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## A RESISTOR FURNACE, WITH SOME PRELIMINARY RESULTS UP TO 2,000° C

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### ABSTRACT

A laboratory furnace, electrically heated with special oxide resistors, is described. The atmosphere within the furnace is oxidizing, and definite heating and cooling schedules can be maintained. Results are given of preliminary tests in which  $\text{ThO}_2$ ,  $\text{ZrO}_2$ ,  $\text{BeO}$ ,  $\text{CeO}_2$ ,  $\text{MgO}$ , and  $\text{Al}_2\text{O}_3$  were heated singly or in various combinations in the temperature range from 1,800° to 2,000° C.

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### I. INTRODUCTION

The attaining of temperatures above about 1,800° C, under conditions which can be controlled satisfactorily for the maturing of preformed shapes as practiced in the ceramic art, involves, generally speaking, a reducing atmosphere. This is true of the furnace developed by Arsem [1],<sup>1</sup> who used a graphite resistor, and of the high-frequency induction furnace [2] when graphite is used as the heating element. The electric arc also is available for high-temperature work, and reducing conditions can be avoided [3]. However, neither the electric arc, nor a source of heat such as the oxyhydrogen and oxyacetylene flames, has been adapted to the heating of preformed articles.

Research laboratories have long needed equipment in which investigations, such as phase-equilibria studies, could be carried above the 1,600° C, which is the approximate upper limit of platinum-rhodium wire-wound furnaces. Increasingly higher temperatures, at present approaching 1,800° C, are being used in the manufacture of special ceramics, and it is to be expected that furnaces producing from 1,800° to 2,000° C will soon find industrial application. Tungsten and molybdenum wire-wound furnaces [4] have been used in the

<sup>1</sup> Figures in brackets indicate the literature references at the end of this paper.

laboratory; but here again the furnace atmosphere must be free from oxygen, and the cost of the wire would make such an installation impracticable for industrial purposes.

It was to meet the need for a furnace in which specimens could be heated on a definite schedule, and in an oxidizing atmosphere, that the heating units described in this paper were developed. In this work the development of a unit based on principles which could be applied to industrial heating was kept in mind.

The idea of using electrically heated oxide resistors of the Nernst filament type is not new. Nernst [5] himself experimented with such resistors, but dropped the idea in favor of an iridium resistor for his laboratory. Also, small furnaces [6] heated with oxide resistors were used to "bake" the filaments then being made for the Nernst lamp.

In Harker's furnace [6] the resistor, in the form of a tube from 9 to 10 mm in diameter and 60 to 100 mm long, formed the wall of the heating chamber. It appears that difficulty was experienced in maintaining satisfactory contact between the resistor and the platinum lead-in wires, and also in obtaining a resistor sufficiently uniform and free from cracks to conduct the current satisfactorily. The cracks are caused by the large decrease in volume which takes place when the resistors become conducting for the first time and are heated to a temperature well above that at which they are heated preparatory to use. These and other shortcomings of the earlier furnaces were considered in the design of the furnace described in this paper.

## II. FURNACE DESIGN AND CONTROL

Many compositions and designs of heating units were experimented with, the object being to (a) obtain a resistor of sufficiently low electrical resistivity to become conducting, with the available maximum potential of about 700 volts, at an easily obtainable temperature; (b) have enough temperature drop from the resistor to the lead-in wires so that the metal would not melt; and (c) maintain good contact with the metal.

There was sufficient information in the literature [7] to permit the selection of promising compositions for experimentation. For the resistor of the type shown in figure 1, tests showed a mixture containing 85 percent of electrically fused  $\text{ThO}_2$  and 15 percent of  $\text{CeO}_2$  (composition 4, table 1 and fig. 2) to be satisfactory, but the use of  $\text{Y}_2\text{O}_3$  (compositions 21 and 22) instead of  $\text{CeO}_2$  reduced the resistivity materially (table 1). Also, the  $\text{ThO}_2$ - $\text{Y}_2\text{O}_3$  resistors became conducting at a much lower temperature, as shown by the curves in figure 2. Resistors having even a relatively low  $\text{ZrO}_2$  content, such as composition 12 (table 1), deformed when the furnace was heated above  $1,800^\circ$  to  $1,850^\circ$  C. For the contact blocks, it is desirable to have a composition of appreciably higher electrical conductivity than that of the resistor, and for this purpose a mixture containing 85 percent of  $\text{ZrO}_2$  and 15 percent of  $\text{Y}_2\text{O}_3$  was used. As figure 1 shows, the metal conductors, composed of 60 platinum-40 rhodium wire, were cast into the contact block so that the block would shrink against the metal and maintain contact.

The design of the furnace used for the preliminary tests is shown in figure 3. The choice of materials was governed by their melting points, by the eutectic temperature of any two materials in mutual contact, and by their electrical conductivity at high temperatures.

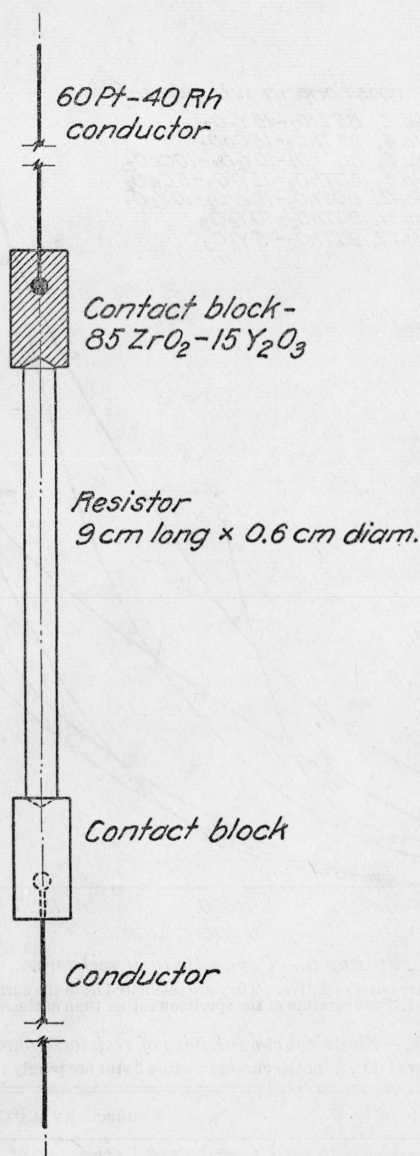


FIGURE 1.— Typical heating unit.

For example,  $ZrO_2$  is not used for the innermost parts because its conductivity might cause short circuits [8]. On the other hand, the  $ZrO_2$  is suitable for separating the  $ThO_2$  and  $Al_2O_3$ , this separation being necessary because  $ThO_2$  and  $Al_2O_3$  react at about  $1,900^\circ C$  to form a liquid of rather low viscosity.

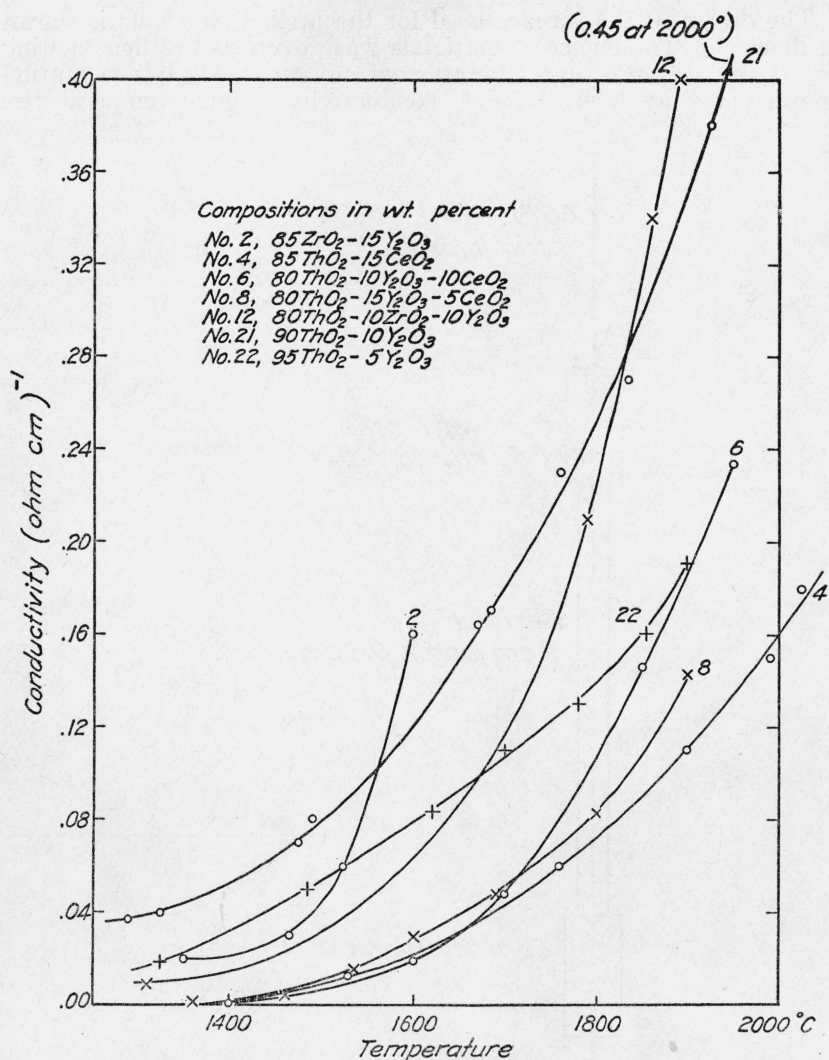


FIGURE 2.—Conductivity of resistors.

These conductivity values are purely relative. They are calculated from the current, the over-all resistance of a heating unit, and the temperature of the specimen rather than of the resistor itself.

TABLE 1.—Electrical conductivity of resistors (ohm cm)<sup>-1</sup>  
 [Values are taken from the curves in figure 2 and are purely relative]

Resistors		Conductivity at (°C)—							
No.	Composition (wt percent)	1,300°	1,400°	1,500°	1,600°	1,700°	1,800°	1,900°	2,000°
		Mho	Mho	Mho	Mho	Mho	Mho	Mho	Mho
2.....	85 ZrO <sub>3</sub> , 15 Y <sub>2</sub> O <sub>3</sub> .....		0.021	0.044	0.16				
4.....	85 ThO <sub>3</sub> , 15 CeO <sub>2</sub> .....		.001	.010	.024	0.043	0.074	0.11	0.16
6.....	80 ThO <sub>3</sub> , 10 Y <sub>2</sub> O <sub>3</sub> , 10 CeO <sub>2</sub> .....		.001	.006	.020	.050	.10	.19	
8.....	80 ThO <sub>3</sub> , 15 Y <sub>2</sub> O <sub>3</sub> , 5 CeO <sub>2</sub> .....		.003	.010	.030	.050	.085	.14	
12.....	80 ThO <sub>3</sub> , 10 ZrO <sub>3</sub> , 10 Y <sub>2</sub> O <sub>3</sub> .....	0.010	.014	.030	.064	.11	.23	.41	
21.....	90 ThO <sub>3</sub> , 10 Y <sub>2</sub> O <sub>3</sub> .....	.038	.050	.076	.12	.18	.25	.35	.45
22.....	95 ThO <sub>3</sub> , 5 Y <sub>2</sub> O <sub>3</sub> .....	.015	.030	.042	.078	.11	.14	.19	

\* Deforms.

The available data on the materials used for the resistors, and for the innermost parts of the furnace, are given in section III-2.

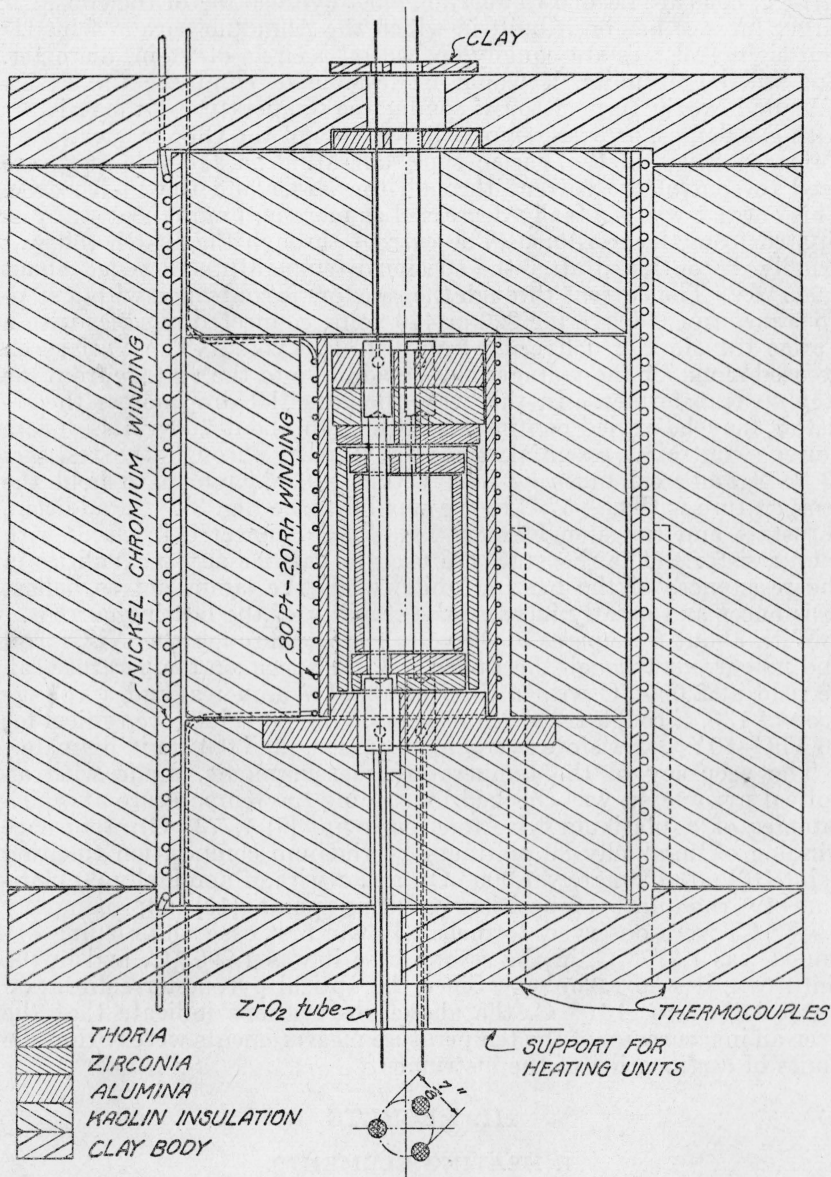


FIGURE 3.—Furnace.

In this furnace, the 80 platinum-20 rhodium coil is wound on an Alundum core 5 in. long and 2¼ in. ID. The three resistors are equally spaced on a circle of 7/8-in. diameter. Other dimensions may be scaled from the drawing.

For the furnace shown in figure 3, the 80 platinum-20 rhodium heating coil is wound on a 2½-in. ID Alundum core, and three resistors<sup>2</sup>

<sup>2</sup> In discussing the furnace, the metallic heating elements will be referred to as "coils," and the oxide resistors simply as "resistors."

are equally spaced on a circle of  $\frac{7}{8}$ -in. diameter. The thermocouples placed next to the platinum-rhodium (Pt-Rh) and nickel-chromium (Ni-Cr) coils are needed to guard against overheating of the coils. A larger furnace has been built in which the Alundum core is 4 in. ID and eight resistors are equally spaced on a circle of  $2\frac{1}{4}$ -in. diameter. For still larger units, it would be feasible to eliminate the Pt-Rh coil and heat the furnace to the conducting temperature of the resistors with gas flames, or with removable resistors of the Globalar type.

Transformers of the Variac type, operating on 110-volt lines, are used to control the current through the Ni-Cr and the Pt-Rh coils. This current was gradually decreased as more and more heat was dissipated from the resistors. The current through the Pt-Rh coil was usually discontinued after the specimen temperature exceeded about  $1,900^{\circ}\text{C}$ . The current through the resistors is controlled with a step-up transformer, delivering 220 or 440 volts, connected in series with a Variac transformer delivering from 0 to 270 volts. The Variac can be used alone, or the voltage may be additive to the voltage from the step-up transformer. In this way, the potential drop across the resistors may be varied continuously from 0 to about 700 volts. Close voltage control is essential, since the current through the resistors (3 to 8 amperes) must be held within  $\pm 0.05$  ampere to hold the temperature within  $\pm 5^{\circ}\text{C}$  in the small furnace (fig. 3). In addition, rheostats and tungsten filament lamps are connected in series with each resistor. The rheostats are used to balance any inequalities in the resistances of the heating units, while the lamps act as ballast resistances and greatly increase the stability of the heating current.

With about 6 amperes at 80 volts passing through the Ni-Cr coil and no current through the Pt-Rh coil, the specimen temperature can be held at  $2,000^{\circ}\text{C}$  with a total of about 7 amperes, and a voltage drop of 130, through the three resistors. These values are typical for  $90\text{ThO}_2\text{-}10\text{Y}_2\text{O}_3$  resistors averaging 9 cm long and 0.6 cm in diameter.

The accuracy of the temperature measurements, made with an optical pyrometer, was checked by reading the temperature at which samples of a platinum wire (melting point [9]  $1,773^{\circ}\text{C}$ ), a furnace winding of nominally 80 platinum-20 rhodium composition (melting point [10] approximately  $1,900^{\circ}\text{C}$ ), and a wire of nominally 60 platinum-40 rhodium composition (melting point [10] approximately  $1,945^{\circ}\text{C}$ ) were observed to melt. In the first case the reading obtained was  $1,777^{\circ}\text{C}$ , in the second case it was  $1,890^{\circ}\text{C}$ , and in the third case it was  $1,935^{\circ}\text{C}$ . Since the optical pyrometer calibration was certified to  $\pm 10^{\circ}\text{C}$ , the above observations indicate that the over-all inaccuracies of the temperature measurements were within the limits of certification of the instrument.

### III. RESULTS

#### 1. HEATING ELEMENTS

The conductivity values plotted in figure 2 and given in table 1 are relative and approximate only. They are calculated from the current and from the potential drop across the heating unit, including the resistor proper and the contact blocks. Also, the temperatures given in table 1 and plotted in figure 2 are those obtained by sighting the optical pyrometer on the specimen and therefore do not represent the temperatures of the resistors themselves. These temperatures

were, of necessity, higher. The observed conductance of a heating unit was invariably lower while heating than while cooling the furnace, showing that better contact had been established at the highest temperatures. The conductance was also lower for "new" resistors. For example, the current through new resistors of composition 21 (table 1) increased slowly at 1,450° C under 540 volts. After the resistors had been used previously in heating the furnace, the current started to flow through them at 960° C, and built up rapidly, at 540 volts, or at 1,050° C at 350 volts.

The data plotted in figure 2 were obtained with previously used resistors and during the cooling of the furnace.

## 2. MATERIALS AND EXPERIMENTAL MIXTURES

The materials described in this section were used in the construction of the furnace, and in the resistor units and experimental

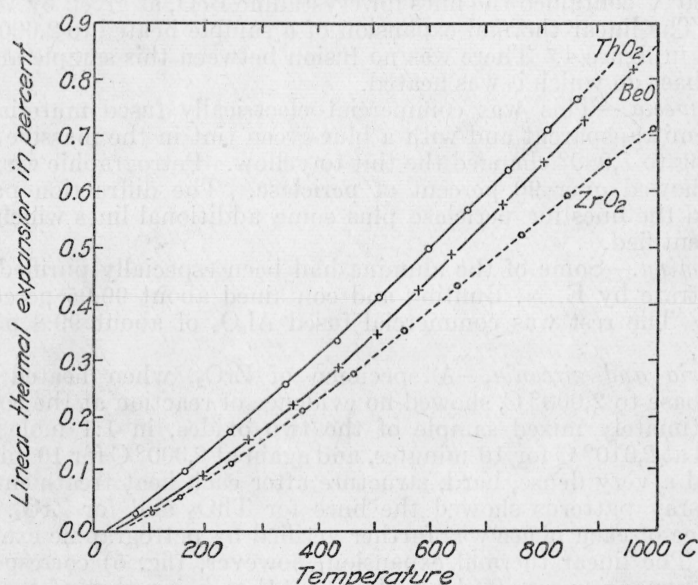


FIGURE 4.—Linear thermal-expansion curves.

These curves were obtained on specimens which had been heated at 2,000° C for 10 minutes. The determinations were made by A. S. Creamer.

mixtures. Most of the specimens were heated to determine the possibilities of the various oxide combinations for high-temperature work, and a few mixtures were tested as preliminary steps to future phase-equilibria studies.

*Thoria.*—This material was described by the producer as containing at least 99 percent of ThO<sub>2</sub>. It was used in preparing the resistors and furnace parts. A specimen, heated to 2,000° C, was nonporous, hard, and brittle. The linear thermal expansion is shown in figure 4, and the X-ray pattern was that of a face-centered cubic structure with  $a=5.57\text{\AA}$ .

*Zirconia.*—Material described by the producer as containing over 97 percent of ZrO<sub>2</sub> was used for the furnace parts, and material of over 99-percent purity was used for the contact blocks, experimental resistors, and body mixtures. Both had been electrically fused. The

X-ray pattern of a sample of  $ZrO_2$  heated to  $2,000^\circ C$  was too complex to analyze; its linear thermal expansion is shown in figure 4.

*Yttria.*—At best, this material should be considered as predominantly  $Y_2O_3$ . A spectrogram showed medium to strong lines for Dy, La, Nd, Sm, Sr, and Yb.

*Ceria.*—This oxide was obtained from several sources, but none of the samples was analyzed. An especially purified sample, prepared by C. J. Rodden, was heated at  $2,005^\circ C$  for 5 minutes in an iridium container. After this treatment, the color was a pale buff and it was found to have sintered. This behavior shows that the melting point is above  $2,000^\circ C$ , as shown by Wartenburg and Gurr [11], and that the value  $1,950^\circ C$ , given by Ruff [12], is low.

*Beryllia.*—This was commercial material, described by the producer as of high purity, containing approximately 0.003 percent of Fe and 0.004 percent of CaO. The X-ray pattern of a specimen heated to  $1,900^\circ C$  contained the lines for crystalline BeO, as given by Wyckoff [13]. The linear thermal expansion of a sample heated to  $2,000^\circ C$  is shown in figure 4. There was no fusion between this sample and the  $ThO_2$  base on which it was heated.

*Magnesia.*—This was commercial electrically fused material. It was semitransparent and with a blue-green tint in the massive form. Heating to  $1,980^\circ$  changed the tint to yellow. Petrographic examination showed over 90 percent of periclase. The diffraction pattern showed the lines for periclase plus some additional lines which were not identified.

*Alumina.*—Some of the alumina had been especially purified from the nitrate by E. N. Bunting and contained about 99.95 percent of  $Al_2O_3$ . The rest was commercial fused  $Al_2O_3$  of about 99.8 percent purity.

*Thoria and zirconia.*—A specimen of  $ZrO_2$ , when heated on a  $ThO_2$  base to  $2,000^\circ C$ , showed no evidence of reaction at the contact. An intimately mixed sample of the two oxides, in 1:1 mole ratio, heated at  $2,010^\circ C$  for 10 minutes, and again at  $2,000^\circ C$  for 10 minutes, showed a very dense, hard, structure after each heat treatment, and the X-ray patterns showed the lines for  $ThO_2$  and for  $ZrO_2$ . The presence of each phase was further verified by petrographic examination. The linear thermal expansion, however, (fig. 5) corresponded to the expansion reported by Merritt [14] as being that of the compound  $ThO_2 \cdot ZrO_2$ . The linear expansion of a specimen of the material originally reported on by Merritt was redetermined (fig. 5). Re-examination of this specimen by H. Insley showed the presence of  $ThO_2$  and of  $ZrO_2$  identically as found in the sample prepared in this study. The X-ray patterns do show that the unit cell of  $ThO_2$  had been decreased so that  $a=5.53$  A, indicating that the  $ThO_2$  had taken some  $ZrO_2$  in solid solution. The conclusion must be drawn that  $ThO_2$  and  $ZrO_2$  did not react to form a compound. This is in accord with the findings of Ruff, Ebert, and Weitinek [15].

*Thoria and alumina.*— $Al_2O_3$  of 99.95 percent purity, when heated at  $1,850^\circ C$  for 10 minutes in a  $ThO_2$  crucible, was unaffected. When heated at  $1,900^\circ C$  for 10 minutes, there was partial fusion. When heated at  $1,950^\circ C$ , a very fluid melt was formed. These data support the finding of Wartenburg and Reusch [16] of a eutectic melting at about  $1,900^\circ C$ .

*Thoria and magnesia.*—An intimate mixture in the mole ratio 40



$\text{ThO}_2$  to 60 MgO, heated in a magnesia crucible at  $2,010^\circ\text{C}$  for 10 minutes, showed sintering but no evidence of fusion. This indicates that the eutectic is above  $2,000^\circ\text{C}$ . The X-ray pattern contained the lines for periclase (MgO) and for crystalline thoria, with no change or shift from lines for either material heated alone. In the above experiment there was no reaction between the MgO crucible and the  $\text{ThO}_2$  base upon which it was placed.

*Zirconia and alumina.*—After heating at  $1,955^\circ$  for 5 minutes,  $\text{Al}_2\text{O}_3$  in a  $\text{ZrO}_2$  crucible had not reacted with the crucible. After

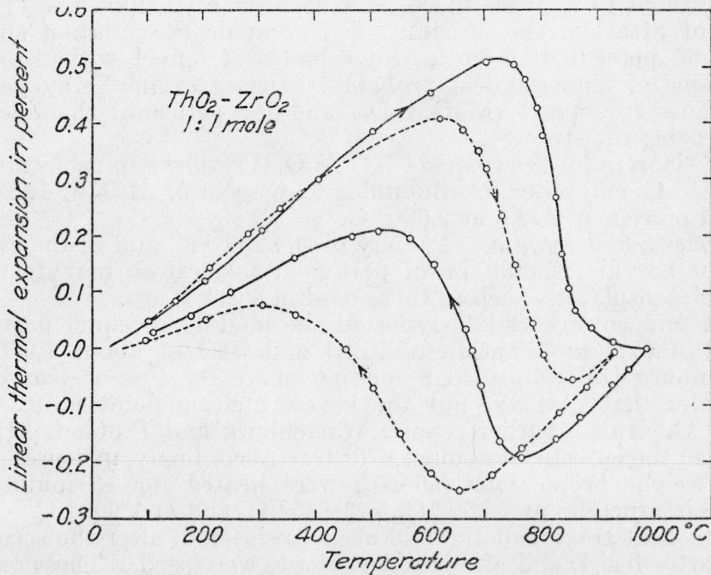


FIGURE 5.—Linear thermal-expansion curves.

The values connected with the continuous line were obtained on a specimen made of  $\text{ZrO}_2$  and  $\text{ThO}_2$  in 1:1 mole proportions and twice heated to approximately  $2,000^\circ\text{C}$  for 10 minutes. The values connected with the broken line were obtained on a sample originally reported on by Geo. E. Merritt (Trans. Am. Electrochem. Soc. 50, 165, 1926) and made by fusion at about  $3,500^\circ \pm 500^\circ\text{C}$ . (The determinations were made by A. S. Creamer.)

heating to  $1,990^\circ$ , it had reacted to form a vesicular mass. The X-ray pattern of this vesicular material gave only the lines for monoclinic  $\text{ZrO}_2$  with a slightly decreased unit cell, indicating solid solution of  $\text{Al}_2\text{O}_3$  in the  $\text{ZrO}_2$ . When, however, an intimate mixture, in equal mole ratio, of  $\text{ZrO}_2$  and  $\text{Al}_2\text{O}_3$  (99.9-percent purity) was heated in a  $\text{ZrO}_2$  crucible at  $1,940^\circ\text{C}$  for 15 minutes, a friable, highly vesicular mass was produced. The diffraction pattern showed strong lines for  $\text{ZrO}_2$ , and weak lines for alpha-corundum, with no shift in the lines for either phase. A eutectic at  $1,920^\circ\text{C}$  is reported by Wartenburg, Linde, and Jung [17] for approximately 1:1 mole proportions of  $\text{Al}_2\text{O}_3$  and  $\text{ZrO}_2$ .

*Zirconia and beryllia.*—There was marked attack on the  $\text{ZrO}_2$  crucible when BeO was heated in it at  $1,975^\circ\text{C}$  for 15 minutes. The X-ray pattern showed the lines for BeO and for  $\text{ZrO}_2$ , with no change or shift from the lines for either phase. Wartenburg and Gurr [11] show a eutectic temperature at about  $2,250^\circ\text{C}$  with 35 mole percent of  $\text{ZrO}_2$ . There was no fusion when shapes were heated in contact at  $1,925^\circ\text{C}$ .

*Beryllia and ceria.*—A mixture of 21 BeO-79 CeO<sub>2</sub>, in weight percent (1.83:1 mole ratio), heated at 1,985° C for 10 minutes showed incipient fusion. The diffraction pattern contained the lines for BeO, with no shift in position, and also lines which were not identified but were probably those of CeO<sub>2</sub>. This agrees fairly well with Wartenburg and coworkers [18], who report the above mixture as a simple eutectic melting at about 1,960° C.

*Magnesia and alumina.*—A mixture of spinel composition was heated in a MgO crucible at 1,980° for 20 minutes. The mixture had sintered to a dense, hard, and coarsely crystalline mass which had not attacked the crucible. Petrographic examination showed about 85 percent of large isotropic plates of spinel with isotropic inclusions of higher index, probably periclase. The X-ray pattern gave lines for spinel (MgO·Al<sub>2</sub>O<sub>3</sub>) and for periclase, the lines for spinel being the stronger.

The diagram for the system MgO-Al<sub>2</sub>O<sub>3</sub> [19] shows spinel as melting at 2,135° C, and eutectics containing 92 percent of Al<sub>2</sub>O<sub>3</sub> at 1,925° C, and 55 percent of Al<sub>2</sub>O<sub>3</sub> at 2,030° C.

*Magnesia and beryllia.*—A study of this system, and of the system alumina-beryllia, should be of particular interest to manufacturers of special insulators, such as those used in spark plugs.

Ruff and coworkers [20] reported the melting of equal parts, by weight (0.62:1 mole ratio), of MgO and BeO at about 1,960° C. Wartenburg [18] published a melting curve for this system which resembles that of Ruff, but the lowest melting point is at about 1,860° C. In an earlier report, Wartenburg and Prophet [21] had obtained the eutectic at about 1,670° C. Accordingly, mixtures in the same weight proportions (50-50), were heated for 15 minutes in magnesia crucibles at 1,800° C, at 1,845° C, and at 1,900° C. After the first heat treatment the mixture was sintered, after the second it was partly fused, and after the last it was well fused. These results, therefore, support the Wartenburg value of 1,860° C.

*Beryllia and alumina.*—The information published by Wartenburg [16] shows a fairly sharp eutectic at 1,890° C for a mixture of BeO and Al<sub>2</sub>O<sub>3</sub> in the 1:1 mole ratio. He points out that there was no evidence of the formation of chrysoberyl.

Mixtures in the mole ratio 1 BeO:1 Al<sub>2</sub>O<sub>3</sub> were heated in beryllia crucibles for 30 minutes at each of the following temperatures and with the results described:

1,800° C.—This sample was definitely porous. The X-ray pattern contained strong lines corresponding to those for chrysoberyl (BeO·Al<sub>2</sub>O<sub>3</sub>), and a weak line corresponding to the strongest line in the bromellite (BeO) pattern. The observed indices of refraction (1.732 minimum and 1.741 maximum) do not agree with those given for the mineral chrysoberyl ( $\alpha$ =1.747,  $\beta$ =1.748,  $\gamma$ =1.757 [22]), but the lines for chrysoberyl in the X-ray patterns are identical with those for the mineral obtained from the National Museum, through the courtesy of E. P. Henderson, from a deposit at Topsham, Maine. The indices of refraction of this mineral sample were  $\alpha$ =1.741,  $\gamma$ =1.751. The patterns for the prepared samples contained also several lines which do not correspond to those for  $\alpha$  or  $\beta$  Al<sub>2</sub>O<sub>3</sub>, or for BeO.

1,825° C.—The specimen was vitrified and was practically one phase, with indices of refraction ranging from 1.732 minimum to 1.741

maximum. The crystals were platy. There was no free BeO or  $\text{Al}_2\text{O}_3$  detectable with the microscope.

1,855° C.—This treatment produced uniform vitrification. The crystals were well developed, platy, and with indices ranging from 1.732 to 1.741. The X-ray pattern was identical with that for the sample heated at 1,800° C.

1,880° C.—The charge had fused to what must have been a liquid of low viscosity, since nearly all had been absorbed by the porous crucible. A few large, tabular crystals remained on the crucible bottom, and the diffraction pattern of chrysoberyl for these crystals was identical with the patterns for the samples heated at 1,800° C and at 1,855° C. The indices of refraction ranged between 1.732 and 1.741. The melting point of this chrysoberyl lies between 1,855° and 1,880° C. Weigel and Kaysser [23] report the melting point of sample of mineral chrysoberyl as  $1,817^\circ \pm 6^\circ \text{C}$ .

All of the X-ray diffraction patterns described in this paper were prepared and interpreted by H. F. McMurdie. The powdered samples were mounted on fine glass rods in the center of cylindrical cameras, having radii of about 5.7 cm, and were rotated during exposure to the  $\text{CuK}\alpha$  radiation.

#### IV. SUMMARY AND DISCUSSION

A furnace is described which is heated electrically with resistors of the Nernst filament type, supplemented with a Pt-Rh coil to bring the resistors to conducting temperature. The suitability of this furnace for laboratory tests involving oxidizing atmospheres, at temperatures above the upper limit of conventional "platinum-wound furnaces" (1,600° C), is considered to have been demonstrated. It is believed that heating units made on the same principles as those used in this work can be adapted also to larger furnaces, possibly in the commercial production of ceramic specialties. In larger furnaces, the heating coils could be replaced with gas flames, or with removable resistors of the Globar type.

The principal difficulty encountered in the operation of the furnace results from the "after-shrinkage" of the resistors, and of the  $\text{ThO}_2$  and the  $\text{ZrO}_2$  furnace parts. This shrinkage may cause deformation of the resistors, and almost invariably causes the progressive cracking of the furnace parts. It could probably be overcome by heating the shapes uniformly, prior to use, at a temperature appreciably higher than was possible in this work. The shapes and resistors used were cast, dried, and then given a preliminary heating at from 1,425° to 1,500° C.

$\text{Al}_2\text{O}_3$ , BeO,  $\text{CeO}_2$ , MgO,  $\text{ThO}_2$ , and  $\text{ZrO}_2$  were heated singly and in various combinations for periods of time ranging from 5 to 30 minutes, and at temperatures ranging from 1,800° to 2,000° C. The principal results, which are quite preliminary in nature, may be summarized as follows:

Shapes (a) of magnesia and of thoria, (b) of beryllia and of thoria, and (c) of zirconia and of thoria were heated in mutual contact at temperatures as high as 2,000° C without harmful effects.

No interaction occurred when (a) shapes of alumina and of thoria were heated in contact at 1,850° C, (b) shapes of alumina and of zirconia were heated under the same conditions at 1,900° C, (c) when shapes of beryllia and of zirconia were heated in contact at 1,925° C,

and (d) when shapes of magnesia and of beryllia, and of alumina and of beryllia, were heated in contact at 1,800° C and at 1,825° C, respectively. Considerable fusion did occur when the combinations in question were heated at temperatures approximately 50° C above those mentioned.

When an intimate mixture of zirconia and thoria in equimolecular ratio was heated at approximately 2,000° C, the product had an anomalous thermal expansion, showing a large reversal between approximately 500° and 1,000° C during both heating and cooling. This is in sharp contrast to the regular expansion of either thoria or zirconia after having been heated alone to 2,000° C, and cannot be explained by the formation of a compound since the X-ray patterns and petrographic examination show only the presence of the original oxides.

When an intimate mixture of magnesia and alumina in 1:1 mole ratio was heated at 1,980° C, the principal product was spinel.

When intimate mixtures of beryllia and alumina in 1:1 mole ratio were heated at from 1,800° to 1,880° C, the principal product, as shown by diffraction patterns, was chrysoberyl. This compound fused between 1,855° and 1,880° C.

## V. REFERENCES

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