JOURNAL OF RESEARCH of the National Bureau of Standards—C. Engineering and Instrumentation
Vol. 67C, No. 4, October–December 1963

Studies on the Tungsten-Rhenium Thermocouple to 2000 °C

Douglas B. Thomas

(June 19, 1963)

Various lots of tungsten and rhenium wire were obtained from leading American manufacturers. Eleven tungsten-rhenium thermocouples were made up from these wire samples and tested at approximately 100 deg C intervals up to 2000 °C. A fourth order equation and a third order equation were selected to represent the emf of the tungsten-rhenium thermocouple in the range from 0 to 1000 °C and from 1000 to 2000 °C respectively. Using these two equations, reference tables were established and are presented in 5 deg C intervals from 0 to 2000 °C and in 10 deg F intervals from 32 to 3640 °F. Inverse tables giving temperature in °C and °F at 20 microvolt intervals are also included. Information is furnished on variations due to wire size and among different wire lots and different wire manufacturers. Spectrochemical analyses of the tungsten and rhenium elements that were used to represent the tables of temperature versus emf are listed. A graphic comparison is made between the NBS emf values and values from other investigators.

1. Introduction

In 1931 Goedicke [1] [1] investigated the possibility of using tungsten and rhenium as high temperature thermocouple elements. However, this early work was quite limited in scope and did not, for example, result in a precise relationship between temperature and emf for these thermocouple elements.

Between 1952 and 1956 the Battelle Memorial Institute conducted the first detailed investigation of various properties of rhenium [2, 3] and in 1957–58 their studies included the thermoelectric properties of rhenium, tungsten, and other high temperature thermocouple elements [4, 5]. In this latter work a power series was used to express the temperature-emf relationship of the tungsten-rhenium thermocouple between room temperature and 2200 °C. The workers at Battelle concluded that rhenium had several distinct advantages as a high temperature thermocouple element e.g., it was found to have excellent strength from room temperature to 2000 °C. was highly resistant to the water cycle and retained it ductility after thermal cycling above its recrystallization [2] temperature. Unfortunately, tungsten is affected by the water cycle and in addition becomes quite brittle upon reaching its recrystallization temperature. The recrystallization temperature of tungsten is not well defined. Smithells [6] reports that recrystallization can occur at any temperature from 1000 to 2000 °C depending upon the metallurgical properties of the tungsten, and Hall and Sikora [7] report partial recrystallization of commercially pure sintered tungsten at 1715 °C and complete recrystallization at 2090 °C. The brittleness of tungsten due to recrystallization can be somewhat inhibited by a process called "doping." This process involves the addition to the tungsten of small quantities of materials such as compounds of potassium, silicon, or aluminum. These "doping" compounds reduce grain growth and essentially raise the recrystallization temperature of the tungsten. In the case of pure tungsten, however, very little can be done to inhibit the brittleness resulting from recrystallization.

The water cycle effect which occurs at elevated temperatures alters the chemical and metallurgical properties of tungsten. In the case of tungsten thermocouple elements, this effect will eventually erode the metal to a point where the thermocouple fails. Langmuir [8] first demonstrated the water cycle effect with a tungsten filament lamp. A small amount of water vapor was released in a vacuum lamp and the filament was heated to incandescence. The water vapor coming into contact with the filament was decomposed, the oxygen combining with the tungsten and the hydrogen being evolved. The oxide distilled to the glass envelope where it was reduced to metallic tungsten by the atomic hydrogen given off by the filament. Reduction of the oxide resulted in the reconstitution of water vapor and the "water cycle" was able to repeat itself indefinitely. Thus, in applications where tungsten is used in a vacuum as a thermocouple element, care must be taken to keep the area surrounding the thermocouple free from water vapor at elevated temperatures.

Additional investigations concerning the tungsten-rhenium thermocouple were undertaken by Lachman and Kuether [9–11] and included useful information such as chemical analysis of the thermoelements, emf reproducibility of the thermocouple after prolonged temperature cycling and a table of temperature versus emf from 50 to 4000 °F.

The above workers concluded that the tungsten-rhenium thermocouple has the following advantages:

1. High thermoelectric potential.
2. High thermoelectric power.
3. Very high melting point of both elements of the thermocouple.

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[1] Figures in brackets indicate the literature references at the end of this paper.

[2] Recrystallization is defined as the formation of a new, strain-free grain structure from that existing in the cold worked metal, usually accomplished by heating.

4. Chemical stability in vacuum, inert or reducing atmospheres up to 2200 °C.
5. Calibration accuracy of 0.1 mv up to 2200 °C.
6. Low cost of the tungsten element.
7. Good reproducibility after thermal cycling at 2200 °C.

Some of the disadvantages of the thermocouple are
1. Brittleness of the tungsten element after recrystallization.
2. Susceptibility of the tungsten element to destructive erosion due to the water cycle effect.
3. High cost of the rhenium element.
4. It cannot be used in an oxidizing atmosphere.

In view of the favorable advantages of the tungsten-rhenium thermocouple as a high temperature measuring instrument, a program was initiated at the National Bureau of Standards to carry out studies on this thermocouple. Although various studies were conducted on the tungsten-rhenium thermocouple by the authors mentioned, it was felt that an effort should be made at NBS to further evaluate this thermocouple using thermoelements that represent a variety of wire lots from various manufacturers. The results of this study could then be compared to the earlier reported results in order to ascertain the thermoelectric reproducibility of these materials.

2. Thermocouple Materials

2.1. Tungsten Elements

The tungsten elements that were used in this study were obtained from three major American tungsten wire manufacturers and represent a total of eight lots of wire. Although this tungsten wire was manufactured primarily for electronic applications, the chemical purity of the wire as determined by spectrochemical analysis (see table 1) was sufficiently high as to render it acceptable for this particular work. All of the tungsten elements consisted of two types of tungsten. One type of tungsten referred to by the manufacturers as "black as drawn" tungsten comprises five of the eight lots i.e., lots L–2, M–2, M–3, M–4, and N–1. The letters BL have been placed in parenthesis after each of these lot designations to denote the "black as drawn" wire type. The second type of tungsten is referred to as "chemically cleaned" tungsten and comprises three lots i.e., lots L–1, M–1, and N–2. The letters CL are used to denote this type of wire. According to the manufacturers, the "black as drawn" wire receives no additional treatment or processing after it has been drawn to the desired size. On the other hand, the chemically cleaned wire after having been drawn to the desired size is immersed into a hot caustic solution (usually KOH or NaOH), is rinsed and then dried. All of the tungsten elements contained "doping" compounds as reported by the manufacturers.

The prefixes L, M, and N designate the three manufacturers from whom the tungsten lots were obtained. One element was selected from each of the eight tungsten lots and labeled the same as the lot number followed by the letter "A." Five of these eight tungsten elements were used only once to represent the positive (+) leg of a particular tungsten-rhenium thermocouple and the other three elements viz, L–1(CL)A, M–4(BL)A and N–2(CL)A were used twice as a positive leg. For example, the element L–1(CL)A was paired with the two rhenium elements 219A and 228A, the combinations being designated thermocouple No. 1 and thermocouple No. 9 (see table 3). This arrangement resulted in a total of 11 thermocouples. This method of thermocouple selection was chosen rather than a method whereby all possible thermocouple combinations (each tungsten element versus each rhenium element) could be represented. All thermocouple combinations could be equally represented by averaging the data in figures 1 and 2, and then combining the averages via measurements of a

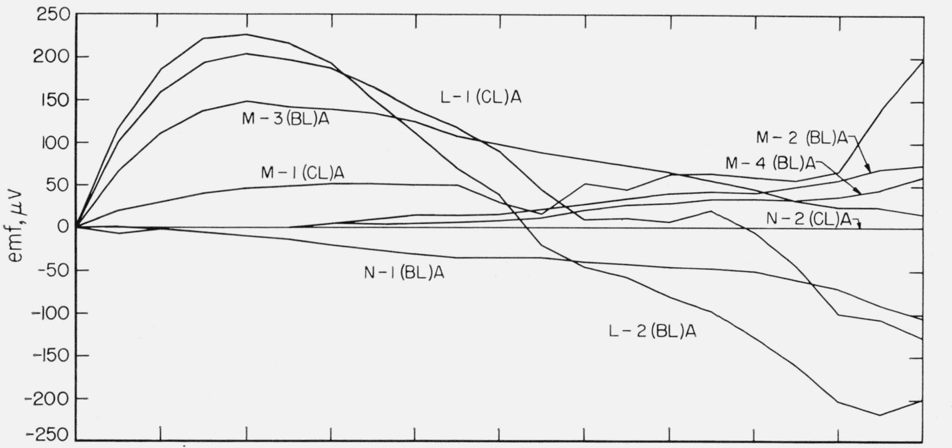

FIGURE 1. *Emf differences between eight tungsten elements.*
[With N–2(CL)A as the reference element]

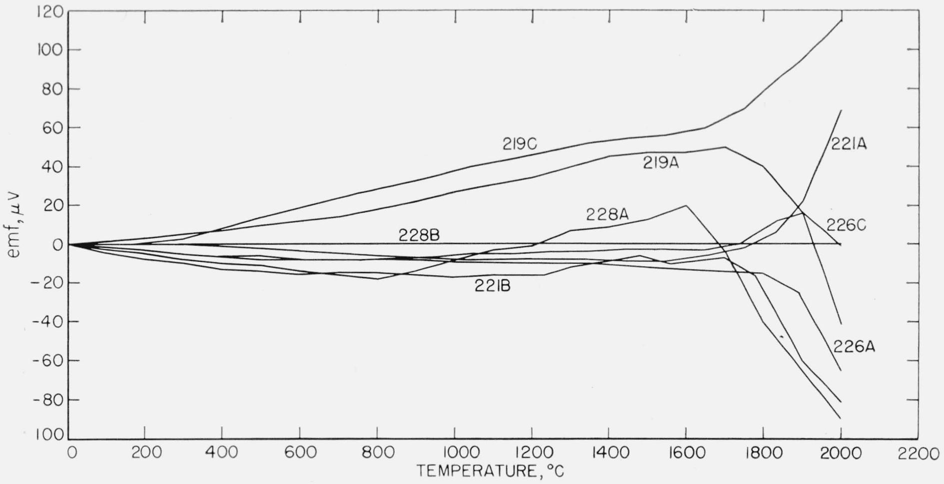

FIGURE 2. *Emf differences between eight rhenium elements.*
[With 228B as the reference element]

single tungsten-rhenium combination (see also in Experimental Procedure). However, in order to use this method effectively, the following must be realized.

(a) The tungsten and rhenium elements that are used as reference elements must be reproducible. Since all of the elements could not be tested in one furnace run, it was necessary to heat the reference elements several times. The tungsten and rhenium elements that were tested gave indications of not being reproducible from one furnace run to the next (Experimental Procedure).

(b) A considerable amount of weight would be placed on the single tungsten-rhenium combination measurement. If large errors were encountered in this measurement (poor optical pyrometer readings, for example), these errors would be grossly reflected in the final temperature—emf relationship.

Each of the eight tungsten elements was spectrochemically analyzed. A listing of the magnitude of the impurities is given in table 1.

2.2. Rhenium Elements

All of the rhenium elements associated with this study were obtained from the Chase Brass and Copper Company which is the sole American producer of rhenium wire in commercial quantities. Eight rhenium elements were paired with various tungsten elements as listed in table 3. These rhenium elements were taken from four lots of wire, numerically designated 219, 221, 226, and 228, with each element labeled A, B, or C of a particular lot [3]. All eight elements were 0.020 in. in diameter. As in the case of the tungsten elements, five of the eight rhenium elements were used only once to represent the negative leg of a particular tungsten-rhenium thermocouple and the three elements, 219A, 226C, and 228B, were used twice.

TABLE 1. *Spectrochemical analysis of tungsten elements*

Chemical element	Tungsten element							
	L–1 (CL)A	L–2 (BL)A	M–1 (CL)A	M–2 (BL)A	M–3 (BL)A	M–4 (BL)A	N–1 (BL)A	N–2 (CL)A
Ag	—	—	—?	—	E	—?	—?	D
Al	—	—	—	—	—	—	—	—
B	—	—	—	—	—	—	—	—
Ba	—	—	—	—	—	—	—	—
Be	—	—	—	—	—	—	—	—
Bi	—	—	—	—	—	—	—	—
Ca	D	D	—	—	D	—	—?	—?
Cd	—	—	—	—	—	—	—	—
Co	—	—	—	—	—	—	—	—
Cr	D	D	D	—	C	D	—	—
Cu	D	D	E	—?	—?	E	E	E
Fe	D	D	D	D	D	D	D	C
Hf	—	—	—	—	—	—	—	—
Ir	—	—	—	—	—	—	—	—
Mg	D	D	D	D	D	D	D	C
Mn	—	—	—	—	—?	—	—	—
Mo	—?	—?	—?	—?	C	—	—?	—
Na	—	—	—	—	—	—	—	—
Ni	C	C	—	—	C	—	—	—
Os	—	—	—	—	—	—	—	—
Pt	—	—	—	—	—	—	—	—
Si	B	C	B	C	B	B	B	C
Sn	—	—	—	—	—	—	—	—
Sr	—	—	—	—	—	—	—	—
Ta	—?	—	—	—	—?	—	—	—
Th	—	—	—	—	—	—	—	—
Ti	—	—	—	—	—	—	—	—
Zn	—	—	—	—	—	—	—	—
Zr	—	—	—	—	—	—	—	—

A=1.0%–0.1%.
B=0.1%–0.01%.
C=0.01%–0.001%.
D=0.001%–0.0001%.
E=Less than 0.0001%.
—=Not detected.

The eight rhenium elements were spectrochemically analyzed by the same laboratory [4] that analyzed the tungsten elements and the results of the analysis are listed in table 2.

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[3] Elements A, B, and C of a particular lot were remote from each other as far as the position of each element on a spool of wire is concerned.

[4] Spectrochemistry Section of the National Bureau of Standards.

TABLE 2. *Spectrochemical analysis of rhenium elements*

Chemical element	Rhenium element							
	219A	219C	221A	221B	226A	226C	228A	228B
Ag	—	—	—	—	—	—	—	—
Al	D	D	D?	D?	D?	D?	D?	D?
B	—	—	—?	—?	—?	—?	—?	—?
Ba	—	—	—	—	—	—	—	—
Be	—	—	—	—	—	—	—	—
Bi	—	—	—	—	—	—	—	—
Ca	D	C	D	D	D	D	D	D
Cd	—	—	—	—	—	—	—	—
Co	—?	—?	—	—	—	—	—	—
Cr	—	—	—?	—?	—?	—?	—?	—?
Cu	C	C	A	B	A	C	C	D
Fe	C	C	A	C	B	C	B	C
Hf	—	—	—	—	—	—	—	—
Ir	—	—	—	—	—	—	—	—
K	B	B	—?	—?	—?	—?	—?	—?
Mg	D	C	C	D	B	A	C	C
Mn	—?	—?	—?	—?	—?	—?	—?	—
Mo	B	B	C	B	C	B	C	C
Ni	C	B	—	—	—	—	—	—
Os	—	—	—	—	—	—	—	—
Pb	—?	D	—	—	—	—	—	—
Pt	C	C	D	—	—	—	—	—
Si	C	B	D	D	C	C	C	C
Sn	—	—	—	—	—	—	—	—
Ta	—	—	—	—	—	—	—	—
Th	—	—	—	—	—	—	—	—
Ti	—	—	—	—	—	—	—	—
V	—	—	—	—	—	—	—	—
Zn	—	—	—	—	—	—	—	—
Zr	—	—	—	—	—	—	—	—

A=1.0%–0.1%.
B=0.1%–0.01%.
C=0.01%–0.001%.
D=0.001%–0.0001%.
E=Less than 0.0001%.
—=Not detected.

3. Apparatus

All of the thermocouple and thermoelement tests between 0 and 2000 °C were performed in one furnace. This furnace consists of a tantalum tube that serves as a heating element. The tantalum tube furnace is fully described elsewhere. [12] The thermocouples and thermoelements were vertically suspended inside the tantalum tube with the measuring junctions located in a molybdenum blackbody which was also suspended in the central region of the tantalum tube. All tests were conducted in a purified helium atmosphere, the pressure of which varied from 360 mm Hg at 20 °C to about 660 mm Hg at 2000 °C. The helium was purified by passing it through a titanium-zirconium purifying apparatus [12] before being released into the furnace chamber.

In the range from 100 to 1000 °C the instrument used for temperature determinations was a Pt 1 percent Rh versus Pt 30 percent Rh thermocouple. A modified commercial optical pyrometer was used in the 1000 to 2000 °C range. The "1 percent-30 percent" thermocouple was calibrated by direct comparison to a standard platinum versus platinum 10 percent rhodium thermocouple. The latter thermocouple received a fixed point calibration as described in the literature [13]. An estimate of the maximum uncertainty in the comparison calibration is ±0.5 °C. The optical pyrometer was calibrated and used on a basis of temperature versus optical pyrometer lamp current. The calibration was performed by sighting the pyrometer on a tungsten ribbon filament lamp, the temperature of which was determined by the Fairchild optical pyrometer [5] at NBS. An estimate of the maximum uncertainties in the optical pyrometer calibration is ±3.0° at 1000 °C and ±6.0° at 2000 °C. The lamp current was determined by measuring the voltage drop across a 1-ohm standard resistor in series with the lamp. The thermocouple emf measurements were made with a L & N K–3 type potentiometer having a limit of error of about 0.7 μv at 1000 μv and 10 μv at 50,000 μv.

4. Experimental Procedure

In the tests conducted in the 0 the 1000 °C range, the Pt 1 percent Rh versus Pt 30 percent Rh thermocouple and the tungsten and rhenium elements were placed in high purity aluminum oxide insulating tubes with the measuring junctions exposed at one end. The measuring junction of the 1 percent-30 percent thermocouple was mechanically and thermally bound to the measuring junction of the tungsten and rhenium elements by wrapping with platinum wire. Generally, a total of six thermoelements (two tungsten, two rhenium, and the two platinum-rhodium elements) were placed in the furnace at one time. The emfs of thermocouples No. 1 through No. 11 (table 3) were measured at approximately 100 deg intervals from 100 to 1000 °C with the reference junctions maintained at 0 °C. In addition to these measured values, an assumed emf of 0.000 mv at 0 °C for each thermocouple gave a total of 121 data points for the 0 to 1000 °C range. At each of the calibration points, the temperature in the hot zone of the furnace as determined by the 1 percent-30 percent thermocouple was allowed to stabilize before the emfs of the tungsten-rhenium thermocouples were measured.

TABLE 3. *Thermocouple elements*

(All elements were 0.020 in. in diameter.)

Thermocouple number	Rhenium elements	Tungsten elements	
	Element number	Element number	Manufacturer
1	219A	L–1(CL)A	L
2	219A	M–4(BL)A	M
3	219C	N–1(BL)A	N
4	221A	M–3(BL)A	M
5	221B	N–2(CL)A	N
6	226A	M–2(BL)A	M
7	226C	L–2(BL)A	L
8	226C	M–4(BL)A	M
9	228A	L–1(CL)A	L
10	228B	M–1(CL)A	M
11	228B	N–2(CL)A	N

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[5] The NBS Fairchild optical pyrometer, also referred to in the literature [14] as "The NBS Optical Pyrometer" is a high precision instrument designed by C. O. Fairchild of NBS and is used at NBS for testing other optical pyrometers and pyrometer lamps submitted for calibration.

The eleven tungsten-rhenium thermocouples were also tested at approximately 100 deg intervals between 1000 and 2000 °C with the reference junctions at 0 °C. At each of the 100 deg intervals the emf of the thermocouple was read three times and an optical pyrometer observation was made three times but in an alternating sequence.[6] This resulted in a total of approximately 360 temperature-emf determinations. The data that were recorded for each thermocouple at each of the 100 deg intervals were averaged. This resulted in 101 averaged temperature-emf data points in the range from 1000 to 2000 °C. In most instances, and particularly at temperatures above 1700 °C, it was necessary to anneal the thermocouples at a slighty higher temperature than the temperature at which the data were taken. For example, in order to render the thermocouples stable at 1800 °C, it was necessary to raise the temperature of the furnace to about 1825 °C for a 5 to 10-min period and then lower the temperature to the initial 1800 °C. During the time that the thermocouple emf and optical pyrometer readings were recorded, the temperature in the hot zone of the furnace was not fluctuating by more than 0.05 percent per minute and in most cases the fluctuations were considerably less than this amount.

Since the tantalum tube furnace design allows the thermocouple to be freely suspended vertically, it was possible to avoid the use of ceramic supports, thereby eliminating two possible effects: (a) chemical contamination, and (b) electrical errors due to conduction in the ceramic material.

A d-c electric arc operating in a helium atmosphere was used to fuse the measuring junction of the tungsten and rhenium elements.

All of the emf measurements related to the tungsten and rhenium elements listed in table 3 were conducted in four separate test series. These four test series, in chronological order were as follows: (1) The emf's of the eleven thermocouples were measured between 1000 and 2000 °C, (2) the emf's of the eleven thermocouples were measured between 0 and 1000 °C, (3) the emf differences between the tungsten elements and between the rhenium elements were measured between 0 and 1000 °C, and (4) the emf differences between the tungsten elements and between the rhenium elements were measured between 1000 and 2000 °C. All readings were made with increasing temperature. After the first test series was completed, it was necessary to remove from 6 to 8 in. of wire from the measuring junction end of the tungsten elements since this portion of the wire had become brittle upon heating to 2000 °C. This removal of the embrittled portion of each tungsten element was necessary in order to reweld the elements for the succeeding parts of the test series.

Since short portions of the tungsten elements were removed after the first test series, it is apparent that the emf's that were measured in the second, third, and fourth test series would in some cases be inconsistent with those measured in the first series. If the emf's of the eleven thermocouples tested in the first and second series are compared with the calculated[7] emf's of the same thermocouples as derived from the differences measured between elements in the third and fourth series, it can be seen that the respective values are not consistent in all cases. These inconsistencies can be attributed to (a) the lack of emf reproducibility of the tungsten elements before and after the brittle portions of the elements were removed, (b) the lack of emf reproducibility of the rhenium elements, and (c) experimental errors encountered in each of the test series.

The long-term stability of the tungsten-rhenium thermocouples was not determined in this study. However, four test thermocouples were made up from the tungsten and rhenium wire lots pertinent to this study and were thermally cycled between 1100 and 2000 °C. The elements of these four thermocouples were none of the elements listed in table 3. The thermocouples were initially heated to 1100 °C (approx.) and their emf's were measured at that temperature. Then the thermocouples were heated to 2000 °C (approx.), the emf's again being measured, and then the temperature was lowered to 1100 °C. This heating cycle was repeated twice. The third and final measurement at 1100 °C showed that the emf's of the four thermocouples had increased (as compared to the initial measurement at 1100 °C) between 60 and 122 μv. This is equivalent to 3.5 and 7.2 °C, respectively. The total heating time during this cycling test was approximately 5 hr.

None of the tungsten and rhenium elements listed in table 3 were heat treated prior to testing except in the test series involving emf measurements between 1000 and 2000 °C. In this case, of course, the elements were heated to 1000 °C before emf measurements were begun.

5. Computations

In order to represent the raw data that were obtained in this study in a useful and concise form, several electronic computer programs were utilized. This data handling was performed with an IBM 7090 computer.

One of the first computation steps was to derive one or more polynomial equations that would represent the thermocouple data over the entire temperature range. For investigative purposes, the computer was programmed to derive by the least squares method (a) a single polynomial equation to represent the 0 to 2000 °C range and (b) one polynomial equation to represent the 0 to 1000 °C range and another polynomial equation to represent the 1000 to 2000 °C range. The function fitting was applied

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[6] In a few cases four thermocouple emf readings and four optical pyrometer observations were made in alternating sequence.

[7] The emf was measured between the elements N–2 (CL) A and 228B as thermocouple No. 11 and also between each of these elements and the other 7 tungsten and 7 rhenium elements. From this relationship the other 10 thermocouple emf's can be determined.

to all of the thermocouple data in each of the temperature ranges, i.e., 121 data points in the low temperature range and 101 data points in the high temperature range. The results of this investigation showed that a sixth order equation would be needed to adequately represent the thermocouple data over the 0 to 2000 °C range. The same conclusion was reached by Sims, Gaines, et al. [5] over the temperature range of investigation. In the (b) part of the investigation it was determined that a fourth order equation and a third order equation would adequately represent the 0 to 1000 °C and the 1000 to 2000 °C ranges respectively. In practical applications, considerable time and effort is saved by using two equations. Hence, this method was selected to represent the temperature-emf relationship of the tungsten-rhenium thermocouple.

In examining these two equations it was found that the derivative dE/dt was not the same for both equations at 1000 °C and that the emfs at 1000 °C differed by about 19 μv. A computer operation was used to adjust the coefficients of the fourth order equation (for the 0 to 1000 °C range) such that the emf and slope of the two equations at 1000 °C were equal.

The equations for the average emf E in millivolts of the tungsten-rhenium thermocouples at a temperature t(°C) are

for the range 0 to 1000 °C

$$E=0.62893850\times10^{-2}t+0.20717363\times10^{-4}t^2 -0.15067280\times10^{-7}t^3+0.37778323\times10^{-11}t^4$$

for the range 1000 to 2000 °C

$$E=-3.3363162+0.18710331\times10^{-1}t +0.21067552\times10^{-5}t^2-0.17634201\times10^{-8}t^3.$$

The emf deviations of each of the eleven tungsten rhenium thermocouples from the above equations are shown graphically in figure 5 for the range 0 to 1000 °C and in figure 6 for the range 1000 to 2000 °C. The standard deviation of the form $S=\sqrt{\frac{\Sigma d^2}{n-N}}$ where d is the emf deviation of each data point from the respective polynomial equation, n is the number of data points [8] and N is the number of coefficients in the polynomial equation was determined for the two temperature ranges. For the 0 to 1000 °C range the standard deviation was 74.1 μv and for the 1000 to 2000 °C range it was 70.1 μv. An estimation of the maximum uncertainties in the temperature measurements made between 0 and 1000 °C is ±1.0 °C and between 1000 and 2000 °C is ±0.35 percent.

6. Results

Tables for the tungsten-rhenium thermocouple are presented giving emf at 5 °C and 10 °F intervals (tables 5 and 7). Inverse tables giving temperature in °C and °F at 20 μv intervals are also included (tables 4 and 6).

The emf differences were measured between each of the eight tungsten elements. N–2(CL)A was arbitrarily chosen as a reference element and the emfs developed between it and the other seven tungsten elements were measured between 0 and 2000 °C (fig. 1).[9]

Two of the eight tungsten lots were selected for studying the emf differences between elements of various diameters. The two lots selected were N–2(CL) and M–3(BL). From each lot three elements were obtained and designated with the suffixes B, C, and D. These were 0.020, 0.024, and 0.028 in. in diameter (nominal) respectively. N–2(CL)A[10] was again chosen as a reference element

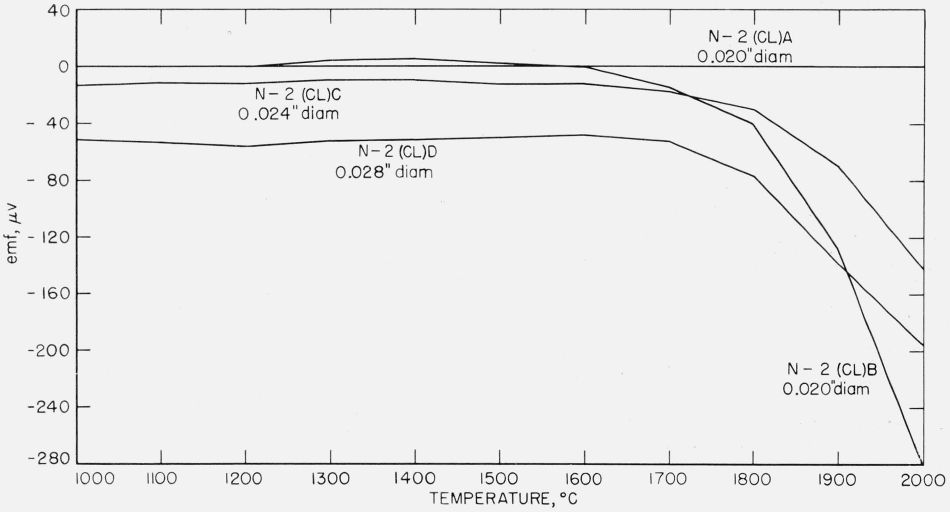

FIGURE 3. *Emf differences between tungsten elements of various diameters from Lot N–2(CL)*
[With N–2(CL)A as the reference element]

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[8] In the low temperature range, n was 121 data points and in the high temperature range n was the 101 averaged data points.

[9] The reference element, N–2(CL)A was connected to the negative post of the potentiometer.

[10] N–2(CL)A and N–2(CL)B were adjacent elements cut from one spool of wire. The same is true for the M–3(BL)A and M–3(BL)B elements.

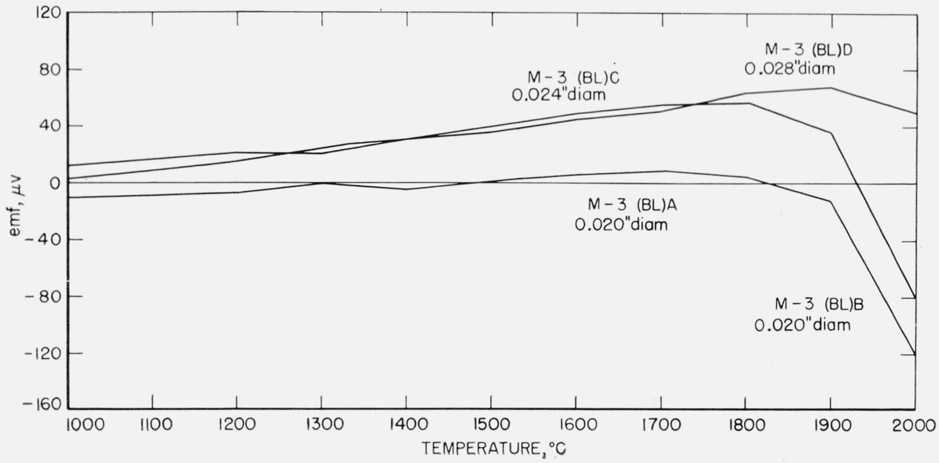

FIGURE 4. *Emf differences between tungsten elements of various diameters from Lot M–3 (BL).*
[With M–3(BL)A as the reference element]

and the emf's developed between it and elements N–2(CL)B, C, and D in the temperature range from 1000 to 2000 °C are shown graphically in figure 3. These measurements give an indication of the emf differences that can occur between two adjacent elements and also the differences that can occur between elements from the same lot but of varying diameters.

Similar measurements were conducted with the elements M–3(BL)A, B, C, and D, using M–3(BL)A as a reference element. Emf differences related to these elements are shown in figure 4. All of the measurements related to the tungsten elements of varying diameters were made after the four series of tests previously mentioned.

The emf differences between the eight rhenium elements were measured in the range 0 to 2000 °C by using 228B as a reference element.[11] These differences are shown in figure 2.

Since rhenium elements of diameters other than 0.020 in. were not available from the manufacturer for the four lots 219, 221, 226, and 228, no tests were conducted to denote emf differences between rhenium elements of various diameters.

The thermoelectric power of the tungsten-rhenium thermocouples included in this study average about 17.6, 17.6, 13.1, and 6.0 μv per deg C at 500, 1000, 1500, and 2000 °C, respectively. A maximum thermoelectric power of 18.33 μv per deg C occurs at 715 °C.

7. Discussion

In general it can be concluded that the total emf spread of the eleven tungsten-rhenium thermocouples included in this study is not exceedingly large if one considers that the thermocouple elements represent four wire manufacturers and twelve lots of wire. The greatest emf spread of the eleven thermocouples in the range 0 to 1000 °C was 246 μv at 370 °C (fig. 5). This corresponds to approximately 15.2 °C. Likewise, in the range 1000 to 2000 °C the greatest emf spread was 263 μv at 2000 °C corresponding to approximately 44.0 °C (fig. 6). The large emf spread of some of the thermocouples at 370 °C was rather surprising. It is interesting to note that all of the thermocouples (except No. 10) deviate a considerable amount from the table values in the 0 to 700 °C range. In the range 1000 to 2000 °C the deviations of all of the thermocouples from the table values are quite random.

Figures 1 and 2 definitely show that the large emf deviations of some of the thermocouples from the table values in the 0 to 700 °C range are, for the most part, due to the tungsten elements. The maximum emf spread of the eight tungsten elements at 400 °C is 237 μv and the maximum spread of the eight rhenium elements at that same temperature is 22 μv. The greatest emf spread between any two tungsten elements and any two rhenium elements occurred at 2000 °C in both cases. These maximum emf spreads at 2000 °C are 400 μv for the tungsten elements and 205 μv for the rhenium elements. It should be pointed out that the maximum emf spread of all of the tungsten elements should not be directly compared to that of all of the rhenium elements since the former represents three different manufacturers and the latter represents only one manufacturer. If the maximum emf spread of the elements produced by each of the four manufacturers are intercompared, it can be seen that these maximums are not significantly different i.e., the maximum spreads are all between 105 and 205 μv.

The tests that were conducted to determine the emf differences between tungsten elements of various diameters were limited in scope but gave a general

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[11] The reference element 228B was connected to the negative post of the potentiometer.

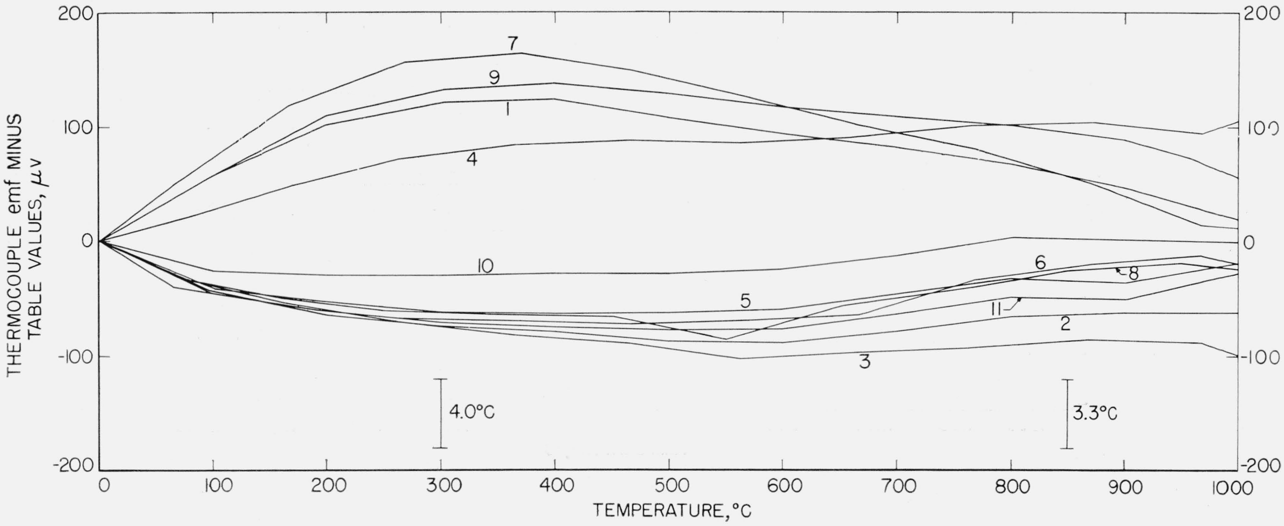

Figure 5. *Deviations of thermocouples No. 1 through No. 11 from the table values in the range 0 to 1000 °C.*

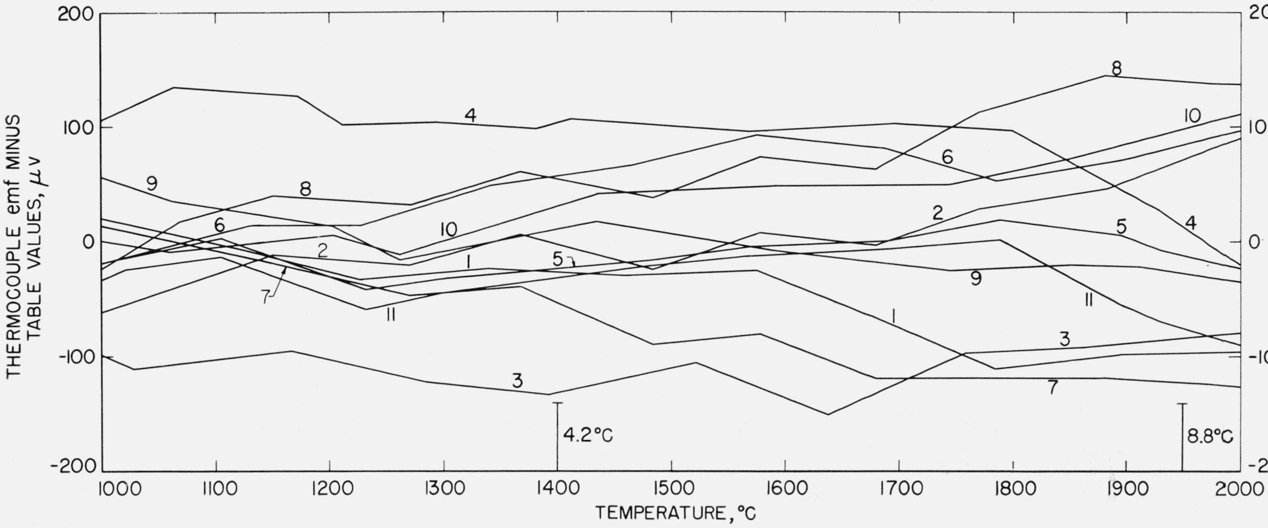

Figure 6. *Deviations of thermocouples No. 1 through No. 11 from the table values in the range 1000 to 2000 °C.*

indication of the magnitude of the differences that can occur. These tests show that the emf differences between tungsten elements of various diameters from one particular lot can be as large as the emf differences between elements from different lots and different manufacturers. At temperatures above 1800 °C the two elements N–2(CL) A and N–2(CL)B, which were adjacent samples on a spool of wire, developed a fairly large emf and at 2000 °C the emf was larger than that developed between the reference element and elements "C" and "D" (fig. 3). This same thing occurred between the two adjacent elements M–3(BL)A and M–3(BL)B at temperatures near 2000 °C (fig. 4). At temperatures between 1000 and 1800 °C the emf developed between elements of various diameters remained relatively small.

In general, the results of the spectrochemical analysis of the thermocouple elements show that the tungsten elements were of a higher purity than the rhenium elements. Of the eight tungsten elements that were analyzed, the element M–3(BL)A showed the greatest amount of impurities and M–2(BL)A showed the least impurities. If an average value is taken for the percentage range associated with each impurity listed (table 1), the total percent of impurities for M–3(BL)A would be 0.0665 percent. Likewise, the total impurities for M–2(BL)A would be 0.0060 percent. For comparison purposes, the impurities in reference grade thermocouple platinum reportedly [14, 15] are of the order of 0.001 percent. Thus, the purity of M–2(BL)A is approaching that of reference grade platinum and M–3(BL)A contains over 60 times the total impurities in reference platinum.

Of the eight rhenium elements that were analyzed, 221A showed the largest percentage of impurities with 1.012 percent and element 228B showed the least impurities with 0.0215 percent (table 2). Thus, element 221A contains more than a thousand times the impurities of reference grade platinum.

In view of the above analysis, it can be concluded that although termocouple elements of the same type are relatively pure, they may be appreciably different thermoelectrically. The opposite behavior, thermoelectric similarity in spite of differences of composition is shown by the two rhenium elements 221A and 228B. The emf developed between these two elements from 0 to 1900 °C was less than 20 μv (fig. 2) and yet element 221A contained nearly 50 times more impurities than element 228B. These results strongly indicate that rhenium possesses a thermoelectric uniqueness which manifests itself by the relatively small emfs produced between rhenium elements that contain significantly different quantities of impurities.

The emf differences that were recorded between the reference tungsten element N–2(CL)A and the other seven tungsten elements (fig. 1) show no unusual emf characteristics of the "chemically cleaned" wire as opposed to the "black as drawn" type of wire.

Figure 7 is a graphic presentation of the emf differences between the values for the tungsten-rhenium thermocouple as given in this paper and the values reported by Sims, Gaines, et al., [5] and Lachman [11]. The values from the three sources agree reasonably well between 1000 and 2000 °C but in the range 0 to 1000 °C the differences between the NBS values and the values from Sims, Gaines, et al., [5] are quite large. The largest emf difference over the entire range occurs at 340 °C with a 415 μv difference between the NBS values and the values from Sims, Gaines, et al., [5]. This corresponds to approximately 26.4 °C. The greater part of the differences that occur between the values from the three investigators is probably due to chemical and/or metallurgical differences between the thermocouple elements rather than errors arising from temperature measurement techniques.

The results of the various tests that were conducted in this study indicate that the thermoelectric quality of commercially available tungsten and rhenium wire could be improved. Causes of the large emf differences that may exist between tungsten elements from different lots and from different manufacturers might be identified by studying the individual effects of chemical and metallurgical variables on the thermal emf. Identification of the important variables could then lead to their control during the manufacturing process. Although some of the rhenium elements contained relatively large percentages of impurities, it was apparent that these impurities did not cause as large emf differences as in the tungsten elements. If the impurities in future lots of rhenium wire can be considerably reduced, perhaps the emf spread between elements would correspondingly be reduced.

It should be emphasized that the various tests indicate that the emf produced by a particular tungsten-rhenium thermocouple at a specific temperature is highly dependent on the lot of wire from which the thermocouple was fabricated and the degree of heat treatment (annealing) the thermocouple has received. In view of these factors, caution should be exercised in using the table values cited herein as the correct values for a specific tungsten-rhenium thermocouple.

It is anticipated that reference tables for the tungsten 3 percent rhenium versus tungsten 25 percent rhenium thermocouple and/or the tungsten 5 percent rhenium versus tungsten 25 percent rhenium thermocouple will be prepared at NBS in the near future.

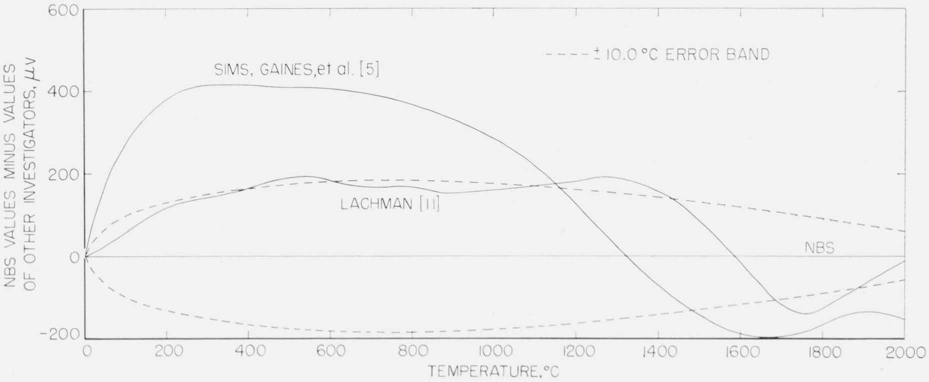

Figure 7. *Emf differences between NBS W-Re thermocouple tables and tables by other investigators.*

TABLE 4. *Tungsten versus rhenium thermocouples*

Electromotive force in absolute millivolts. Temperature in degrees C (Int. 1948). Reference junctions at 0 °C.

Millivolts	0.000	0.020	0.040	0.060	0.080	0.100	0.120	0.140	0.160	0.180	0.200	*Millivolts*
0.000	0.0	3.1	6.2	9.3	12.2	15.2	18.0	20.8	23.6	26.4	29.1	0.000
0.200	29.1	31.7	34.4	37.0	39.5	42.1	44.6	47.0	49.5	51.9	54.3	0.200
0.400	54.3	56.6	59.0	61.3	63.6	65.9	68.1	70.4	72.6	74.8	77.0	0.400
0.600	77.0	79.1	81.3	83.4	85.5	87.6	89.7	91.7	93.8	95.8	97.8	0.600
0.800	97.8	99.9	101.9	103.8	105.8	107.8	109.7	111.6	113.6	115.5	117.4	0.800
1.000	117.4	119.3	121.1	123.0	124.9	126.7	128.6	130.4	132.2	134.0	135.8	1.000
1.200	135.8	137.6	139.4	141.2	143.0	144.7	146.5	148.2	149.9	151.7	153.4	1.200
1.400	153.4	155.1	156.8	158.5	160.2	161.9	163.6	165.3	166.9	168.6	170.2	1.400
1.600	170.2	171.9	173.5	175.2	176.8	178.4	180.0	181.7	183.3	184.9	186.5	1.600
1.800	186.5	188.1	189.6	191.2	192.8	194.4	195.9	197.5	199.1	200.6	202.2	1.800
2.000	202.2	203.7	205.2	206.8	208.3	209.8	211.4	212.9	214.4	215.9	217.4	2.000
2.200	217.4	218.9	220.4	221.9	223.4	224.9	226.3	227.8	229.3	230.8	232.2	2.200
2.400	232.2	233.7	235.1	236.6	238.0	239.5	240.9	242.4	243.8	245.3	246.7	2.400
2.600	246.7	248.1	249.5	251.0	252.4	253.8	255.2	256.6	258.0	259.4	260.8	2.600
2.800	260.8	262.2	263.6	265.0	266.4	267.8	269.2	270.6	271.9	273.3	274.7	2.800
3.000	274.7	276.1	277.4	278.8	280.2	281.5	282.9	284.2	285.6	286.9	288.3	3.000
3.200	288.3	289.6	291.0	292.3	293.7	295.0	296.3	297.7	299.0	300.3	301.6	3.200
3.400	301.6	303.0	304.3	305.6	306.9	308.2	309.6	310.9	312.2	313.5	314.8	3.400
3.600	314.8	316.1	317.4	318.7	320.0	321.3	322.6	323.9	325.2	326.5	327.8	3.600
3.800	327.8	329.0	330.3	331.6	332.9	334.2	335.4	336.7	338.0	339.3	340.5	3.800
4.000	340.5	341.8	343.1	344.3	345.6	346.9	348.1	349.4	350.6	351.9	353.1	4.000
4.200	353.1	354.4	355.7	356.9	358.2	359.4	360.6	361.9	363.1	364.4	365.6	4.200
4.400	365.6	366.9	368.1	369.3	370.6	371.8	373.0	374.3	375.5	376.7	377.9	4.400
4.600	377.9	379.2	380.4	381.6	382.8	384.1	385.3	386.5	387.7	388.9	390.1	4.600
4.800	390.1	391.4	392.6	393.8	395.0	396.2	397.4	398.6	399.8	401.0	402.2	4.800
5.000	402.2	403.4	404.6	405.8	407.0	408.2	409.4	410.6	411.8	413.0	414.2	5.000
5.200	414.2	415.4	416.6	417.8	419.0	420.2	421.3	422.5	423.7	424.9	426.1	5.200
5.400	426.1	427.3	428.4	429.6	430.8	432.0	433.2	434.3	435.5	436.7	437.9	5.400
5.600	437.9	439.0	440.2	441.4	442.6	443.7	444.9	446.1	447.2	448.4	449.6	5.600
5.800	449.6	450.7	451.9	453.1	454.2	455.4	456.5	457.7	458.9	460.0	461.2	5.800
6.000	461.2	462.3	463.5	464.7	465.8	467.0	468.1	469.3	470.4	471.6	472.7	6.000
6.200	472.7	473.9	475.0	476.2	477.3	478.5	479.6	480.8	481.9	483.1	484.2	6.200
6.400	484.2	485.4	486.5	487.6	488.8	489.9	491.1	492.2	493.4	494.5	495.6	6.400
6.600	495.6	496.8	497.9	499.0	500.2	501.3	502.5	503.6	504.7	505.9	507.0	6.600
6.800	507.0	508.1	509.3	510.4	511.5	512.7	513.8	514.9	516.0	517.2	518.3	6.800
7.000	518.3	519.4	520.6	521.7	522.8	523.9	525.1	526.2	527.3	528.4	529.6	7.000
7.200	529.6	530.7	531.8	532.9	534.1	535.2	536.3	537.4	538.5	539.7	540.8	7.200
7.400	540.8	541.9	543.0	544.1	545.3	546.4	547.5	548.6	549.7	550.8	551.9	7.400
7.600	551.9	553.1	554.2	555.3	556.4	557.5	558.6	559.7	560.9	562.0	563.1	7.600
7.800	563.1	564.2	565.3	566.4	567.5	568.6	569.8	570.9	572.0	573.1	574.2	7.800
8.000	574.2	575.3	576.4	577.5	578.6	579.7	580.8	581.9	583.1	584.2	585.3	8.000
8.200	585.3	586.4	587.5	588.6	589.7	590.8	591.9	593.0	594.1	595.2	596.3	8.200
8.400	596.3	597.4	598.5	599.6	600.7	601.8	602.9	604.0	605.1	606.2	607.3	8.400
8.600	607.3	608.4	609.5	610.6	611.7	612.8	613.9	615.0	616.1	617.2	618.3	8.600
8.800	618.3	619.4	620.5	621.6	622.7	623.8	624.9	626.0	627.1	628.2	629.3	8.800
9.000	629.3	630.4	631.5	632.6	633.7	634.8	635.9	637.0	638.1	639.2	640.3	9.000
9.200	640.3	641.4	642.5	643.6	644.7	645.7	646.8	647.9	649.0	650.1	651.2	9.200
9.400	651.2	652.3	653.4	654.5	655.6	656.7	657.8	658.9	660.0	661.1	662.2	9.400
9.600	662.2	663.3	664.3	665.4	666.5	667.6	668.7	669.8	670.9	672.0	673.1	9.600
9.800	673.1	674.2	675.3	676.4	677.5	678.5	679.6	680.7	681.8	682.9	684.0	9.800
10.000	684.0	685.1	686.2	687.3	688.4	689.5	690.6	691.6	692.7	693.8	694.9	10.000
10.200	694.9	696.0	697.1	698.2	699.3	700.4	701.5	702.6	703.7	704.7	705.8	10.200
10.400	705.8	706.9	708.0	709.1	710.2	711.3	712.4	713.5	714.6	715.7	716.7	10.400
10.600	716.7	717.8	718.9	720.0	721.1	722.2	723.3	724.4	725.5	726.6	727.7	10.600
10.800	727.7	728.7	729.8	730.9	732.0	733.1	734.2	735.3	736.4	737.5	738.6	10.800
11.000	738.6	739.7	740.8	741.8	742.9	744.0	745.1	746.2	747.3	748.4	749.5	11.000
11.200	749.5	750.6	751.7	752.8	753.9	754.9	756.0	757.1	758.2	759.3	760.4	11.200
11.400	760.4	761.5	762.6	763.7	764.8	765.9	767.0	768.1	769.2	770.2	771.3	11.400
11.600	771.3	772.4	773.5	774.6	775.7	776.8	777.9	779.0	780.1	781.2	782.3	11.600
11.800	782.3	783.4	784.5	785.6	786.7	787.8	788.8	789.9	791.0	792.1	793.2	11.800
12.000	793.2	794.3	795.4	796.5	797.6	798.7	799.8	800.9	802.0	803.1	804.2	12.000
12.200	804.2	805.3	806.4	807.5	808.6	809.7	810.8	811.9	813.0	814.1	815.2	12.200
12.400	815.2	816.3	817.4	818.5	819.6	820.7	821.8	822.9	824.0	825.1	826.1	12.400
12.600	826.1	827.2	828.3	829.4	830.5	831.6	832.7	833.9	835.0	836.1	837.2	12.600
12.800	837.2	838.3	839.4	840.5	841.6	842.7	843.8	844.9	846.0	847.1	848.2	12.800

These tables are based on eleven thermocouples representing four manufacturers. The third decimal place in the emf values is given for interpolating purposes and does not represent table accuracy. Statements concerning accuracy are given in the text of this paper.

TABLE 4. *Tungsten versus rhenium thermocouples*—Continued

Millivolts	0.000	0.020	0.040	0.060	0.080	0.100	0.120	0.140	0.160	0.180	0.200	*Millivolts*
13.000	848.2	849.3	850.4	851.5	852.6	853.7	854.8	855.9	857.0	858.1	859.2	13.000
13.200	859.2	860.3	861.4	862.5	863.6	864.7	865.8	866.9	868.1	869.2	870.3	13.200
13.400	870.3	871.4	872.5	873.6	874.7	875.8	876.9	878.0	879.1	880.2	881.3	13.400
13.600	881.3	882.4	883.6	884.7	885.8	886.9	888.0	889.1	890.2	891.3	892.4	13.600
13.800	892.4	893.5	894.7	895.8	896.9	898.0	899.1	900.2	901.3	902.4	903.6	13.800
14.000	903.6	904.7	905.8	906.9	908.0	909.1	910.2	911.3	912.5	913.6	914.7	14.000
14.200	914.7	915.8	916.9	918.0	919.2	920.3	921.4	922.5	923.6	924.7	925.9	14.200
14.400	925.9	927.0	928.1	929.2	930.3	931.4	932.6	933.7	934.8	935.9	937.0	14.400
14.600	937.0	938.2	939.3	940.4	941.5	942.6	943.8	944.9	946.0	947.1	948.3	14.600
14.800	948.3	949.4	950.5	951.6	952.7	953.9	955.0	956.1	957.2	958.4	959.5	14.800
15.000	959.5	960.6	961.7	962.9	964.0	965.1	966.2	967.4	968.5	969.6	970.8	15.000
15.200	970.8	971.9	973.0	974.1	975.3	976.4	977.5	978.6	979.8	980.9	982.0	15.200
15.400	982.0	983.2	984.3	985.4	986.6	987.7	988.8	990.0	991.1	992.2	993.4	15.400
15.600	993.4	994.5	995.6	996.8	997.9	999.0	1000.2	1001.3	1002.4	1003.6	1004.7	15.600
15.800	1004.7	1005.8	1007.0	1008.1	1009.2	1010.4	1011.5	1012.6	1013.8	1014.9	1016.1	15.800
16.000	1016.1	1017.2	1018.4	1019.5	1020.6	1021.8	1022.9	1024.1	1025.2	1026.4	1027.5	16.000
16.200	1027.5	1028.7	1029.8	1030.9	1032.1	1033.2	1034.4	1035.5	1036.7	1037.8	1039.0	16.200
16.400	1039.0	1040.1	1041.3	1042.4	1043.6	1044.8	1045.9	1047.1	1048.2	1049.4	1050.5	16.400
16.600	1050.5	1051.7	1052.8	1054.0	1055.2	1056.3	1057.5	1058.6	1059.8	1061.0	1062.1	16.600
16.800	1062.1	1063.3	1064.4	1065.6	1066.8	1067.9	1069.1	1070.3	1071.4	1072.6	1073.8	16.800
17.000	1073.8	1074.9	1076.1	1077.3	1078.4	1079.6	1080.8	1081.9	1083.1	1084.3	1085.5	17.000
17.200	1085.5	1086.6	1087.8	1089.0	1090.2	1091.3	1092.5	1093.7	1094.9	1096.0	1097.2	17.200
17.400	1097.2	1098.4	1099.6	1100.8	1101.9	1103.1	1104.3	1105.5	1106.7	1107.9	1109.0	17.400
17.600	1109.0	1110.2	1111.4	1112.6	1113.8	1115.0	1116.2	1117.4	1118.5	1119.7	1120.9	17.600
17.800	1120.9	1122.1	1123.3	1124.5	1125.7	1126.9	1128.1	1129.3	1130.5	1131.7	1132.9	17.800
18.000	1132.9	1134.1	1135.3	1136.5	1137.7	1138.9	1140.1	1141.3	1142.5	1143.7	1144.9	18.000
18.200	1144.9	1146.1	1147.3	1148.5	1149.7	1150.9	1152.1	1153.3	1154.5	1155.8	1157.0	18.200
18.400	1157.0	1158.2	1159.4	1160.6	1161.8	1163.0	1164.3	1165.5	1166.7	1167.9	1169.1	18.400
18.600	1169.1	1170.3	1171.6	1172.8	1174.0	1175.2	1176.5	1177.7	1178.9	1180.1	1181.4	18.600
18.800	1181.4	1182.6	1183.8	1185.0	1186.3	1187.5	1188.7	1190.0	1191.2	1192.4	1193.7	18.800
19.000	1193.7	1194.9	1196.1	1197.4	1198.6	1199.8	1201.1	1202.3	1203.6	1204.8	1206.0	19.000
19.200	1206.0	1207.3	1208.5	1209.8	1211.0	1212.3	1213.5	1214.8	1216.0	1217.3	1218.5	19.200
19.400	1218.5	1219.8	1221.0	1222.3	1223.5	1224.8	1226.0	1227.3	1228.5	1229.8	1231.1	19.400
19.600	1231.1	1232.3	1233.6	1234.8	1236.1	1237.4	1238.6	1239.9	1241.2	1242.4	1243.7	19.600
19.800	1243.7	1245.0	1246.2	1247.5	1248.8	1250.0	1251.3	1252.6	1253.9	1255.1	1256.4	19.800
20.000	1256.4	1257.7	1259.0	1260.3	1261.5	1262.8	1264.1	1265.4	1266.7	1268.0	1269.3	20.000
20.200	1269.3	1270.5	1271.8	1273.1	1274.4	1275.7	1277.0	1278.3	1279.6	1280.9	1282.2	20.200
20.400	1282.2	1283.5	1284.8	1286.1	1287.4	1288.7	1290.0	1291.3	1292.6	1293.9	1295.2	20.400
20.600	1295.2	1296.5	1297.8	1299.1	1300.4	1301.8	1303.1	1304.4	1305.7	1307.0	1308.3	20.600
20.800	1308.3	1309.7	1311.0	1312.3	1313.6	1314.9	1316.3	1317.6	1318.9	1320.2	1321.6	20.800
21.000	1321.6	1322.9	1324.2	1325.6	1326.9	1328.2	1329.6	1330.9	1332.2	1333.6	1334.9	21.000
21.200	1334.9	1336.3	1337.6	1339.0	1340.3	1341.7	1343.0	1344.4	1345.7	1347.1	1348.4	21.200
21.400	1348.4	1349.8	1351.1	1352.5	1353.8	1355.2	1356.6	1357.9	1359.3	1360.6	1362.0	21.400
21.600	1362.0	1363.4	1364.7	1366.1	1367.5	1368.9	1370.2	1371.6	1373.0	1374.4	1375.7	21.600
21.800	1375.7	1377.1	1378.5	1379.9	1381.3	1382.7	1384.0	1385.4	1386.8	1388.2	1389.6	21.800
22.000	1389.6	1391.0	1392.4	1393.8	1395.2	1396.6	1398.0	1399.4	1400.8	1402.2	1403.6	22.000
22.200	1403.6	1405.0	1406.4	1407.8	1409.3	1410.7	1412.1	1413.5	1414.9	1416.4	1417.8	22.200
22.400	1417.8	1419.2	1420.6	1422.1	1423.5	1424.9	1426.3	1427.8	1429.2	1430.6	1432.1	22.400
22.600	1432.1	1433.5	1435.0	1436.4	1437.9	1439.3	1440.8	1442.2	1443.7	1445.1	1446.6	22.600
22.800	1446.6	1448.0	1449.5	1450.9	1452.4	1453.9	1455.3	1456.8	1458.3	1459.7	1461.2	22.800
23.000	1461.2	1462.7	1464.2	1465.6	1467.1	1468.6	1470.1	1471.6	1473.1	1474.5	1476.0	23.000
23.200	1476.0	1477.5	1479.0	1480.5	1482.0	1483.5	1485.0	1486.5	1488.0	1489.5	1491.1	23.200
23.400	1491.1	1492.6	1494.1	1495.6	1497.1	1498.6	1500.2	1501.7	1503.2	1504.7	1506.3	23.400
23.600	1506.3	1507.8	1509.3	1510.9	1512.4	1514.0	1515.5	1517.1	1518.6	1520.2	1521.7	23.600
23.800	1521.7	1523.3	1524.8	1526.4	1527.9	1529.5	1531.1	1532.6	1534.2	1535.8	1537.4	23.800
24.000	1537.4	1538.9	1540.5	1542.1	1543.7	1545.3	1546.9	1548.4	1550.0	1551.6	1553.2	24.000
24.200	1553.2	1554.8	1556.4	1558.1	1559.7	1561.3	1562.9	1564.5	1566.1	1567.8	1569.4	24.200
24.400	1569.4	1571.0	1572.6	1574.3	1575.9	1577.5	1579.2	1580.8	1582.5	1584.1	1585.8	24.400
24.600	1585.8	1587.4	1589.1	1590.8	1592.4	1594.1	1595.8	1597.4	1599.1	1600.8	1602.5	24.600
24.800	1602.5	1604.2	1605.8	1607.5	1609.2	1610.9	1612.6	1614.3	1616.0	1617.8	1619.5	24.800
25.000	1619.5	1621.2	1622.9	1624.6	1626.4	1628.1	1629.8	1631.6	1633.3	1635.0	1636.8	25.000
25.200	1636.8	1638.5	1640.3	1642.1	1643.8	1645.6	1647.3	1649.1	1650.9	1652.7	1654.5	25.200
25.400	1654.5	1656.2	1658.0	1659.8	1661.6	1663.4	1665.2	1667.1	1668.9	1670.7	1672.5	25.400
25.600	1672.5	1674.3	1676.2	1678.0	1679.8	1681.7	1683.5	1685.4	1687.2	1689.1	1691.0	25.600
25.800	1691.0	1692.8	1694.7	1696.6	1698.5	1700.4	1702.3	1704.2	1706.1	1708.0	1709.9	25.800
26.000	1709.9	1711.8	1713.7	1715.6	1717.6	1719.5	1721.5	1723.4	1725.4	1727.3	1729.3	26.000
26.200	1729.3	1731.2	1733.2	1735.2	1737.2	1739.2	1741.2	1743.2	1745.2	1747.2	1749.2	26.200
26.400	1749.2	1751.2	1753.3	1755.3	1757.3	1759.4	1761.4	1763.5	1765.6	1767.6	1769.7	26.400
26.600	1769.7	1771.8	1773.9	1776.0	1778.1	1780.2	1782.3	1784.5	1786.6	1788.7	1790.9	26.600
26.800	2790.9	1793.1	1795.2	1797.4	1799.6	1801.8	1804.0	1806.2	1808.4	1810.6	1812.8	26.800

TABLE 4. *Tungsten versus rhenium thermocouples*—Continued

Millivolts	0.000	0.020	0.040	0.060	0.080	0.100	0.120	0.140	0.160	0.180	0.200	*Millivolts*
27.000	1812.8	1815.0	1817.3	1819.5	1821.8	1824.1	1826.4	1828.6	1830.9	1833.2	1835.6	27.000
27.200	1835.6	1837.9	1840.2	1842.6	1844.9	1847.3	1849.7	1852.0	1854.4	1856.8	1859.3	27.200
27.400	1859.3	1861.7	1864.1	1866.6	1869.0	1871.5	1874.0	1876.5	1879.0	1881.5	1884.1	27.400
27.600	1884.1	1886.6	1889.2	1891.7	1894.3	1896.9	1899.6	1902.2	1904.8	1907.5	1910.2	27.600
27.800	1910.2	1912.8	1915.6	1918.3	1921.0	1923.8	1926.5	1929.3	1932.1	1935.0	1937.8	27.800
28.000	1937.8	1940.7	1943.6	1946.5	1949.4	1952.3	1955.3	1958.3	1961.3	1964.3	1967.4	28.000
28.200	1967.4	1970.4	1973.5	1976.7	1979.8	1983.0	1986.2	1989.4	1992.7	1996.0	1999.3	28.200
28.400	1999.3	2002.7										

TABLE 5. *Tungsten versus rhenium thermocouples*

Electromotive force in absolute millivolts. Temperature in degrees C (Int. 1948). Reference junctions at 0 °C.

Temp. ° *C*	0	5	10	15	20	25	30	35	40	45	50	Temp. ° *C*.
0	0.000	0.032	0.065	0.099	0.134	0.170	0.207	0.245	0.284	0.324	0.364	0
50	0.364	0.406	0.449	0.492	0.537	0.582	0.628	0.675	0.723	0.772	0.821	50
100	0.821	0.872	0.923	0.975	1.028	1.081	1.136	1.191	1.247	1.303	1.361	100
150	1.361	1.419	1.477	1.537	1.597	1.658	1.719	1.782	1.844	1.908	1.972	150
200	1.972	2.037	2.102	2.168	2.235	2.302	2.370	2.438	2.507	2.576	2.647	200
250	2.647	2.717	2.788	2.860	2.932	3.005	3.078	3.151	3.225	3.300	3.375	250
300	3.375	3.451	3.527	3.603	3.680	3.757	3.835	3.913	3.992	4.071	4.150	300
350	4.150	4.230	4.310	4.390	4.471	4.552	4.634	4.715	4.798	4.880	4.963	350
400	4.963	5.046	5.130	5.213	5.297	5.382	5.466	5.551	5.636	5.722	5.807	400
450	5.807	5.893	5.979	6.066	6.152	6.239	6.326	6.414	6.501	6.589	6.677	450
500	6.677	6.765	6.853	6.941	7.030	7.119	7.208	7.297	7.386	7.476	7.565	500
550	7.565	7.655	7.744	7.834	7.924	8.015	8.105	8.195	8.286	8.376	8.467	550
600	8.467	8.558	8.649	8.739	8.830	8.922	9.013	9.104	9.195	9.286	9.378	600
650	9.378	9.469	9.561	9.652	9.744	9.835	9.927	10.018	10.110	10.201	10.293	650
700	10.293	10.385	10.476	10.568	10.660	10.751	10.843	10.935	11.026	11.118	11.209	700
750	11.209	11.301	11.392	11.484	11.575	11.667	11.758	11.850	11.941	12.032	12.124	750
800	12.124	12.215	12.306	12.397	12.488	12.579	12.670	12.761	12.852	12.942	13.033	800
850	13.033	13.124	13.214	13.305	13.395	13.486	13.576	13.666	13.756	13.846	13.936	850
900	13.936	14.026	14.116	14.205	14.295	14.385	14.474	14.563	14.653	14.742	14.831	900
950	14.831	14.920	15.009	15.098	15.187	15.275	15.364	15.452	15.541	15.629	15.717	950
1000	15.717	15.805	15.893	15.981	16.069	16.156	16.243	16.331	16.417	16.504	16.591	1000
1050	16.591	16.677	16.764	16.850	16.935	17.021	17.107	17.192	17.277	17.362	17.447	1050
1100	17.447	17.532	17.616	17.700	17.784	17.868	17.952	18.036	18.119	18.202	18.285	1100
1150	18.285	18.368	18.450	18.532	18.614	18.696	18.778	18.859	18.941	19.022	19.103	1150
1200	19.103	19.183	19.264	19.344	19.424	19.504	19.583	19.663	19.742	19.821	19.899	1200
1250	19.899	19.978	20.056	20.134	20.212	20.289	20.366	20.444	20.520	20.597	20.673	1250
1300	20.673	20.749	20.825	20.901	20.976	21.051	21.126	21.201	21.275	21.350	21.424	1300
1350	21.424	21.497	21.571	21.644	21.717	21.789	21.862	21.934	22.006	22.077	22.149	1350
1400	22.149	22.220	22.290	22.361	22.431	22.501	22.571	22.640	32.710	22.778	22.847	1400
1450	22.847	22.915	22.984	23.051	23.119	23.186	23.253	23.320	23.386	23.452	23.518	1450
1500	23.518	23.583	23.649	23.713	23.778	23.842	23.906	23.970	24.033	24.097	24.159	1500
1550	24.159	24.222	24.284	24.346	24.408	24.469	24.530	24.590	24.651	24.711	24.771	1550
1600	24.771	24.830	24.889	24.948	25.006	25.064	25.122	25.179	25.237	25.293	25.350	1600
1650	25.350	25.406	25.462	25.517	25.572	25.627	25.682	25.736	25.790	25.843	25.896	1650
1700	25.896	25.949	26.001	26.053	26.105	26.156	26.207	26.258	26.308	26.358	26.408	1700
1750	26.408	26.457	26.506	26.554	26.603	26.650	26.698	26.745	26.792	26.838	26.884	1750
1800	26.884	26.929	26.975	27.020	27.064	27.108	27.152	27.195	27.238	27.281	27.323	1800
1850	27.323	27.365	27.406	27.447	27.488	27.528	27.568	27.607	27.646	27.685	27.723	1850
1900	17.723	27.761	27.799	27.836	27.873	27.909	27.945	27.980	28.015	28.050	28.084	1900
1950	28.084	28.118	28.152	28.185	28.217	28.249	28.281	28.312	28.343	28.374	28.404	1950
2000	28.404											2000

These tables are based on eleven thermocouples representing four manufacturers. The third decimal place in the emf values is given for interpolating purposes and does not represent table accuracy. Statements concerning accuracy are given in the text of this paper.

TABLE 6. *Tungsten versus rhenium thermocouples*

Electromotive force in absolute millivolts. Temperature in degrees F.* Reference junctions at 32 °F.

Millivolts	0.000	0.020	0.040	0.060	0.080	0.100	0.120	0.140	0.160	0.180	0.200	Millivolts
0.000	32.0	37.7	43.2	48.7	54.0	59.3	64.4	69.5	74.5	79.5	84.3	0.000
0.200	84.3	89.1	93.9	98.5	103.1	107.7	112.2	116.6	121.0	125.4	129.7	0.200
0.400	129.7	134.0	138.2	142.3	146.5	150.6	154.6	158.7	162.7	166.6	170.5	0.400
0.600	170.5	174.4	178.3	182.1	185.9	189.7	193.4	197.1	200.8	204.5	208.1	0.600
0.800	208.1	211.7	215.3	218.9	222.4	226.0	229.5	233.0	236.4	239.9	243.3	0.800
1.000	243.3	246.7	250.1	253.4	256.8	260.1	263.4	266.7	270.0	273.2	276.5	1.000
1.200	276.5	279.7	282.9	286.1	289.3	292.5	295.6	298.8	301.9	305.0	308.1	1.200
1.400	308.1	311.2	314.3	317.3	320.4	323.4	326.5	329.5	332.5	335.5	338.4	1.400
1.600	338.4	341.4	344.4	347.3	350.2	353.2	356.1	359.0	361.9	364.8	367.6	1.600
1.800	367.6	370.5	373.4	376.2	379.0	381.9	384.7	387.5	390.3	393.1	395.9	1.800
2.000	395.9	398.7	401.4	404.2	407.0	409.7	412.4	415.2	417.9	420.6	423.3	2.000
2.200	423.3	426.0	428.7	431.4	434.1	436.7	439.4	442.1	444.7	447.4	450.0	2.200
2.400	450.0	452.6	455.2	457.9	460.5	463.1	465.7	468.3	470.9	473.5	476.0	2.400
2.600	476.0	478.6	481.2	483.7	486.3	488.8	491.4	493.9	496.4	499.0	501.5	2.600
2.800	501.5	504.0	506.5	509.0	511.5	514.0	516.5	519.0	521.5	524.0	526.4	2.800
3.000	526.4	528.9	531.4	533.8	536.3	538.7	541.2	543.6	546.1	548.5	550.9	3.000
3.200	550.9	553.3	555.8	558.2	560.6	563.0	565.4	567.8	570.2	572.6	575.0	3.200
3.400	575.0	577.3	579.7	582.1	584.5	586.8	589.2	591.6	593.9	596.3	598.6	3.400
3.600	598.6	601.0	603.3	605.7	608.0	610.3	612.7	615.0	617.3	619.6	622.0	3.600
3.800	622.0	624.3	626.6	628.9	631.2	633.5	635.8	638.1	640.4	642.7	645.0	3.800
4.000	645.0	647.2	649.5	651.8	654.1	656.3	658.6	660.9	663.1	665.4	667.7	4.000
4.200	667.7	669.9	672.2	674.4	676.7	678.9	681.2	683.4	685.6	687.9	690.1	4.200
4.400	690.1	692.3	694.6	696.8	699.0	701.2	703.5	705.7	707.9	710.1	712.3	4.400
4.600	712.3	714.5	716.7	718.9	721.1	723.3	725.5	727.7	729.9	732.1	734.3	4.600
4.800	734.3	736.4	738.6	740.8	743.0	745.2	747.3	749.5	751.7	753.8	756.0	4.800
5.000	756.0	758.2	760.3	762.5	764.7	766.8	769.0	771.1	773.3	775.4	777.6	5.000
5.200	777.6	779.7	781.9	784.0	786.1	788.3	790.4	792.6	794.7	796.8	799.0	5.200
5.400	799.0	801.1	803.2	805.3	807.5	809.6	811.7	813.8	815.9	818.1	820.2	5.400
5.600	820.2	822.3	824.4	826.5	828.6	830.7	832.8	834.9	837.0	839.1	841.2	5.600
5.800	841.2	843.3	845.4	847.5	849.6	851.7	853.8	855.9	858.0	860.1	862.1	5.800
6.000	862.1	864.2	866.3	868.4	870.5	872.5	874.6	876.7	878.8	880.9	882.9	6.000
6.200	882.9	885.0	887.1	889.1	891.2	893.3	895.3	897.4	899.5	901.5	903.6	6.200
6.400	903.6	905.6	907.7	909.8	911.8	913.9	915.9	918.0	920.0	922.1	924.1	6.400
6.600	924.1	926.2	928.2	930.3	932.3	934.4	936.4	938.5	940.5	942.6	944.6	6.600
6.800	944.6	946.6	948.7	950.7	952.7	954.8	956.8	958.8	960.9	962.9	964.9	6.800
7.000	964.9	967.0	969.0	971.0	973.1	975.1	977.1	979.1	981.2	983.2	985.2	7.000
7.200	985.2	987.2	989.3	991.3	993.3	995.3	997.3	999.3	1001.4	1003.4	1005.4	7.200
7.400	1005.4	1007.4	1009.4	1011.4	1013.5	1015.5	1017.5	1019.5	1021.5	1023.5	1025.5	7.400
7.600	1025.5	1027.5	1029.5	1031.5	1033.5	1035.5	1037.5	1039.5	1041.6	1043.6	1045.6	7.600
7.800	1045.6	1047.6	1049.6	1051.6	1053.6	1055.6	1057.6	1059.6	1061.5	1063.5	1065.5	7.800
8.000	1065.5	1067.5	1069.5	1071.5	1073.5	1075.5	1077.5	1079.5	1081.5	1083.5	1085.5	8.000
8.200	1085.5	1087.5	1089.5	1091.4	1093.4	1095.4	1097.4	1099.4	1101.4	1103.4	1105.4	8.200
8.400	1105.4	1107.3	1109.3	1111.3	1113.3	1115.3	1117.3	1119.2	1121.2	1123.2	1125.2	8.400
8.600	1125.2	1127.2	1129.2	1131.1	1133.1	1135.1	1137.1	1139.1	1141.0	1143.0	1145.0	8.600
8.800	1145.0	1147.0	1148.9	1150.9	1152.9	1154.9	1156.9	1158.8	1160.8	1162.8	1164.8	8.800
9.000	1164.8	1166.7	1168.7	1170.7	1172.6	1174.6	1176.6	1178.6	1180.5	1182.5	1184.5	9.000
9.200	1184.5	1186.5	1188.4	1190.4	1192.4	1194.3	1196.3	1198.3	1200.3	1202.2	1204.2	9.200
9.400	1204.2	1206.2	1208.1	1210.1	1212.1	1214.0	1216.0	1218.0	1219.9	1221.9	1223.9	9.400
9.600	1223.9	1225.9	1227.8	1229.8	1231.8	1233.7	1235.7	1237.7	1239.6	1241.6	1243.6	9.600
9.800	1243.6	1245.5	1247.5	1249.5	1251.4	1253.4	1255.3	1257.3	1259.3	1261.2	1263.2	9.800
10.000	1263.2	1265.2	1267.1	1269.1	1271.1	1273.0	1275.0	1277.0	1278.9	1280.9	1282.9	10.000
10.200	1282.9	1284.8	1286.8	1288.8	1290.7	1292.7	1294.6	1296.6	1298.6	1300.5	1302.5	10.200
10.400	1302.5	1304.5	1306.4	1308.4	1310.4	1312.3	1314.3	1316.2	1318.2	1320.2	1322.1	10.400
10.600	1322.1	1324.1	1326.1	1328.0	1330.0	1332.0	1333.9	1335.9	1337.9	1339.8	1341.8	10.600
10.800	1341.8	1343.7	1345.7	1347.7	1349.6	1351.6	1353.6	1355.5	1357.5	1359.5	1361.4	10.800
11.000	1361.4	1363.4	1365.4	1367.3	1369.3	1371.3	1373.2	1375.2	1377.1	1379.1	1381.1	11.000
11.200	1381.1	1383.0	1385.0	1387.0	1388.9	1390.9	1392.9	1394.8	1396.8	1398.8	1400.7	11.200
11.400	1400.7	1402.7	1404.7	1406.6	1408.6	1410.6	1412.5	1414.5	1416.5	1418.4	1420.4	11.400
11.600	1420.4	1422.4	1424.3	1426.3	1428.3	1430.3	1432.2	1434.2	1436.2	1438.1	1440.1	11.600
11.800	1440.1	1442.1	1444.0	1446.0	1448.0	1450.0	1451.9	1453.9	1455.9	1457.8	1459.8	11.800
12.000	1459.8	1461.8	1463.8	1465.7	1467.7	1469.7	1471.6	1473.6	1475.6	1477.6	1479.5	12.000
12.200	1479.5	1481.5	1483.5	1485.5	1487.4	1489.4	1491.4	1493.4	1495.3	1497.3	1499.3	12.200
12.400	1499.3	1501.3	1503.2	1505.2	1507.2	1509.2	1511.2	1513.1	1515.1	1517.1	1519.1	12.400
12.600	1519.1	1521.0	1523.0	1525.0	1527.0	1529.0	1530.9	1532.9	1534.9	1536.9	1538.9	12.600
12.800	1538.9	1540.9	1542.8	1544.8	1546.8	1548.8	1550.8	1552.8	1554.7	1556.7	1558.7	12.800

*Based on the International Practical Temperature Scale of 1948.

These tables are based on eleven thermocouples representing four manufacturers. The third decimal place in the emf values is given for interpolating purposes and does not represent table accuracy. Statements concerning accuracy are given in the text of this paper.

TABLE 6. *Tungsten versus rhenium thermocouples*—Continued

Millivolts	0.000	0.020	0.040	0.060	0.080	0.100	0.120	0.140	0.160	0.180	0.200	*Millivolts*
13.000	1558.7	1560.7	1562.7	1564.7	1566.7	1568.6	1570.6	1572.6	1574.6	1576.6	1578.6	13.000
13.200	1578.6	1580.6	1582.6	1584.5	1586.5	1588.5	1590.5	1592.5	1594.5	1596.5	1598.5	13.200
13.400	1598.5	1600.5	1602.5	1604.5	1606.4	1608.4	1610.4	1612.4	1614.4	1616.4	1618.4	13.400
13.600	1618.4	1620.4	1622.4	1624.4	1626.4	1628.4	1630.4	1632.4	1634.4	1636.4	1638.4	13.600
13.800	1638.4	1640.4	1642.4	1644.4	1646.4	1648.4	1650.4	1652.4	1654.4	1656.4	1658.4	13.800
14.000	1658.4	1660.4	1662.4	1664.4	1666.4	1668.4	1670.4	1672.4	1674.4	1676.4	1678.4	14.000
14.200	1678.4	1680.5	1682.5	1684.5	1686.5	1688.5	1690.5	1692.5	1694.5	1696.5	1698.5	14.200
14.400	1698.5	1700.6	1702.6	1704.6	1706.6	1708.6	1710.6	1712.6	1714.6	1716.7	1718.7	14.400
14.600	1718.7	1720.7	1722.7	1724.7	1726.7	1728.8	1730.8	1732.8	1734.8	1736.8	1738.9	14.600
14.800	1738.9	1740.9	1742.9	1744.9	1746.9	1749.0	1751.0	1753.0	1755.0	1757.1	1759.1	14.800
15.000	1759.1	1761.1	1763.1	1765.2	1767.2	1769.2	1771.2	1773.3	1775.3	1777.3	1779.4	15.000
15.200	1779.4	1781.4	1783.4	1785.4	1787.5	1789.5	1791.5	1793.6	1795.6	1797.6	1799.7	15.200
15.400	1799.7	1801.7	1803.7	1805.8	1807.8	1809.8	1811.9	1813.9	1816.0	1818.0	1820.0	15.400
15.600	1820.0	1822.1	1824.1	1826.2	1828.2	1830.2	1832.3	1834.3	1836.4	1838.4	1840.4	15.600
15.800	1840.4	1842.5	1844.5	1846.6	1848.6	1850.7	1852.7	1854.8	1856.8	1858.9	1860.9	15.800
16.000	1860.9	1863.0	1865.0	1867.1	1869.2	1871.2	1873.3	1875.3	1877.4	1879.5	1881.5	16.000
16.200	1881.5	1883.6	1885.6	1887.7	1889.8	1891.8	1893.9	1896.0	1898.0	1900.1	1902.2	16.200
16.400	1902.2	1904.3	1906.3	1908.4	1910.5	1912.6	1914.6	1916.7	1918.8	1920.9	1923.0	16.400
16.600	1923.0	1925.0	1927.1	1929.2	1931.3	1933.4	1935.5	1937.5	1939.6	1941.7	1943.8	16.600
16.800	1943.8	1945.9	1948.0	1950.1	1952.2	1954.3	1956.4	1958.5	1960.6	1962.7	1964.8	16.800
17.000	1964.8	1966.9	1969.0	1971.1	1973.2	1975.3	1977.4	1979.5	1981.6	1983.7	1985.8	17.000
17.200	1985.8	1987.9	1990.1	1992.2	1994.3	1996.4	1998.5	2000.6	2002.8	2004.9	2007.0	17.200
17.400	2007.0	2009.1	2011.2	2013.4	2015.5	2017.6	2019.8	2021.9	2024.0	2026.1	2028.3	17.400
17.600	2028.3	2030.4	2032.5	2034.7	2036.8	2039.0	2041.1	2043.2	2045.4	2047.5	2049.7	17.600
17.800	2049.7	2051.8	2054.0	2056.1	2058.2	2060.4	2062.6	2064.7	2066.9	2069.0	2071.2	17.800
18.000	2071.2	2073.3	2075.5	2077.6	2079.8	2082.0	2084.1	2086.3	2088.5	2090.6	2092.8	18.000
18.200	2092.8	2095.0	2097.1	2099.3	2101.5	2103.7	2105.8	2108.0	2110.2	2112.4	2114.5	18.200
18.400	2114.5	2116.7	2118.9	2121.1	2123.3	2125.5	2127.7	2129.8	2132.0	2134.2	2136.4	18.400
18.600	2136.4	2138.6	2140.8	2143.0	2145.2	2147.4	2149.6	2151.8	2154.0	2156.2	2158.4	18.600
18.800	2158.4	2160.6	2162.8	2165.1	2167.3	2169.5	2171.7	2173.9	2176.1	2178.4	2180.6	18.800
19.000	2180.6	2182.8	2185.0	2187.3	2189.5	2191.7	2193.9	2196.2	2198.4	2200.6	2202.9	19.000
19.200	2202.9	2205.1	2207.3	2209.6	2211.8	2214.1	2216.3	2218.6	2220.8	2223.1	2225.3	19.200
19.400	2225.3	2227.6	2229.8	2232.1	2234.3	2236.6	2238.8	2241.1	2243.4	2245.6	2247.9	19.400
19.600	2247.9	2250.2	2252.4	2254.7	2257.0	2259.3	2261.5	2263.8	2266.1	2268.4	2270.7	19.600
19.800	2270.7	2272.9	2275.2	2277.5	2279.8	2282.1	2284.4	2286.7	2289.0	2291.3	2293.6	19.800
20.000	2293.6	2295.9	2298.2	2300.5	2302.8	2305.1	2307.4	2309.7	2312.0	2314.3	2316.7	20.000
20.200	2316.7	2319.0	2321.3	2323.6	2325.9	2328.3	2330.6	2332.9	2335.2	2237.6	2339.9	20.200
20.400	2339.9	2342.2	2344.6	2346.9	2349.3	2351.6	2354.0	2356.3	2358.7	3361.0	2363.4	20.400
20.600	2363.4	2365.7	2368.1	2370.4	2372.8	2375.2	2377.5	2379.9	2382.3	2384.6	2387.0	20.600
20.800	2387.0	2389.4	2391.7	2394.1	2396.5	2398.9	2401.3	2403.7	2406.0	2408.4	2410.8	20.800
21.000	2410.8	2413.2	2415.6	2418.0	2420.4	2422.8	2425.2	2427.6	2430.0	2432.5	2434.9	21.000
21.200	2434.9	2437.3	2439.7	2442.1	2444.6	2447.0	2449.4	2451.8	2454.3	2456.7	2459.1	21.200
21.400	2459.1	2461.6	2464.0	2466.5	2468.9	2471.3	2473.8	2476.2	2478.7	2481.2	2483.6	21.400
21.600	2483.6	2486.1	2488.5	2491.0	2493.5	2495.9	2498.4	2500.9	2503.4	2505.8	2508.3	21.600
21.800	2508.3	2510.8	2513.3	2515.8	2518.3	2520.8	2523.3	2525.8	2528.3	2530.8	2533.3	21.800
22.000	2533.3	2535.8	2538.3	2540.8	2543.3	2545.9	2548.4	2550.9	2553.4	2556.0	2558.5	22.000
22.200	2558.5	2561.0	2563.6	2566.1	2568.7	2571.2	2573.8	2576.3	2578.9	0 2581.4	2584.0	22.200
22.400	2584.0	2586.6	2589.1	2591.7	2594.3	2596.8	2599.4	2602.0	2604.6	2607.2	2609.8	22.400
22.600	2609.8	2612.3	2614.9	2617.5	2620.1	2622.7	2625.4	2628.0	2630.6	2632.2	2635.8	22.600
22.800	2635.8	2638.4	2641.1	2643.7	2646.3	2649.0	2651.6	2654.2	2656.9	2659.5	2662.2	22.800
23.000	2662.2	2664.8	2667.5	2670.2	2672.8	2675.5	2678.2	2680.8	2683.5	2686.2	2688.9	23.000
23.200	2688.9	2691.6	2694.3	2696.9	2699.6	2702.3	2705.0	2707.8	2710.5	2713.2	2715.9	23.200
23.400	2715.9	2718.6	2721.4	2724.1	2726.8	2729.6	2732.3	2735.0	2737.8	2740.5	2743.3	23.400
23.600	2743.3	2746.1	2748.8	2751.6	2754.4	2757.1	2759.9	2762.7	2765.5	2768.3	2771.1	23.600
23.800	2771.1	2773.9	2776.7	2779.5	2782.3	2785.1	2787.9	2790.7	2793.6	2796.4	2799.2	23.800
24.000	2799.2	2802.1	2804.9	2807.8	2810.6	2813.5	2816.3	2819.2	2822.1	2825.0	2827.8	24.000
24.200	2827.8	2830.7	2833.6	2836.5	2839.4	2842.3	2845.2	2848.1	2851.0	2854.0	2856.9	24.200
24.400	2856.9	2859.8	2862.8	2865.7	2868.6	2871.6	2874.5	2877.5	2880.5	2883.4	2886.4	24.400
24.600	2886.4	2889.4	2892.4	2895.4	2898.4	2901.4	2904.4	2907.4	2910.4	2913.4	2916.5	24.600
24.800	2916.5	2919.5	2922.5	2925.6	2928.6	2931.7	2934.7	2937.8	2940.9	2944.0	2947.0	24.800
25.000	2947.0	2950.1	2953.2	2956.3	2959.4	2962.6	2965.7	2968.8	2971.9	2975.1	2978.2	25.000
25.200	2978.2	2981.4	2984.5	2987.7	2990.9	2994.0	2997.2	3000.4	3003.6	3006.8	3010.0	25.200
25.400	3010.0	3013.2	3016.5	3019.7	3022.9	3026.2	3029.4	3032.7	3036.0	3039.2	3042.5	25.400
25.600	3042.5	3045.8	3049.1	3052.4	3055.7	3059.0	3062.4	3065.7	3069.0	3072.4	3075.8	25.600
25.800	3075.8	3079.1	3082.5	3085.9	3089.3	3092.7	3096.1	3099.5	3102.9	3106.3	3109.8	25.800

TABLE 6. *Tungsten versus rhenium thermocouples*—Continued

Millivolts	0.000	0.020	0.040	0.060	0.080	0.100	0.120	0.140	0.160	0.180	0.200	*Millivolts*
26.000	3109.8	3113.2	3116.7	3120.2	3123.6	3127.1	3130.6	3134.1	3137.6	3141.2	3144.7	26.000
26.200	3144.7	3148.2	3151.8	3155.3	3158.9	3162.5	3166.1	3169.7	3173.3	3176.9	3180.6	26.200
26.400	3180.6	3184.2	3187.9	3191.5	3195.2	3198.9	3202.6	3206.3	3210.0	3213.8	3217.5	26.400
26.600	3217.5	3221.3	3225.0	3228.8	3232.6	3236.4	3240.2	3244.1	3247.9	3251.7	3255.6	26.600
26.800	3255.6	3259.5	3263.4	3267.3	3271.2	3275.2	3279.1	3283.1	3287.1	3291.1	3295.1	26.800
27.000	3295.1	3299.1	3303.1	3307.2	3311.3	3315.3	3319.4	3323.6	3327.7	3331.8	3336.0	27.000
27.200	3336.0	3340.2	3344.4	3348.6	3352.9	3357.1	3361.4	3365.7	3370.0	3374.3	3378.7	27.200
27.400	3378.7	3383.0	3387.4	3391.8	3396.3	3400.7	3405.2	3409.7	3414.2	3418.7	3423.3	27.400
27.600	3423.3	3427.9	3432.5	3437.1	3441.8	3446.5	3451.2	3455.9	3460.7	3465.5	3470.3	27.600
27.800	3470.3	3475.1	3480.0	3484.9	3489.8	3494.8	3499.8	3504.8	3509.8	3514.9	3520.1	27.800
28.000	3520.1	3525.2	3530.4	3535.6	3540.9	3546.2	3551.5	3556.9	3562.3	3567.8	3573.2	28.000
28.200	3573.2	3578.8	3584.4	3590.0	3595.7	3601.4	3607.2	3613.0	3618.9	3624.8	3630.8	28.200
28.400	3630.8	3636.8	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------

TABLE 7. *Tungsten versus rhenium thermocouples*

Electromotive force in absolute millivolts. Temperature in degrees F.* Reference junctions at 32 ° F.

Temp. ° *F*	0	10	20	30	40	50	60	70	80	90	100	Temp. ° *F*
0	----------	----------	----------	----------	0.028	0.065	0.103	0.142	0.182	0.224	0.266	0
100	0.266	0.310	0.355	0.401	0.449	0.497	0.547	0.597	0.649	0.702	0.756	100
200	0.756	0.810	0.866	0.923	0.981	1.040	1.099	1.160	1.222	1.284	1.348	200
300	1.348	1.412	1.477	1.544	1.611	1.678	1.747	1.816	1.887	1.958	2.030	300
400	2.030	2.102	2.176	2.250	2.325	2.400	2.476	2.553	2.631	2.709	2.788	400
500	2.788	2.868	2.948	3.029	3.110	3.192	3.275	3.358	3.442	3.527	3.612	500
600	3.612	3.697	3.783	3.870	3.957	4.044	4.132	4.221	4.310	4.399	4.489	600
700	4.489	4.579	4.670	4.761	4.853	4.945	5.037	5.130	5.223	5.316	5.410	700
800	5.410	5.504	5.598	5.693	5.788	5.884	5.979	6.075	6.172	6.268	6.365	800
900	6.365	6.462	6.560	6.657	6.755	6.853	6.951	7.050	7.148	7.247	7.346	900
1000	7.346	7.446	7.545	7.645	7.744	7.844	7.944	8.045	8.145	8.245	8.346	1000
1100	8.346	8.447	8.548	8.649	8.750	8.851	8.952	9.053	9.154	9.256	9.357	1100
1200	9.357	9.459	9.561	9.662	9.764	9.866	9.967	10.069	10.171	10.273	10.375	1200
1300	10.375	10.476	10.578	10.680	10.782	10.884	10.985	11.087	11.189	11.291	11.392	1300
1400	11.392	11.494	11.596	11.697	11.799	11.900	12.002	12.103	12.205	12.306	12.407	1400
1500	12.407	12.508	12.609	12.710	12.811	12.912	13.013	13.114	13.214	13.315	13.415	1500
1600	13.415	13.516	13.616	13.716	13.816	13.916	14.016	14.116	14.215	14.315	14.414	1600
1700	14.414	14.514	14.613	14.712	14.811	14.910	15.009	15.108	15.206	15.305	15.403	1700
1800	15.403	15.502	15.600	15.698	15.796	15.893	15.991	16.088	16.185	16.282	16.379	1800
1900	16.379	16.475	16.572	16.668	16.764	16.859	16.955	17.050	17.145	17.239	17.334	1900
2000	17.334	17.428	17.522	17.616	17.710	17.803	17.896	17.989	18.082	18.174	18.266	2000
2100	18.266	18.358	18.450	18.541	18.633	18.724	18.814	18.905	18.995	19.085	19.174	2100
2200	19.174	19.264	19.353	19.442	19.530	19.618	19.707	19.794	19.882	19.969	20.056	2200
2300	20.056	20.143	20.229	20.315	20.401	20.486	20.571	20.656	20.741	20.825	20.909	2300
2400	20.909	20.993	21.076	21.160	21.242	21.325	21.407	21.489	21.571	21.652	21.733	2400
2500	21.733	21.813	21.894	21.974	22.053	22.133	22.212	22.290	22.369	22.447	22.525	2500
2600	22.525	22.602	22.679	22.756	22.832	22.908	22.984	23.059	23.134	23.208	23.283	2600
2700	23.283	23.357	23.430	23.503	23.576	23.649	23.721	23.792	23.864	23.935	24.005	2700
2800	24.005	24.076	24.145	24.215	24.284	24.353	24.421	24.489	24.557	24.624	24.691	2800
2900	24.691	24.757	24.823	24.889	24.954	25.019	25.084	25.148	25.211	25.275	25.337	2900
3000	25.337	25.400	25.462	25.523	25.585	25.645	25.706	25.766	25.825	25.884	25.943	3000
3100	25.943	26.001	26.059	26.116	26.173	26.230	26.286	26.342	26.397	26.452	26.506	3100
3200	26.506	26.560	26.613	26.666	26.719	26.771	26.823	26.874	26.924	26.975	27.024	3200
3300	27.024	27.074	27.123	27.171	27.219	27.267	27.314	27.360	27.406	27.452	27.497	3300
3400	27.497	27.541	27.585	27.629	27.672	27.715	27.757	27.799	27.840	27.881	27.921	3400
3500	27.921	27.961	28.000	28.038	28.077	28.114	28.152	28.188	28.224	28.260	28.295	3500
3600	28.295	28.330	28.364	28.397	28.430	----------	----------	----------	----------	----------	----------	3600

*Based on the International Practical Temperature Scale of 1948.

These tables are based on eleven thermocouples representing four manufacturers. The third decimal place in the emf is given for interpolating purposes and does not represent table accuracy. Statements concerning accuracy are given in the text of this paper.

The author acknowledges the contributions made by the following employees of the National Bureau of Standards in the computer program development and data handling that were utilized for the presentation of this paper: John S. Gallagher of the Temperature Physics Section, Daniel R. Flynn of the Heat Transfer Section, and Joseph Hilsenrath of the Equation of State Section.

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(Paper 67C4–146)

JOURNAL OF RESEARCH of the National Bureau of Standards—C. Engineering and Instrumentation
Vol. 67C, No. 4, October–December 1963

Publications of the National Bureau of Standards*

Selected Abstracts

Standard X-ray diffraction powder patterns, H. E. Swanson, M. C. Morris, R. P. Stinchfield, and E. H. Evans, *NBS Mono. 25, Section 2 (May 3, 1963), 35 cents.*

Standard X-ray diffraction powder patterns are presented for the following thirty-seven substances: $Al\ (PO_3)_3$, SbF_3*, $Ba_3(AsO_4)_2$*, $Ba(ClO_4)_2.3H_2O$, $Cd(CN)_2$*, $CdWO_4$, Cs_2OsBr_6*, Cs_2OsCl_6*, α-$CrPO_4$, $Co[Hg(CNS)_4]$*, β-$CoSO_4$, $Dy_3Ga_2(GaO_4)_3$*, $ErMnO_3$*, $Eu_3Ga_2\ (GaO_4)_3$*, $Gd_3Ga_2(GaO_4)_3$*, Li_3AsO_4*, $Li_3P_3O_9.3H_2O$*, $Li_2WO_4.\frac{1}{2}H_2O$*, $Lu_3Ga_2(GaO_4)_3$*, $LuMnO_3$*, $MnWO_4$ (huebnerite), HgF_2*, $NiSO_4$, $NiWO_4$*, K_2ReCl_6, K_2RuCl_5NO*, $RbClO_4$*, $RbIO_4$*, Ag_2SeO_4*, $NaCNO$*, $Na_2WO_4.2H_2O$, β-$Na_4P_4O_{12}.4H_2O$, $Sr_3(AsO_4)_2$*, Tl_3AsO_4*, $TlClO_4$*, $YAsO_4$, $ZnWO_4$*. Eleven are to replace patterns already given in the X-ray Powder Data File issued by the American Society for Testing and Materials, and twenty-six patterns indicated by asterisks are for substances not previously included. The X-ray Powder Data File is a compilation of diffraction patterns from many sources and is used for the identification of unknown crystalline materials by matching spacing and intensity measurements. The patterns were made with a Geiger counter X-ray diffractometer, using samples of high purity. When possible, the *d*-values were assigned Miller indices determined by comparison with calculated interplanar spacings and from space group extinctions. The densities and lattice constants were calculated, and the refractive indices were measured whenever possible.

Mechanical behavior of crystalline solids (*Proceedings of an American Ceramic Society Symposium, New York City, April 1962*), *NBS Mono. 59 (Mar. 25, 1963), $1.75.*

This Monograph represents the Proceedings of a Symposium on The Mechanical Behavior of Crystalline Solids, held under the auspices of the Ceramic Educational Council of the American Ceramic Society, with the cooperation of the National Bureau of Standards, and under the sponsorship of the Edward Orton Junior Ceramic Foundation, and the Office of Naval Research. The Symposium took place at the 64th Annual Meeting of the American Ceramic Society, in New York, on April 28 and 29, 1962.

Testing of metal volumetric standards, J. C. Hughes and B. C. Keysar, *NBS Mono. 62 (Apr. 1, 1963), 15 cents.*

The National Bureau of Standards has for many years calibrated and certified metal measures which are used as standards by weights and measures officials and others in the calibration of instruments for measuring the volumes of fluids. No complete specifications or tolerances for these standards have ever been published, however, nor have standardized procedures for the calibration and use of the liquid measures been available.

The information contained in this Monograph should assist in the purchase of quality instruments and the proper use of the standards in calibrating other measures for liquids and gases.

Reduction of data for piston gage pressure measurements, J. L. Cross, *NBS Mono. 65 (June 17, 1963), 15 cents.*

Pressure measurements made with piston gages are affected by gravity, temperature, pressure, and several other variables. For accurate determinations of pressure the calculations must take these variables into account. A general equation is developed and simplified procedures for calculating pressure are illustrated.

Tabulation of data on receiving tubes, C. P. Marsden and J. K. Moffitt, *NBS Handb. 83 (May 23, 1963), $1.25.* (*Supersedes Handb. 68.*)

A tabulation of Receiving-Type Electron Tubes with some characteristics of each type has been prepared in the form of two major listings, a Numerical Listing in which the tubes are arranged by type number, and a Characteristic Listing in which the tubes are arranged by tube type and further ordered on the basis of one or two important parameters. The tabulation is accompanied by a listing of similar tube types and basing connections for the listed tubes.

Transistorized building blocks for data instrumentation, R. L. Hill, *NBS Tech, Note 168 (Apr. 1, 1963), 55 cents.*

The National Bureau of Standards has developed a number of modular transistorized digital circuits that have been used in automatizing many data recording and preliminary processing tasks encountered in its scientific operations. These versitile building blocks can be connected together systematically to form digital circuits that accept raw data from experimental equipment and transpose these data into a form suitable for input to a high-speed electronic computer. Each assembly of packages can be tailored to fit the special requirements of the project and can be used at the site of the experiment. The output from the system can be: 1) fed directly to a computer, 2) recorded on a medium (paper tape, magnetic tape, etc.) suitable for computer input at a later date, or 3) used to drive display equipment that keeps the scientist informed of the progress of his experiment.

As a result of experience in the application of these units, some of the original packages have been modified and additional types developed. In addition to describing the modified and new package types, this report also includes a description of a new series of packages consisting of identical circuitry, but utilizing a different type of mating connector and a smaller circuit-board.

Phototypesetting of computer output, an example using tabular data, W. R. Bozman, *NBS Tech, Note 170 (June 25, 1963), 10 cents.*

A photocomposition machine controlled by the magnetic tape output from a computer was used to prepare a 559-page table of atomic transition probabilities at the National Bureau of Standards. This method makes possible the publication of computed data in high quality typography in a reasonable time and at a reasonable cost. Many styles of type are readily available to the programmer including Greek, italic, mathematical symbols, upper and lower case alphabets, etc.

Practical methods for calibration of potentiometers, D. Ramaley, *NBS Tech. Note 172 (Mar. 25, 1963), 30 cents.*

Potentiometer circuitry, particularly as related to calibration, is discussed with the primary consideration given to the required circuit measurements. The more feasible means of calibrating potentiometers are described in considerable detail. Emphasis is placed upon the use of the Universal Ratio Set as the basic implement for accomplishing the major portion of potentiometer calibrations.

Table of attenuation error as a function of vane-angle error for rotary vane attenuators, W. Larson, *NBS Tech. Note 177 (May 20, 1963), 75 cents.*

The table of attenuation error as a function of vane-angle error gives the error in decibels caused by vane misalinement which is common in the rotary vane attenuator. The attenuation errors corresponding to vane-angle errors ranging from zero to 0.499° (in increments of 0.001°) are presented for selected angles over the range of attenuation values from 0.01 to 70 db. The table is divided into the following intervals of attenuation value increments: 0.01–0.1 db in 0.01-db increments, 0.1–1.0 db in 0.1–db increments, 1–20 db in 1–db increments, and 20–70 db in 5–db increments.

With the aid of this table, the calibration data of a rotary vane attenuator can be analyzed for numerous characteristics, including the following: misalinement between rotor and stator sections, realinement techniques, resettability, and backlash.

Tabulation of published data on Soviet electron devices, C. P. Marsden, *NBS Tech. Note 186 (June 3, 1963), 45 cents.*
This tabulation includes published data on Soviet electron devices as collected from various publications, mostly handbooks published by the various ministries and institutes of the USSR. Information is given on all active devices ranging from receiving to microwave devices, semiconductor devices, and various miscellaneous devices such as, for example, photographic flash tubes and thermistors.

Calibration of volt-ampere converters, E. S. Williams, *NBS Tech. Note 188 (Apr. 25, 1963), 20 cents.*
These notes have been prepared to describe the National Bureau of Standards calibration services for volt-ampere converters (or transfer volt-ammeters), to suggest procedures for d-c standardization in the user's laboratory, and to describe a voltage comparator which can be used to make such calibrations quickly and easily.

Tables describing small-sample properties of the mean, median, standard deviation, and other statistics in sampling from various distributions, C. Eisenhart, L. S. Deming, and C. S. Martin, *NBS Tech. Note 191 (June 14, 1963), 20 cents.*
This note includes a collection of tables useful for study of the sampling distributions of some frequently-used statistics, with brief discussions of their construction and use. (1) The probability level $P(\epsilon,n)$ of any continuous parent distribution corresponding to level ϵ of the distribution of the median. (2) Probability points of certain sample statistics for samples from six distributions: normal and double-exponential (mean, median), rectangular (mean, median, midrange), Cauchy, Sech, Sech^2 (median). In all the above tables, the sample size $n=3(2)15(10)95$ and the probability levels are $\epsilon=.001$, .005, .01, .025, .05, .10, .20, .25. Together with the tables listed under (2) are given the values of certain ratios useful for comparing the various statistics. (3) Probability that the standard deviation of a normal distribution will be underestimated by the sample standard deviation s and by unbiased estimators of σ based on s, on the mean deviation, and on the sample range. Divisors are given for obtaining the corresponding "median unbiased" estimators.

National standard reference data program, background information, *NBS Tech. Note 194 (June 1963), 25 cents.*
Plans are proposed for a National Standard Reference Data System that will provide critically evaluated data in the physical sciences on a national basis. It will be conducted as a decentralized operation across the country, with central coordination and administration by NBS. Data will be centrally stored at NBS and disseminated through a series of services tailored to user needs in science and industry.

New absolute null method for the measurement of magnetic susceptibilities in weak low-frequency fields, C. T. Zahn, *Rev. Sci. Instr.* **34;** *No. 3, 285–291 (Mar. 1963).*
Use is made of the magnetic equivalence of a uniformly polarized volume of paramagnetic material and a solenoid carrying electric current, to design a permanent variable standard of magnetic susceptibility. Such a standard is incorporated into a magnetic susceptibility bridge in a simple manner, surrounding the specimen; and the bridge is thereby transformed into an absolute null instrument of high accuracy and sensitivity, and of great ease and low cost of construction and operation. By this method numerous particular advantages of other methods are combined; and some of their notable limitations are overcome. A preliminary application was made showing that the bridge performs as expected. Important features in the design of this bridge are discussed. A detailed consideration of sources of error suggests that it may eventually be possible by this method to obtain greater absolute accuracy than by other known methods.

A method for measuring the instability of resistance strain gages at elevated temperatures, R. L. Bloss and J. T. Trumbo, *ISA Trans.* **2;** *No. 2, 112–116 (Apr. 1963).*
The usefulness of resistance strain gages at elevated temperatures is frequently limited by the instability of gage resistance with time. Methods and equipment that have been developed to measure this effect are described.

Maximum efficiency of a two-arm waveguide junction, R. W. Beatty, *IEEE Trans. Microwave Theory and Tech.* **MTT-11,** *94 (Jan. 1963).*
Given the scattering coefficients of a 2-arm waveguide junction, an equation is presented to calculate Γ_M, the reflection coefficient of the load for which the efficiency of a 2-arm waveguide junction is η_M, the maximum efficiency. Once Γ_M has been calculated, an equation is given to determine η_M and the relationship between η_M and A_I, the intrinsic attenuation of the waveguide junction, is given.

Applications of a semiconductor-surface-state charge-storage device, L. J. Swartzendruber, *Solid-State Elec.* **6,** *59–61 (Pergamon Press, Inc., New York, N.Y. 1963).*
Several possible applications of a new two terminal semiconductor device which utilizes surface phenomena to produce a charge storage effect are described. The major advantage of the device lies in the magnitude of the charges which can be stored and the ease with which it can be controlled by small bias currents.

Audio-frequency compliances of prestressed quartz, fused silica, and aluminum, M. Greenspan and C. Tschiegg, *Proc. Fourth Intern. Congr. on Acoustics, Part I, Paper P12 (Copenhagen, Denmark, Aug. 21–28, 1962).*
An attempt was made to find the excess compliances associated with dispersions found by Fitzgerald. Compliances were obtained from resonant frequencies of fixed-free composite reeds. Prestress was either piezoelectrically or thermally induced. No excess compliances were observed.

Ten-kilocycle pound-type kylstron stabilizer, H. E. Radford, *Rev. Sci. Instr.* **34,** *No. 3, 304–305 (Mar. 1963).*
Through a simple circuit modification, commercial klystron frequency stabilizers of the FM type can be made to function alternatively as CW Pound-type stabilizers, with greater spectral purity of the klystron output. The performance of such a stabilizer is discussed.

Kihara parameters and second viral coefficients for cryogenic fluids and their mixtures, J. M. Prausnitz and A. L. Myers, *A. I. Ch. E. Journal* **9,** *No. 1, 5–11 (Jan. 1963).*
The volumetric properties of sixteen fluids of interest in cryogenic engineering have been used to calculate second viral coefficients over as large a temperature range as possible. These coefficients were then fitted to theoretical expressions based on the Kihara potential function. For helium, hydrogen, and neon quantum corrections were applied. For nitrogen, carbon dioxide, and acetylene corrections for quadrupole interactions were made. It was found that the theoretical expressions give an extremely good fit of all reliable experimental data. The theoretical expressions may therefore be used with confidence to predict volumetric behavior at very low temperatures where data are frequently unavailable.
With the aid of semiempirical mixing rules the theoretical expressions may be used to predict second viral coefficients for mixtures. Agreement with the very limited amount of experimental mixture data is satisfactory. Finally it is shown that calculations based on the Kihara potential may be employed to make useful predictions of phase equilibria such as the solubility of a solid in a compressed gas.

Transparent rigid mount for vacuum stopcock, M. M. Anderson, *Rev. Sci. Instr.* **34,** *No. 2, 178 (Feb. 1963).*
A transparent block of plastic, moulded around a glass stopcock, then drilled and tapped for mounting, reduces vacuum system breakage and allows visual inspection of the grease seal.

Design of low voltage electron guns, J. A. Simpson and C. E. Kuyatt, *Rev. Sci. Instr.* **34,** *No. 3, 265–268 (Mar. 1963).*
It is shown that by use of a multistage technique in which electrons are drawn from a cathode by a high potential and

decelerated to the required final energy, guns can be designed capable of forming beams in which the current is limited only by space charge in the beam itself. The design principles and procedures are given and illustrated by two examples of electron guns giving highly collimated beams and operating at energies of 30 and 500 eV. The measured currents obtained are somewhat greater than the space charge limited beam maximum because of ion neutralization.

Thermometry, !ow temperature, R. P. Hudson, *Encyclopaedic Dictionary of Physics* **7,** *323–325* (*1962*).
A discussion is given of apparatus and methods for thermometry in the range 1°–100°K in a style and brevity suited to an entry in a scientific encyclopaedia.

Effect of outdoor exposure on some properties of chrome-retanned leather, T. J. Carter, *J. Am. Leather Chemists Assoc.* **LVIII,** *No. 3, 155–160* (*Mar. 1963*).
Two groups of specimens of chrome-retanned leather were subjected to outdoor exposure and the changes in physical and chemical properties were determined. One group was subjected to all weather conditions while the other group was shielded from the sun. The effect of the exposure was determined by measurements of physical properties, such as flex tension and impact resistance, elongation, stitch tearing strength, tensile strength, change in area, relative stiffness, and shrinkage temperature, and of chemical properties, such as grease content and *p*H.
Results show that specimens shielded from the sun changed little in impact resistance, stitch tear strength, elongation of tensile strength specimens, and stiffness, but changed significantly in flex tension resistance, elongation (due to flexing), area, and shrinkage temperature. Specimens exposed to the sun showed deleterious changes in all the physical properties studied. Shrinkage temperature declined significantly under both conditions, the decrease being somewhat greater for specimens exposed to direct sunlight. The chemical properties, grease content and *p*H values, showed only slight changes under either condition of exposure.

APPA-TAPPI reference material program. II. Effectiveness of a reference material in reducing the between-laboratory variability of TAPPI standard T 414 m-49 for internal tearing resistance of paper, T. W. Lashof, *Tappi* **46,** *No. 3, 145–150* (*Mar. 1963*).
The effectiveness of a reference material was predicted on the basis of the results of the first round robin which was reported in Part I. The analysis was modified for the second round robin so as to provide corrections in terms of measurements on the reference material. If the current TAPPI procedure is followed (5 replications, no standard reference material), the total coefficient of variation, including both within- and between-laboratory variability, is about 4½ to 5%, as shown in both round robins. As shown in this second part, a standard reference material and increased replication may be used to reduce the total coefficient of variation to about 3%. It is also shown that the correction curve or nomograph based on the measurements on the reference material may be used for at least four to five months, provided that there are no changes in observer, instrument, or conditions.
The limitation to further reduction in the total coefficient of variation is $V(\lambda)$, the random interaction between interfering properties of the materials being tested and laboratory conditions or instrument peculiarities. It is shown that a portion of this is probably due to insufficient control of relative humidity. Since $V(\lambda)$ is higher for laboratories using new-type instruments than for those using old-type instruments, further work must be done to determine whether this is due to the instruments or to laboratory conditions.

Some characteristics of a simple cryopump, L. O. Mullen and R. B. Jacobs, *1962 Trans. Ninth Natl. Vacuum Symp., Am. Vacuum Soc., pp. 220–226* (*1962*).
A simple and easily definable cryopump was constructed as a stage in a pumping system, and data were obtained to permit the computation of pumping speeds, performance decay and capture coefficients. Information on the pumping of CO_2 and N_2 as well as outgassing vapors, by surfaces at 77°K and 20°K is presented. The pressure range of the tests is $5(10)^{-10}$ torr to $5(10)^{-3}$ torr and the gas flow range is 3.6×10^{-7} torr liters cm.$^{-2}$ sec.$^{-1}$ to $3.6(10)^{-2}$ torr liters cm.$^{-2}$ sec.$^{-1}$. Pumping speeds higher than those previously reported and higher than theory predicts were obtained, the results are discussed in detail.

Experimental investigation of Fabry-Perot interferometer, R. W. Zimmerer, *Proc. IEEE* **51,** *475-476* (*Mar. 1963*).
Preliminary measurements of the microwave performance of Fabry-Perot interferometers with spherical mirrors is presented and compared with theory. Of particular interest is the evidence of the stop band recently predicted by Boyd and Kogelnik.

The measurement of moisture boundary layers and leaf transpiration with a microwave refractometer, D. M. Gates, M. J. Vetter, and M. C. Thompson, Jr., Nature **197,** 1070–1072 (Mar. 16, 1963).
A microwave refractometer has been used as a hygrometer to measure the moisture gradient found near a free water surface and near the surface of a leaf. Interesting transpiration effects were observed for begonia and bean leaves when the leaves were stimulated with light. The instrument samples the air through a small orifice and thereby produces very little disturbance to the moisture boundary layer under investigation.

New scale of nuclidic masses and atomic weights, E. Wichers, *Nature* **194,** *No. 4829, 621–624* (*May 10, 1962*).
This is an article written at the request of the Editor of "NATURE."
It reviews the considerations that led to the adoption by the International Unions of Physics and Chemistry of a new scale of nuclidic masses and atomic weights based on $C^{12}=12$.

Calibration of photogrammetric lenses and cameras at the National Bureau of Standards, F. E. Washer, *Photogrammetric Eng.* **XXIX,** *No. 1, 113–119* (*Jan. 1963*).
A summary of calibrations performed at the National Bureau of Standards on lenses and cameras that are used in precise photogrammetric work is given. Brief description of the photographic and visual calibrations most frequently required are given. This paper includes a list of publications by members of the NBS staff that pertain to problems of lens and camera calibration.

Building a simple transistor tester, G. F. Montgomery, *Electronics* **36,** *No. 16, 56* (*Apr. 19, 1963*).
A simple instrument is described for measuring two dc transistor parameters: leakage current and common-emitter current amplification.

A magnetic amplifier for use with diode logic, E. W. Hogue, *Proc. IEEE 1963 Intern. Conf. Nonlinear Magnetics No. T-149, 8.6-1 to 8.6-6* (*Apr. 1963*).
A digital amplifier of simple noncritical design incorporating an emitter-follower and a small magnetic amplifier is described. Timing and some of the operating power are provided by a 300-kc 2-phase 7-volt sine-wave source. In structure and mode of operation, the amplifier is particularly suited for use with two-level diode gating to provide the AND and OR logical operations. A NOT-amplifier provides negation with amplification. The volt-second transfer characteristic of the stage critically determines the stability of propagation of binary signals. Factors governing the required shape of this transfer characteristic are discussed.

The speed of light, A. G. McNish, *IRE. Trans. Instr.* **I–11,** *Nos. 3 and 4, 138–148* (*Dec. 1962*).
Numerous measurements of the speed of light published during the last 30 years lead to widely divergent results as compared with the assigned experimental uncertainties. Because of wide diversity in the methods employed in the measurements, all of the data may not be combined effectively in a grand average. Sufficient data had been obtained by the geodimeter method to group them and derive a statistical estimate of the uncertainty in the speed of light by this method. This result, and conclusions reached from careful examination of several experiments, leads to the conclusion

that the value 299,792.5 km per sec which has been internationally adopted for use in radio propagation and geodetic work is very close to the best value and not likely to be in error by as much as one part in one million.

Performance characteristics of split-type residential air-to-air heat pumps, J. C. Davis and P. R. Achenbach, *Suppl. Bull. Inst. Intern. Refrigeration, p. 1–7 (1961–1962).*
This paper presents test results obtained during a laboratory study of six split-type residential air-to-air heat pumps, a type more widely used than others for residential application in the United States in the last few years. For residential use, these systems are currently selected to satisfy the cooling requirements of the house under design summer conditions, and, if necessary, the heating capacity of the compression-cycle is supplemented with electric resistance heaters. The investigation showed that the compression-cycle heating capacity of the heat pumps equipped with expansion valves increased linearly with increasing outdoor temperature at constant indoor temperature and humidity, whereas the capacity of the heat pumps equipped with capillary tubes also increased but tended toward constant values at higher temperatures. It was shown that the cooling capacity of the heat pumps decreased linearly with outdoor temperature, when indoor temperature and relative humidity were held constant. At constant outdoor temperatures, cooling capacity increased linearly either with increasing indoor temperature or indoor relative humidity. The changes in the latent and sensible fractions of the total cooling capacity caused by change in indoor relative humidity, and the effect of outdoor temperature on coefficient of performance under heating and cooling conditions, are also reported.

Millimeter wavelength resonant structures, R. W. Zimmerer, M. V. Anderson, G. L. Strine, and Y. Beers, *IEEE Trans. Microwave Theory Tech.* **MMT–11,** *142–149 (Mar. 1963).*
This paper discusses the construction of millimeter wave Fabry-Perot resonators, using both planar and spherical reflectors. It also discusses the equivalent circuits of planar reflectors and the method of obtaining efficient power transfer into the resonators.

A simple environmental chamber for rotating beam fatigue testing machines, J. A. Bennett, *Mater. Res. Std.* **3,** *No. 6, 480–482 (June 1963).*
A gas-tight sleeve, made from transparent plastic, permits fatigue testing under controlled atmosphere conditions. Tests of magnesium and aluminum alloys have shown that changes in humidity may change the fatigue strength by more than 10%.

Evidence regarding the mechanism of fatigue from studies of environmental effects, J. A. Bennett, *Acta Met.* **11,** *No. 7, 799–800 (July 1963).*
Fatigue tests of aluminum alloy specimens are being conducted under controlled humidity conditions. Results of tests in which the environment is changed during the test show that there is an initial period during which the humidity has no effect. This is interpreted to indicate that the deformation during that period is not localized.

Calorimetric calibration of the electrical energy measurement in an exploding wire experiment, D. H. Tsai and J. H. Park, *Exploding Wires* **2,** *27–107 (Plenum Press, Inc., New York, N.Y., 1962).*
A discussion is presented on the requirements and the methods for measuring the current and voltage during the transient discharge of a capacitor bank employed in an exploding wire experiment. A method is described for accurately calibrating the measured current, voltage, and electrical energy by comparing the calorimetric heating of a fixed resistance element with the electrical energy dissipated in the element. Results show that the accuracy of the energy measurement is about 1–2%

Oil baths for saturated standard cells, P. H. Lowrie, Jr., *ISA J.* **9,** *No. 12, 47–50 (Dec. 1962).*
The increasing use of saturated standard cells in industry has caused a growing need for information on equipment associated with their use. This paper discusses oil baths suitable for the close temperature control of these cells and describes the oil baths in use at NBS Boulder Laboratories. In these baths, the temperature is controlled by a modified on-off system that limits cyclic variations to less than ±0.001°C from the mean temperature. The mean does not change more than 0.002°C per day in an environment in which the ambient temperature may change by as much as 2°C during the day.

Performance of the barium fluoride film hygrometer element on radiosonde flights, F. E. Jones, *J. Geophys. Res.* **68,** *No. 9, 2735–2751 (May 1, 1963).*
Ten flights of the barium fluoride film electric hygrometer element in a modified radiosonde on the same train with a conventional ithium chloride element in an AN/AMT–11 radiosonde were made from the grounds of the National Bureau of Standards (Wash., D.C.) during the period January 16 through July 21 of 1961. The flights were intended to provide information on the performance of the barium fluoride element under conditions encountered in routine radiosonde flights and to provide information to be used in assessing the value of the element as a research tool.
The results for the flights verified results of laboratory tests in several areas. The element responded to changes in humidity over a range of indicated relative humidity, RH, of 1.5 to 100% in the temperature range 33.1 to −58.7° C, preflight room temperature calibrations indicated that the ten elements flown were typical, in this respect, of elements tested under laboratory conditions, exposure to high humidity and passage through precipitation had no apparent effect on the functioning of the element, the rapid response of the element and its ability to resolve fine humidity structure were demonstrated, indications of saturation or near-saturation were correlated with U.S. Weather Bureau surface observations of clouds and radar weather observations.
In several of the flights, a strong correlation exists between changes in indicated RH and ambient temperature lapse rates. A sharp drop in indicated RH within the first several hundred feet above the surface in at least five of the flights is possibly related to boundary layer phenomena at or near the surface. In two of the flights the element detected supersaturation with respect to ice.
Although the instability with time of the barium fluoride element, in its present state of development, precludes its use in routine radiosonde flights, the ten flights indicated the value of the element for experimental use and as a research tool.
In addition to the flights of the barium fluoride element, one flight was made of a lead iodide film hydrometer element.

Intererfence fringes with long path difference using He-Ne laser, T. Morokuma, K. F. Nefflen, T. R. Lawrence, and T. M. Klucher, *J. Opt. Soc. Am.* **53,** *No. 3, 394–395 (Mar. 1963).*
Interference fringes have been obtained in a Michelson interferometer with path length differences up to 9 meters using a helium neo laser as light source.

Hyrdogen retention system for pressure calibration of microphones in small couplers, W. Koidan, *J. Acoust, Soc. Am.* **35,** *No. 4, 614 (Apr. 1963).*
The pressure calibration of microphones using small hydrogen-filled couplers can be facilitated by connecting relatively large containers of hydrogen to the capillary tubes of the coupler and using additional capillary tubes to vent the large containers to the atmosphere.

Other NBS Publication

Journal of Research 67A (Phys. and Chem.), No. 4 (July–Aug. 1963), 70 cents.

Symmetry splitting of equivalent sites in oxide crystals and related mechanical effects. J. B. Wachtman, Jr., H. S. Peiser, and E. P. Levine.

Relaxation modes for trapped crystal point defects. A. D. Franklin.

A note on the galvanomagnetic and thermoelectric coefficients of tetragonal crystalline materials. W. C. Hernandez, Jr., and A. H. Kahn.

Photolytic behavior of silver iodide. G. Burley.

Correlation of muscovite sheet mica on the basis of color, apparent optic angle, and absorption spectrum. St. Ruthberg, M. W. Barnes, and R. H. Noyce.

Thermodynamic properties of magnesium oxide and beryllium oxide from 298 to 1,200 °K. A. C. Victor and T. B. Douglas.

Heat exchange in adiabatic calorimeters. E. D. West.

Preparation of anhydrous single crystals of rare-earth halides. N. H. Kiess.

A phase study of the system: oxalic acid/acetic acid/water; its significance in oxalic acid crystal growth. J. Strassburger and J. L. Torgesen.

Wavelength calibrations in the far infrared (30 to 1000 microns). K. N. Rao, R. V. de Vore, and E. K. Plyler.

On the fourth order Hamiltonian of an asymmetric rotor molecule of orthorhombic symmetry. Wm. B. Olson and H. C. Allen, Jr.

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