236035		
		2063	237			4092	55			4342	--
32	.023461			61	.120642			89	.240377		
		2181	234			4119	51			4339	--
33	.025642			62	.124761			90	.244716		
		2297	228			4143	46			4336	--
34	.027939			63	.128904			91	.249052		
		2409	222			4165	42			4333	--
35	.030348			64	.133069			92	.253385		
		2519	217			4185	36			4330	--
36	.032867			65	.137254			93	.257715		
		2626	209			4201	32			4327	--
37	.035493			66	.141455			94	.262042		
		2728	199			4217	29			4323	--
38	.038221							95	.266365		
		2825	193								

Spencer's method of smoothing does not yield values at the extreme ends of the table. At the upper end of the table the International Temperature Scale supplied the missing values. At the lower end use was made of the equation $R=A+BT^2+CT^5$ proposed by Landau and Pomerantschusk [19] and also by Baber.[20] These authors point out that the term in T^2 should be important in metals such as platinum, which have incomplete inner shells of electrons. This equation fits the experimental data for thermometer *L6* very well up to 15° K, but above this temperature the deviations rapidly become large. Values of the constants found for thermometer *L6* were

$$A=0.067238$$
$$B=1.04350\times10^{-4}$$
$$C=2.74577\times10^{-8}.$$

With this set of constants the T^5 term is negligible below about 5° K and reaches 90 percent of the T^2 term at 15° K. The range in which the equation was used (10° to 15° K) is too small to provide a thorough test, although it does represent a change of 50 percent in absolute temperature. However, it was considered sufficiently good to be used to extend the table down to the lowest temperature measured.

The results of the intercomparison of the various resistance thermometers are shown in figure 4, where the differences $\Delta w_i=w_i-w_{L6}$ have been plotted against the absolute temperature (the index i refers to any one of the calibrated platinum thermometers). From the original large-scale graphs, values of Δw_i were read off at every degree. These values, taken with table 5, are equivalent to a separate table for each platinum thermometer, all agreeing among themselves to within the accuracy of the resistance measurement. Since, except at the lowest temperatures, the precision of the resistance thermometry was of the order of ten times the precision of the gas thermometry, the additional step of intercomparison introduced little additional error. Tables of Δw_i have not been included, since they are useful only in conjunction with a particular group of thermometers.

The 90Pt:10Rh thermometer *M1* cannot be used with table 5. Figure 5 shows the temperature dependence of the resistance of *M1*, after subtracting a constant resistance of 32.5 ohms. The lower curve represents the resistance of the pure platinum thermometer *L6*. It can be seen that the addition of 10 percent of rhodium corresponds roughly to the addition of a constant resistance of 32.5 ohms to a thermometer such as *L6*. Matthiessen's rule, which may be stated in the form "resistance due to impurity is independent of temperature" is seen to hold even when the amount of rhodium "impurity" is as large as 10 percent.

In resistance thermometry the most common problem is that of computing a temperature from a measured resistance. With table 5 this requires inverse interpolation, which is more difficult than direct interpolation. In addition, linear interpolation is insufficiently accurate in this table below 80° K, according to the usual rule that second differences should not exceed 4. Accordingly, table 6, page 366, was made up, the values being found from table 5 by quadratic interpolation. Entries in this table are so closely spaced that linear interpolation introduces no error greater than 0.0005° above 19° K and no error greater than the equivalent of ½ unit in the last figure of w below this temperature.

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[19] L. Landau and I. Pomerantschusk, Phys. Z. Sowjetunion **10**, 649 (1936).
[20] W. G. Baber, Proc. Roy. Soc. (London) [A] **158**, 383 (1937).

TABLE 6.—*Resistance-temperature table arranged for linear interpolation. Based on platinum thermometer L6*

[Linear interpolation yields temperatures correct to the nearest 0.001° above 19° K, and correct to the equivalent of the nearest unit in the last figure of w below this temperature. $w=R/R_0$]

W	T	$\frac{\Delta T}{\Delta w}$
0. 002800	10. 090	7780
2850	10. 479	7160
2900	10. 837	6700
2950	11. 172	6260
3000	11. 485	5860
3050	11. 778	5520
3100	12. 054	5160
3150	12. 312	4880
3200	12. 556	4640
3250	12. 788	4420
3300	13. 009	4220
3350	13. 220	4040
3400	13. 422	3880
3450	13. 616	3720
3500	13. 802	3600
3550	13. 982	3480
3600	14. 156	3360
3650	14. 324	3260
3700	14. 487	3160
3750	14. 645	3060
3800	14. 798	2980
3850	14. 947	2900
3900	15. 092	2840
3950	15. 234	2740
4000	15. 371	2700
4050	15. 506	2620
4100	15. 637	2580
4150	15. 766	2500
4200	15. 891	
0. 004200	15. 891	2440
4300	16. 135	2350
4400	16. 370	2250

W	T	$\frac{\Delta T}{\Delta w}$
0. 004500	16. 595	2170
4600	16. 812	2110
4700	17. 023	2030
4800	17. 226	1970
4900	17. 423	1910
5000	17. 614	1860
5100	17. 800	1800
5200	17. 980	1770
5300	18. 157	1710
5400	18. 328	1680
5500	18. 496	1630
5600	18. 659	1600
5700	18. 819	1560
5800	18. 975	1530
5900	19. 128	1490
6000	19. 277	1470
6100	19. 424	1430
6200	19. 567	1410
6300	19. 708	1390
6400	19. 847	1350
6500	19. 982	1340
6600	20. 116	1320
6700	20. 248	1290
6800	20. 377	1270
6900	20. 504	1250
7000	20. 629	1240
7100	20. 753	1210
7200	20. 874	1200
7300	20. 994	1180
7400	21. 112	1160
7500	21. 228	1150
7600	21. 343	1130
7700	21. 456	1120

W	T	$\frac{\Delta T}{\Delta w}$
0. 007800	21. 568	1100
7900	21. 678	1090
8000	21. 787	1080
8100	21. 895	1060
8200	22. 001	1050
8300	22. 106	1040
8400	22. 210	1030
8500	22. 313	1010
8600	22. 414	1010
8700	22. 515	990
8800	22. 614	980
8900	22. 712	970
9000	22. 809	
0. 009000	22. 809	960
9200	23. 001	935
9400	23. 188	920
9600	23. 372	905
9800	23. 553	885
0. 010000	23. 730	870
. 010200	23. 904	855
. 010400	24. 075	840
. 010600	24. 243	830
. 010800	24. 409	815
. 011000	24. 572	805
. 011200	24. 733	790
. 011400	24. 891	780
. 011600	25. 047	770
. 011800	25. 201	760
. 012000	25. 353	750
. 012200	25. 503	740
. 012400	25 651	730
. 012600	25. 797	720

TABLE 6.—*Resistance-temperature table arranged for linear interpolation. Based on platinum thermometer L6*—Continued

W	T	$\frac{\Delta T}{\Delta w}$
0.012800	25.941	710
.013000	26.083	705
.013200	26.224	695
.013400	26.363	690
.013600	26.501	680
.013800	26.637	670
.014000	26.771	

W	T	$\frac{\Delta T}{\Delta w}$
0.014000	26.771	663
.014300	26.970	653
.014600	27.166	643
.014900	27.359	637
.015200	27.550	623
.015500	27.737	617
.015800	27.922	607
.016100	28.104	600
.016400	28.284	593
.016700	28.462	587
.017000	28.638	577
.017300	28.811	570
.017600	28.982	567
.017900	29.152	557
.018200	29.319	553
.018500	29.485	547
.018800	29.649	540
.019100	29.811	533
.019400	29.971	530
.019700	30.130	523
.020000	30.287	

W	T	$\frac{\Delta T}{\Delta w}$
0.020000	30.287	518
.020500	30.546	508
.021000	30.800	502
.021500	31.051	494
0.022000	31.298	486
.022500	31.541	480
.023000	31.781	474
.023500	32.018	468
.024000	32.252	462
.024500	32.483	456
.025000	32.711	452
.025500	32.937	444
.026000	33.159	440
.026500	33.379	436
.027000	33.597	432
.027500	33.813	426
.028000	34.026	422
.028500	34.237	418
.029000	34.446	414
.029500	34.653	410
.030000	34.858	408
.030500	35.062	402
.031000	35.263	400
.031500	35.463	396
.032000	35.661	392
.032500	35.857	390
.033000	36.052	386
.033500	36.245	382
.034000	36.436	380
.034500	36.626	378
.035000	36.815	376
.035500	37.003	372
.036000	37.189	368
.036500	37.373	368
.037000	37.557	364
.037500	37.739	362
.038000	37.920	360
.038500	38.100	358
0.039000	38.279	356
.039500	38.457	354
.040000	38.634	

W	T	$\frac{\Delta T}{\Delta w}$
0.040000	38.634	350
.041000	38.984	346
.042000	39.330	342
.043000	39.672	339
.044000	40.011	335
.045000	40.346	332
.046000	40.678	329
.047000	41.007	326
.048000	41.333	323
.049000	41.656	320
.050000	41.976	318
.051000	42.294	314
.052000	42.608	313
.053000	42.921	310
.054000	43.231	307
.055000	43.538	306
.056000	43.844	303
.057000	44.147	301
.058000	44.448	300
.059000	44.748	297
.060000	45.045	296
.061000	45.341	293
.062000	45.634	292
.063000	45.926	290
.064000	46.216	289
.065000	46.505	287
.066000	46.792	285
.067000	47.077	284
.068000	47.361	283
.069000	47.644	281

TABLE 6.—*Resistance-temperature table arranged for linear interpolation. Based on platinum thermometer L6*—Continued

W	T	$\frac{\Delta T}{\Delta w}$	W	T	$\frac{\Delta T}{\Delta w}$	W	T	$\frac{\Delta T}{\Delta w}$
0.070000	47.925	280	0.104000	56.887	250.5	0.150000	68.023	235.8
.071000	48.205	278	.106000	57.388	249.5	.155000	69.202	235.0
.072000	48.483	277	.108000	57.887	249.0	.160000	70.377	234.4
.073000	48.760	276	.110000	58.385	247.5	.165000	71.549	233.8
.074000	49.036	275	.112000	58.880	246.5	.170000	72.718	233.4
.075000	49.311	274	.114000	59.373	246.0	.175000	73.885	233.0
.076000	49.585	272	.116000	59.865	245.0	.180000	75.050	232.6
.077000	49.857	272	.118000	60.355	244.5	.185000	76.213	232.2
.078000	50.129	270	.120000	60.844	243.0	.190000	77.374	231.8
.079000	50.399	269	.122000	61.330	243.0	.195000	78.533	231.4
.080000	50.668		.124000	61.816	242.0	.200000	79.690	231.2
			.126000	62.300	241.0	.205000	80.846	231.0
0.080000	50.668	268.0	.128000	62.782	241.0	.210000	82.001	230.8
.082000	51.204	266.0	.130000	63.264	240.0	.215000	83.155	230.4
.084000	51.736	264.0	.132000	63.744	239.5	.220000	84.307	230.4
.086000	52.264	262.5	.134000	64.223	239.0	.225000	85.459	230.4
.088000	52.789	261.0	.136000	64.701	238.5	.230000	86.611	230.2
.090000	53.311	259.5	.138000	65.178	238.0	.235000	87.762	230.2
.092000	53.830	258.0	.140000	65.654	237.5	.240000	88.913	230.4
.094000	54.346	256.5	.142000	66.129	237.5	.245000	90.065	230.8
.096000	54.859	255.0	.144000	66.604	237.0	.250000	91.219	230.8
.098000	55.369	254.5	.146000	67.078	236.5	.255000	92.373	231.0
.100000	55.878	252.5	.148000	67.551	236.0	.260000	93.528	231.2
.102000	56.383	252.0	.150000	68.023		.265000	94.684	

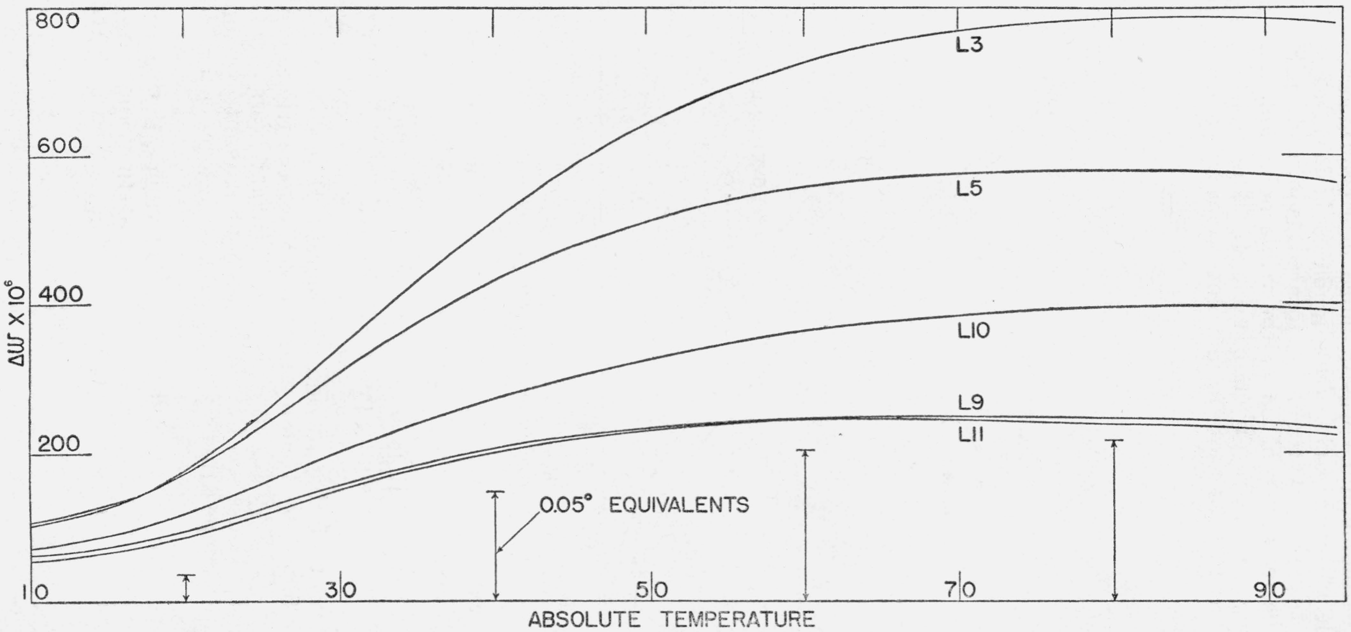

Figure 4.—*Comparison of the six calibrated platinum resistance thermometers.*

$\Delta w_i = w_i - w_{L6}$ and $w = R/R_0$.

After the calibration and intercomparison had been completed, resistance thermometer *L3* was installed in a calorimetric apparatus in which the vapor pressure of hydrogen could be measured, and in which the triple point could be located calorimetrically. Values found for the resistance of *L3* at the triple point and boiling point of normal hydrogen are given in table 4. The resistances of the other thermometers at these fixed points were found by adding the appropriate values of Δw_t, as determined by the intercomparisons. The temperatures corresponding to these resistances are

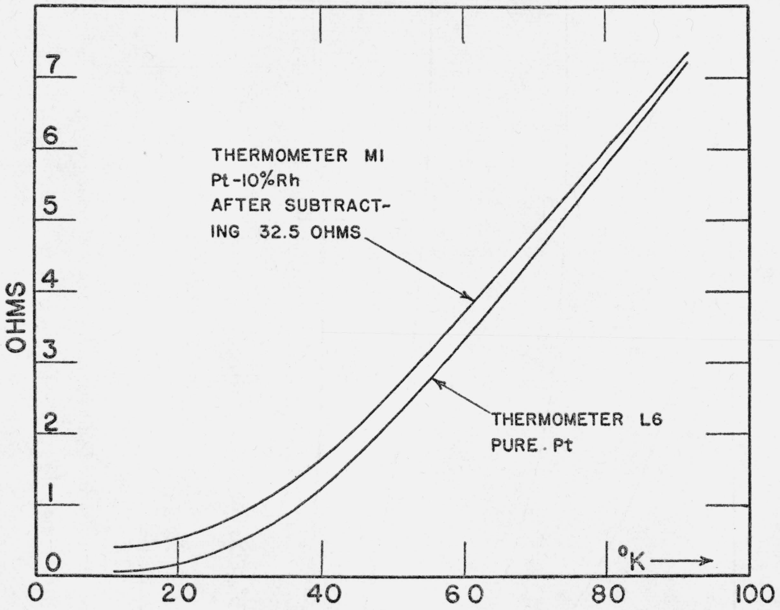

FIGURE 5.—*Temperature dependence of the resistance of pure platinum compared with that of an alloy containing 10 percent of rhodium.*

triple point—13.96° K
boiling point—20.39° K.

The most recent of the previously reported values for these fixed points are 13.96° K by Henning and Otto[21] for the triple point, and −252.754° C (20.37$_6$° K) by Keesom, Bijl, and Van der Horst,[22] and 20.38° K by Heuse and Otto[23] for the boiling point. A summary of work on low-temperature fixed points has been given by Henning and Otto.[24]

Three years prior to obtaining the above values, thermometer *L6* had been used in an apparatus for determining the vapor pressure of hydrogen, and its resistance at the boiling point of normal hydrogen

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[21] F. Henning and J. Otto, Phys. Z. **37**, 601 (1936); **37**, 633 (1936).

[22] W. H. Keesom, A. Bijl, and H. van der Horst, Leiden Commun. 217a (1931). The pressure coefficient used by these authors was 0.0036609, whence $T_{g0}=273.157$ or using the Leiden value of T_g-T_{g0} in table 1, $T_0=273.13$. With this value of T_0 the boiling point is 20.37$_6$° K rather than 20.336, the value given in Henning and Otto's summary.

[23] W. Heuse and J. Otto, Ann. Physik **9**, 486 (1931).

[24] F. Henning and J. Otto, Phys. Z. **37**, 633 (1936).

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had been determined. The temperature computed from this resistance agreed within slightly less than 0.01° with that given above. This was considered satisfactory, in view of the fact that the two determinations were made with entirely different apparatus and with different resistance thermometers.

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VII. ESTIMATION OF ERRORS

Pressure.—Uncertainty in the pressure measurements is responsible for a large part of the scattering of the data. The height of the mercury column could be read on the calibrated glass scale to about 0.1 mm, which is equivalent to about 0.01°. The uncertainty in the temperature of the column was reduced by surrounding it with light aluminum shields, leaving only the two menisci exposed. Even so, it was found necessary on some occasions to circulate the air in the room to keep the top and bottom of the column at the same temperature. Meniscus corrections were made, although the menisci were so regular that they could for the most part have been omitted. Thermal transpiration might be expected to set up a pressure gradient in the capillary. R. B. Scott of this Bureau investigated the effect for helium. His results (unpublished) are in substantial agreement with the theory,[25] and indicate that the pressure at the two ends of the gas-thermometer capillary could not have differed by more than 0.003 mm even under the most unfavorable conditions.

Pressure-transmitting volume.—Errors in the corrections for the pressure-transmitting volume may be due either to errors in the volume ratios V_i/V_0 or to errors in the determination of the temperatures T_i. The temperatures obtained from thermocouple readings were computed from the equation, emf$=a+bT^2+cT^3+dT^4$, proposed by Ahlberg and Lundberg,[26] the constants being determined by calibration at the boiling and triple points of hydrogen and in liquid air at normal and reduced pressure. Of the V_i the most uncertain was the volume where the capillary joined the manometer. This volume was subject to fluctuation, not only because of the difficulty of setting the mercury meniscus exactly on the tip of the pointer, but also because of variations in meniscus height. In the 11-mm manometer tube used, a change in meniscus height from 1.4 to 1.6 mm would increase the transmitting volume by 14 mm ^{3} according to data in the International Critical Tables. In our work variations in meniscus height were actually more serious in their effect on the transmitting volume than in their effect on the pressure.

Thermal expansion of bulb.—The change in volume of the copper bulb from 11° K to 90° K calculated from eq 3 is about 0.11 percent. An error of even 4 percent in the mean expansion coefficient over this range would give rise to a maximum error in temperature of only slightly over 0.001°.

Thermometer constant C.—By obtaining the thermometer constant in the particular manner described in the section on procedure and calculations, continuity with the International Temperature Scale is secured. The value 90.19° K accepted for the oxygen point in determining C may be in error either because of uncertainty in the value −182.97° C assigned to the oxygen point on the International Tem-

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[25] M. Knudsen, Ann. Physik **83**, 797 (1927).

[26] J. E. Ahlberg and W. O. Lundberg, J. Am. Chem. Soc. **57**, 2722 (1935).

perature Scale or because of uncertainty in the value 273.16° K used for the ice point. Since the error introduced in this way is proportional to the temperature, it will in any case be very small at the lower end of the scale.

Since C is inversely proportional to the mass of gas in the thermometer, any loss of gas from the system or change in the effective mass by adsorption will cause error unless corrected for. The loss by diffusion during a single run was entirely negligible. An estimate of the thickness of the layer of gas which would have to be adsorbed to produce appreciable error led us to conclude that this effect was probably negligible.

Reduction to the thermodynamic scale.—The corrections used to reduce to the thermodynamic scale were taken from the results of other investigators. The error introduced is probably small at the higher temperatures but may be rather important below the boiling point of hydrogen.

VIII. COMPARISON WITH PREVIOUS WORK

Comparison of the temperature scales set up by different laboratories is chiefly a matter of comparing the values assigned to fixed points. However, some additional information may be obtained by combining the data of the different laboratories to obtain graphs similar to figure 4. This is of course only possible when the resistance thermometers are of the same material. Figure 6 is such a graph, utilizing recent results from Leiden [27] and the Reichsanstalt.[28] [29] Taking table 5 as a standard, $\Delta\ w_i=w_i-w_{table}$ has been plotted against the absolute temperature. It will be seen that the deviations are much larger than those found by intercomparison of our own thermometers. This is probably due chiefly to greater differences in the samples of platinum. However, the deviation curves are not as smooth as those of our own thermometers, and this lack of smoothness is probably associated with

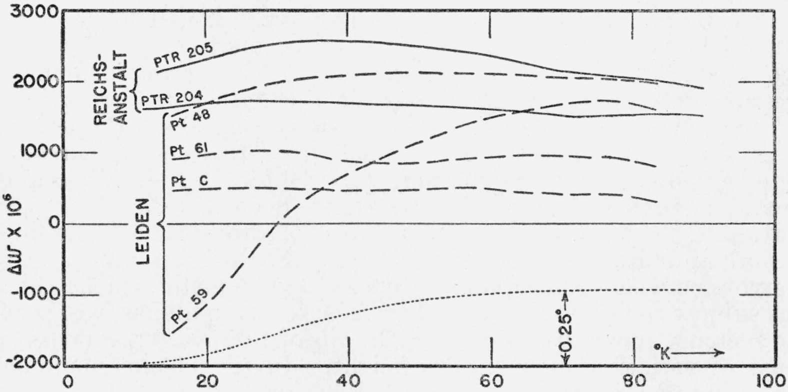

FIGURE 6.—*Comparison of thermometers calibrated by other laboratories with thermometer L6.*

$\Delta w_i=w_i-w_{table\ 5}$ and $w=R/R_0$.

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[27] W. H. Keesom and A. Bijl, Physica **3**, 418 (1936). (Leiden Commun. 242b).
[28] F. Henning and J. Otto, Phys. Z. **37**, 601 (1936);
[29] F. Henning and J. Otto, Actes 6 ème congr. int. froid (Buenos Aires) **2b**, 257 (pub. 1935).

differences in gas thermometry. It should be emphasized that the choice of a standard table was arbitrary and that if the table of another laboratory were chosen the deviations of our thermometers would show a corresponding lack of smoothness. The 11 thermometers for which Δw_t is plotted in figures 4 and 6 represent platinum from at least three different sources. Such a sampling is too limited to allow any general conclusions to be drawn. However, it is of interest to point out certain characteristics of these 11 thermometers. Since resistance thermometers are supposedly constructed only of platinum of high purity, it is to be expected that their curves of w versus T will be very similar in form. All such curves have a common point at 0° C, and it is evident that if their slopes at this temperature are very nearly equal, values of Δw_t will be small for a considerable distance to either side of 0° C. At low temperatures, however, values of Δw_t may become large, even though the curves may still be nearly parallel. Several of the deviation curves of figures 4 and 6 illustrate this type of behavior. Between 60° and 90° K, for example, the curves of figure 4 are all parallel to the T-axis to within the equivalent of about 0.01°. In figure 6 all the curves except one are approximately parallel to the T-axis. The exception is the Leiden thermometer Pt 59, for which the platinum was prepared [30] by decomposition of $PtCOCl_2$.

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WASHINGTON, December 20, 1938.

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[30] W. H. Keesom and A. Bijl, Physica **3**, 418 (1936) (Leiden Commun. 242b).

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