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THERMOELECTRIC MATERIALS

Final Report

Contract No. NObz 78326

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THERMOELECTRIC MATERIALS

FINAL REPORT

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Titanium Alloy Manufacturing Division
Niagara Falls, N. Y.**

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ABSTRACT

Three hundred twenty-three oxide, silicate, and metal hydride combinations were prepared and fabricated into test specimens by a variety of forming and firing techniques. Of these combinations, 309 were examined electrically for Seebeck effect and resistivity from 600 to 1200°C; the remaining few failed in test.

Amongst electronic semiconductors were the following n-type examples. Titanium dioxide plus 2.0^{mol}% Nb₂O₅ exhibited a Seebeck coefficient of -400 μV/°C and resistivity of 0.1 ohm-cm over the entire temperature range of test. Barium titanate plus 0.5^{mol}% Nb₂O₅ had a Seebeck coefficient of -1700 μV/°C at 750°C increasing in magnitude to -3000 μV/°C at 1225°C; the resistivity of this composition is unknown but is certainly greater than 5 ohm-cm. No p-type electronic semiconductor with consistent carrier type over the entire temperature range of test was developed.

Positive Seebeck coefficients of considerable magnitude were developed in ionic conductors; ZrO₂-7^{mol}% Y₂O₃ solid solution plus 10^{mol}% Nb₂O₅ exhibited a Seebeck coefficient of +1000 μV/°C at 800°C rising to +1600 μV/°C at 1100°C. The electrical resistivity of this composition was also greater than 5 ohm-cm. In general, most oxide semiconductors examined were found to be ionic conductors; Li₂TiO₃ was the singular example of such a material.

None of the compositions tested gave indication of truly efficient conversion of heat to electricity; the above TiO₂ plus 2.0^{mol}% Nb₂O₅ had an approximate figure of merit of $7.0 \times 10^{-5}/^{\circ}\text{C}$.

INTRODUCTION

This final report describes work performed during the period Jan. 1960 to Aug. 1963 under Contract No. NObs 78326 (Index Nos. SR-010024-1BR and SR-007-12-01). The Contract Administrator was Mr. B. B. Rosenbaum, Code 342B, Bureau of Ships, Department of The Navy.

The ultimate objective of this work was the direct conversion of thermal to electrical energy using the Seebeck effect. This method of energy conversion is of interest to the Bureau of Ships for silent, maintenance-free ship-board and remote surface installations. Materials for this thermoelectric conversion were desired for operation in the temperature range from atmospheric ambient to approximately 1700°C. The work reported herein, however, was limited to certain more immediate goals. Only polycrystalline ceramic materials were investigated and the investigation itself was of a preliminary nature. Further development work was to be undertaken only if warranted.

The specific material nature of this work had its origin in a Research Proposal submitted by this laboratory to the Bureau of Ships on 1 May 1959. The examination of materials was limited to a broad, screening type evaluation, which was more extensive than intensive. The approach to the problem was as follows. For the temperature range of interest, 700°C to 1300°C, the most favorable materials were considered to be those refractory oxides and silicates which exhibit the property of, or potentiality for, semi conduction. For simplicity, foreign atom metal oxide "doping" was employed to effect semi-conduction by the "controlled valency effect". Fabricated materials were then screened by electrical measurements; resistivity and Seebeck Coefficient were measured as a continuous function of temperature from 600°C to 1250°C. As a preliminary criterion of usefulness, the square of the Seebeck coefficient divided by the electrical resistivity was used to decide if the thermal conductivity should be determined. If the latter was warranted, the thermoelectric efficiency was calculated; this needed doing for only one material.

The work covered by this report was under the general supervision of Dr. Stephen F. Urban, Director of Research. Material preparation, under the guidance of William J. Baldwin, Chief Ceramist, was done by Robert Peters, Jerrald L. Bliton, Harold Olander, Eugene J. Derefinko, Mrs. J. Cologgi, Chester Winiarski, and Joseph A. Vilardo. The design and construction of electrical measuring equipment and the actual measurements and calculations, under the guidance of Ernest G. Graf, Chief Physicist, were carried out by Truman C. Rutt, Anthony D. Janulionis, Eugene J. Derefinko, Joseph J. Goslin, and Joseph A. Vilardo.

Robert Peters wrote the portion of this report that covers material preparation and fabrication, Eugene J. Derefinko wrote the portion that deals with electrical instrumentation and measurement; they also prepared the tabulations and illustrations.

SUMMARY

Certain specific results of this work are collected below under "Conclusions"; the most noteworthy of these are presented in accompanying illustrations. The total remaining results are given in an Appendix of three tables. The "Conclusions" are drawn from observations on approximately 20 compositions; interpretation is confined to the few principles known to apply to the type of materials under investigation. The "Recommendations" following, are prognosticative in nature but very practical in origin.

A satisfactory oxide ceramic composition for efficient conversion of heat to electricity did not evolve from the present work.

Conclusions

Titanium dioxide, when modified by addition of from 1.0 to 5.0^m/o Nb₂O₅ and Ta₂O₅, is a moderate n-type thermoelectric having a Seebeck coefficient of -400 μv/°C from 600 to 1200°C. The Nb₂O₅ additions have an electrical resistivity of approximately 0.1 ohm-cm while that of the Ta₂O₅ additions is about 0.5 ohm-cm. TiO₂ + 2.0^m/o Nb₂O₅ has an approximate figure of merit of $7.0 \times 10^{-5}/^{\circ}\text{C}$.

Niobium pentoxide appears to be a universal dope for conversion of oxide ceramics to thermoelectric semiconductors. In addition to TiO₂, there are CeO₂ + 4.0^m/o Nb₂O₅ exhibiting -500 μv/°C and 1.5 ohm-cm, and BaTiO₃ + 0.5^m/o Nb₂O₅ exhibiting -1700 to -3000 μv/°C and resistivity greater than 5 ohm-cm. Amongst materials having a positive Seebeck coefficient, 10.0^m/o Nb₂O₅ added to ZrO₂ - 7^m/o Y₂O₃ solid solution effects an ionic p-type thermoelectric exhibiting +1000 to +1600 μv/°C and resistivity greater than 5 ohm-cm.

Oxide ceramic thermoelectrics tend to be ionic conductors, particularly those with positive Seebeck coefficients. In addition to the ZrO₂-based compositions as mentioned above, Li₂TiO₃ with additions of oxides of a wide range of oxidation states appear, with one exception, to be ionic conductors. From 900 to 1200°C Li₂TiO₃ + 5.0^m/o CeO₂ has an average Seebeck coefficient of +1400 μv/°C and an average resistivity of 25 ohm-cm. The orthochromites of lanthanum and yttrium are also ionic with +500 to +1100 μv/°C Seebeck coefficient and resistivities down to 1 to 2 ohm-cm.

High temperature p-type electronic semiconductors are extremely difficult to achieve using oxide ceramic materials. All such compositions prepared by controlled-valency doping become intrinsic at high temperature. On the other hand, titanium-containing high dielectric constant insulators are readily converted to n-type electronic semiconductors with appreciable negative Seebeck coefficients; the Nb₂O₅-doped BaTiO₃ above is the prime example.

Structurally, the most favorable materials investigated were based on a face-centered cubic array of oxygen atoms with metallic ions distributed in the interstices. These metallic ions were, in part, of the transition metals and octahedrally surrounded by six oxygen atoms.

Recommendations

Extensive examination of Nb_2O_5 and the niobates should be undertaken to determine if Nb_2O_5 has an even broader use in producing thermoelectric effects in oxide ceramics and to determine if other niobates than those of lead are convertible into thermoelectrics.

High dielectric constant insulators, including titanates, should be tested for thermoelectric effects. Experience indicates that when such materials are converted to semiconductors by doping, the electrical resistivity decreases with increasing temperature. Since the Seebeck coefficient, at least for doped BaTiO_3 , increases in magnitude with increasing temperature, such materials may be susceptible to further modification to take advantage of both a large Seebeck coefficient and the increased number of carriers which are freed at high temperature. Cadmium niobate is suggested as an example.

An investigation should be initiated of refractory oxides for the development of p-type electronic semiconductors which do not become intrinsic at high temperatures. Co-valent oxides which have properties similar to some of those of SiO_2 should be given first consideration and ionic compounds avoided absolutely.

Separate from thermoelectric phenomena, some of the ionic semiconductors observed in this work should be investigated for use as high temperature solid electrolytes. Li_2TiO_3 is strongly recommended for such consideration and LaCrO_3 and YCrO_3 are also suggested.

PREPARATION OF MATERIALS

The raw materials for this work, from some of which further compounds and solid solutions were prepared, are listed in Table I; the compound, purity, and source are given. These materials, which include both base materials and "dopants", were used in two ways; as base materials to which "dopants" were added, and to synthesize other compounds to which "dopants" were then added. The compounds and solid solutions prepared are listed in Table II. For each preparation, the reactants and conditions of synthesis are given. Additions to base materials were of two orders of magnitude. In a few cases major additions were made; these actually resulted in binary system phases. Minor additions were made in most cases and these were limited to several mol percent of "dopant".

For additions to the base materials, a Standard Series of Additions of dopant was chosen as 0.1, 0.2, 0.5, 1.0, 2.0, 5.0 mol percent. This range of concentrations was selected because it covers the apparent pertinent range of doping for oxides to produce semi-conduction by the controlled valency effect. The increment relation was selected because it is approximately equi-spaced linearly through two decades of the base-10 logarithm scale. When results from an entire Standard Series indicated that other dope levels might produce better thermoelectric effects, then intermediate additions of 3.0 and 4.0 mol percent or extended additions of 4.0, 7.0, and 10.0 mol per cent were prepared.

The uniform procedure devised for preparation of all Standard Series of

Additions was as follows. All materials were weighed on balances sensitive relative to the amount being weighed. The addition for each member of the Series was pre-mixed with a small amount of the base material in a Spex Mixer/Mill for 3 minutes. This pre-mix and the remainder of the base material were then wet blended using water in a laboratory ball mill for one-half hour. The mill discharge was dried at 350°F for 16 hours and then passed through a laboratory Mikropulverizer. For those systems requiring calcination prior to fabrication, the calcination was followed by wet ball-milling to -325 mesh.

FABRICATION OF SHAPES

A Standard Ceramic Body was designed as the test shape for electrical properties. It was desired that this final sintered shape be a right parallelepiped having approximate dimensions of $\frac{1}{4}$ " thickness, $\frac{1}{2}$ " width, and $2\frac{1}{2}$ " length. Thus the ratio of thickness to width to length was 1 to 2 to 10. These shape and dimension conditions were chosen in order to meet requirements for determination of electrical resistivity by the 4-point probe method when all four points of contact are co-planar. To effect this shape, an opposing double-plunger die was designed such that the dimensions of the green body were $2\frac{3}{4}$ " by $\frac{7}{10}$ " and of variable thickness depending on the particular material. The female die recess was sufficiently deep to accommodate the necessary amount of material, regardless of density, to insure $\frac{1}{4}$ " sintered thickness. This entire assembly was mounted on a Blackhawk Porto-Power Press provided with double acting 20 ton hydraulic rams.

The final compositions, as -325 mesh powders, were prepared for forming by the addition of a binder; 5^w/o of a solution of 5^w/o polyvinyl alcohol in water was used. The powders were loaded into the die and the green bodies were formed by double action at 10,000 psi for 5 seconds. The green bodies were sintered, under their respective varying conditions, in three different kilns. A muffle-type Harper electric kiln with SiC heating elements was used for sinterings up to 2600°F. For temperatures between 2600°F and 3150°F, a gas-fired, down-draft kiln constructed in this laboratory was employed. For those compositions containing metal hydrides, an especially constructed Harper electric kiln with molybdenum elements and atmospheric control of both element and specimen chambers was used to de-hydrate the oxide-hydride composites. Insofar as it was possible, optimum conditions of sintering were determined experimentally for each composition. The actual conditions of sintering of each composition are given in the tabulations described below.

The sintered Standard Ceramic Body was electroded at each end of one of the lateral surfaces. This was to insure electrical contact between the material and the external current leads for resistance measurements by the 4-point method. Hanovia No. 6082 platinum paste was applied with a small screed and fired-on by heating to 1500°F with a $\frac{1}{2}$ hour hold time.

EQUIPMENT AND TECHNIQUE OF MEASUREMENT

Ceramic Properties

All ceramic properties were determined from the various weighings, described below, of the Standard Ceramic Body. All weighings were made on a Mettler Type H-15 single pan, precision analytical balance. Distilled water was used as the weighing and saturation media; to insure saturation, all specimens were boiled in water for 2 hours. Each Standard Ceramic Body was weighed dry, saturated, and then suspended. From these weighings were determined absorption, apparent density, bulk density, and porosity; only the latter two characteristics are reported as being the most important. The bulk density was obtained as the quotient of dry weight by the difference between saturated weight and suspended weight. The porosity was obtained from the difference between saturated and dry weights divided by the difference between saturated and suspended weights.

Electrical Properties

Measurement of electrical properties, as a function of temperature to 1250°C, was accomplished with a somewhat elaborate complex of equipment. A horizontal tube furnace, with a Kanthal REH 10-30 1800 watt heating element, was constructed to provide the high temperature environment. The heating element contained a 4" OD zircon tube of $\frac{1}{4}$ " wall thickness as a liner; a hot zone of approximately 6" length was obtained within the liner.

A double, parallel position specimen holder of rectangular channel shape, 2" long and $\frac{1}{2}$ " inside width, was fabricated of insulating alumina impregnated with alumina cement. A specimen-contact thermocouple (Pt-Pt 10% Rh) was provided at each end of the bottom of each channel, with a non-contact thermocouple (Pt-Pt 10% Rh) in a well adjacent to the "cold" end contact thermocouple. Four point contacts (Pt), linearly spaced $\frac{1}{2}$ " apart, were provided in an alumina block which fit inside the channel and rested on top of the specimen. These contacts were for the current leads and "floating voltage" probes.

1. Auxiliary Equipment

Figure I is a schematic diagram of the circuitry for control, switching, and timing of all measurement instrumentation. The timer is set for a period long enough to encompass both the heating and cooling cycles of the furnace, 25°C to 1250°C to 600°C, and the timer contacts closed. This furnishes power to the amplifier and the recorder and closes Relay No.3. Relay No.1 is then activated by mechanical pushbutton, turning on the power to the furnace and the Wheelco furnace control. The furnace control then turns on, completing the circuit for the coil of Relay No.1 and also Relay No.2. When Relay No.2 is activated (heating cycle), the circuit for the Automatic Resistance Range Switching Operation (ARRSO) is completed and resistance measurements are made. When the furnace reaches temperature (1250°C), the Wheelco furnace control breaks the circuit for Relays Nos. 1 and 2 shutting off the furnace and Wheelco Control, thus starting the cooling cycle. In the deactivated position Relay No.2 shuts off the power to the ARRSO and furnishes power to the relays of the Automatic Seebeck Coefficient Measuring Apparatus (ASCMA). At the completion of the

cooling cycle the timer opens the timer contacts, S_1 , shutting off the power to the timer motor, amplifier, recorder, and Relay No.3. In the deactivated position, Relay No.3 breaks the power to the ASCMA. Relay No.3 also acts as a fail-safe device in that should the AC power to the recorder fail, the DC power to the ARRSO and ASCMA will be shut off, thus preventing the intermittent duty type relays from burning out if the recorder stops in a position operating the relays.

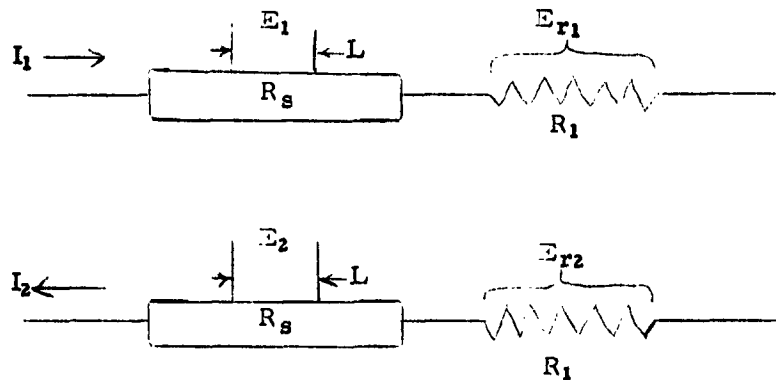
2. Resistance Measurement; Automatic Resistance Range Switching Operation

Figure II is a schematic diagram of circuitry for the measurement of electrical resistance; the operation is as follows: At recorder points 5 and 6 the recorder closes S_2 operating Relays Nos. 1, 2 and 3. Relay No.1 is a SPST relay connecting the power supply output from R_9 through Relays Nos. 2 and 3 to the specimen current probes. Relay No.2 is a 4PDT latching relay which reverses the polarity of the current to the specimen upon activation. Relay No.3 is a 4PDT relay which, in the activated position on recorder points 5 and 6, connects the current supply to sample 1 and connects the top voltage probes of sample 1, through the reversing Relay No.2, to recorder point 5. In the deactivated position Relay No.2 connects the top voltage probes of sample 2, through reversing Relay No.2, to recorder point 11 and connects the current supply to sample 2. During the 10 sec. print interval of recorder point 5, the following takes place: If the voltage across the specimen is greater than 20 mv, S_3 on the recorder is activated; if S_3 remains closed for longer than the one second time delay afforded by R_1 and C_1 of Relay No.4, Relay No.4 closes and remains closed (due to a holding circuit) shorting out the top voltage probes and precision resistors R_7 , R_8 , R_9 . Thus under the conditions where the specimen has a resistivity of 5 ohm-cm or greater, recorder points 5 and 6 print zero. If, on the other hand, when recorder point 5 comes into print position and S_2 is activated and the drop across the top probes is between 2 mv and 20 mv, then no switches are activated and recorder point 5 records the "floating" voltage representative of true resistance and recorder point 6 records the voltage across the known resistance $R_7+R_8+R_9$,

If the drop across the top voltage probes is less than 2 mv, switch S_4 is activated; if S_4 is closed for one second, Relay No.5 is closed which switches out dropping resistor R_4 and precision resistor R_7 . If this increase in current is sufficient to drive the recorder above 2 mv, recorder point 5 prints the top probe voltage as before, and recorder point 6 prints the voltage drop across the known resistance R_8+R_9 . If the recorder still remains below 2 mv, Relay No.6 activates one second after Relay No.5, switching out dropping resistor R_6 and precision resistor R_8 . Then recorder Point 5 prints the top probe voltage and recorder point 6 prints the voltage drop across precision resistor R_9 . Thus there are three approximate current ranges of 2 ma, 15, ma, and 100 ma corresponding to range resistors ($R_7+R_8+R_9$), (R_8+R_9), and R_9 respectively. Now since the top probe voltage and voltage across the appropriate range resistor are known, the exact current can be computed; from the voltage drop, the exact current, and sample dimensions, the resistivity can be computed.

A similar process occurs for recorder point 11 and 12 except that Relays Nos. 2 and 3 are not activated when S_1 is operated for points 11 and 12. Since Relay No. 2 is activated in alternate recorder cycles, the polarity of the current and the consequent polarity of the top voltage probes is reversed for every other recording. Hence it is possible to cancel the Seebeck effect on the resistivity by averaging two successive recordings of the top voltage probes. The time delay circuits are necessary to allow the recorder time to balance in range before switching occurs.

Calculation of resistivity: Consider any given Standard Ceramic Body undergoing two successive measurements, with the indicated current reversal:



Assume that the Seebeck voltage E_s and the sample resistance R_s remain constant for two successive recorder prints of the top probe voltages E_1 and E_2 and of the voltages E_{r1} and E_{r2} across the precision resistors R_1 and R_2 ; then

$$E_1 = I_1 R_s + E_s \text{ and } E_2 = I_2 R_s - E_s$$

adding: $E_1 + E_2 = R_s (I_1 + I_2)$

but $I_1 = \frac{E_{r1}}{R_1} \text{ and } I_2 = \frac{E_{r2}}{R_2}$

substituting $R_s = \frac{(E_1 + E_2) (R_1 R_2)}{E_{r1} R_2 + E_{r2} R_1}$

Under most conditions the Seebeck voltage is not large enough to cause a switching of ranges so $R_1 = R_2$ and $E_{r1} \approx E_{r2}$. Hence the equation for sample resistance becomes

$$R_s = \frac{(E_1 + E_2)}{2 E_{r1}} R_1$$

Knowing the resistance R_s for any given sample, the cross sectional area A , and the distance L between the top voltage probes, the resistivity is

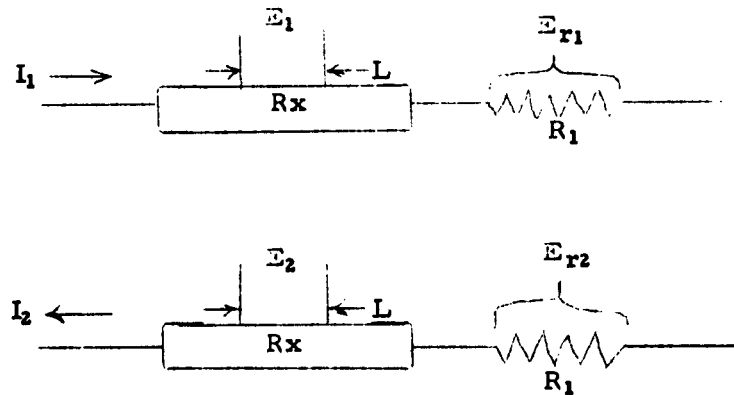
$$P_s = \frac{R_s A}{L}$$

$$\text{or } P_s = \left[\frac{(\mathcal{E}_1 + \mathcal{E}_2) (R_1 R_2)}{\mathcal{E}_{r1} R_2 + \mathcal{E}_{r2} R_1} \right] \left[\frac{A}{L} \right]$$

$$\text{or } P_s = \left[\frac{\mathcal{E}_1 + \mathcal{E}_2}{2} \right] \left[\frac{R_1}{\mathcal{E}_{r1}} \right] \left[\frac{A}{L} \right]$$

3. Resistance Measurement; Manual Operation

Certain Standard Ceramic Bodies with large Seebeck Coefficients, had resistivities greater than the 5 ohm-cm limit of the ARRSO; the resistance of these specimens were measured manually. The 4-point probe method was employed with the same sample holder and contacts designed for the ARRSO. Four $1\frac{1}{2}$ volt dry cell batteries connected in series furnished the current supply. The measured "floating voltage" was read from a Leeds and Northrup K-2 Potentiometer using a galvanometer to indicate balance. The specimen temperature was read from a Leeds and Northrup portable potentiometer indicator. Figure III shows the circuitry and apparatus used to switch the voltage and current connections from one sample to the other. This switch-gear was also used to reverse the current through the specimen so that the effect of the Seebeck voltage could be eliminated. The resistance was obtained from the voltage drop across the specimen, \mathcal{E}_1 , and the voltage drop, \mathcal{E}_{r1} , across the known resistor R_1 . Then the current was reversed and \mathcal{E}_2 and \mathcal{E}_{r2} were obtained. The resistance was calculated as follows:



If R_x = resistance of specimen, and

R_1 = resistance of known resistor, then

$$\frac{\mathcal{E}_1 + \mathcal{E}_2}{R_x} = I_1 + I_2$$

$$\text{and } \frac{\mathcal{E}_{r1} + \mathcal{E}_{r2}}{R_1} = I_1 + I_2 ;$$

equating the left-hand-side of these gives

$$R_x = \frac{(\mathcal{E}_1 + \mathcal{E}_2) R_1}{(\mathcal{E}_{r1} + \mathcal{E}_{r2})}$$

$$\text{and } p = R_x \frac{A \text{ (cross section)}}{L \text{ (probe gauge-length)}}$$

For each set of data, the furnace was allowed to stabilize at temperature so that \mathcal{E}_1 and \mathcal{E}_2 were obtained at the same temperature. A specimen-contact thermocouple, shown in Figure III, was used to obtain the temperature of measurement.

4. Seebeck Coefficient Measurement

Figure IV is a schematic diagram of the Automatic Seebeck Coefficient Measuring Apparatus. The temperature, Seebeck voltage, and temperature gradient producing the Seebeck voltage in the two specimens are all recorded with the Leeds and Northrup Speedomax Type G Recording Potentiometer. The recorder prints at 10 sec. intervals and measures 20 mv. full scale.

For sample 1 the temperature is printed at recorder point 1 from the thermocouple not in contact with the sample. Point 2 prints the Seebeck voltage with respect to platinum from the platinum leads of the two thermocouples in contact with the specimen. The Seebeck voltage is fed to the recorder in series with an external +10.0 mv from a Leeds and Northrup potentiometer indicator. This +10.0 mv. effects a center scale zero on the recorder, the recorder then prints both the sign and magnitude of the Seebeck voltage indicating p- and/or n-type semiconduction. At recorder points 3 and 4 Relay No. 1 is energized connecting the thermocouples from sample 1 to Relays Nos. 2 and 3. At recorder point 3 Relay No. 2 is energized connecting the non-contact, or coldest, thermocouple in differential with the cold zone contact thermocouple; this differential output is amplified 100 X and printed. At recorder point 4 the non-contact thermocouple is connected in differential with the hot-zone contact thermocouple; this output is also amplified 100 x and printed. A similar process takes place at recorder points 7, 8, 9 and 10 for sample 2 with Relay No. 1 in the de-energized position. When both Relays Nos. 3 and 4 are in the de-energized position, the input to the amplifier is shorted out giving faster amplifier response at recorder points 3, 4 and 9, 10.

The difference between recorded emfs of say points 3 and 4, divided by the thermoelectric sensitivity of Pt vs Pt-10% Rh at a given temperature, and then divided by 100 gives the temperature gradient in sample 1. Since the Seebeck voltage has been measured and recorded, the Seebeck coefficient can be calculated. The reason for taking the differential emf between the non-contact and contact thermocouples instead of the contact thermocouples directly is that for large Seebeck voltages and low sample resistances, the resistance of leads and relays, connecting both contact thermocouples in differential, may be as large as the sample resistance and hence the Seebeck effect would dominate the differential circuit to the exclusion of the temperature difference.

The following example illustrates how the Seebeck coefficient is obtained from the recorded data. Recorder point 1 was found to read 5.85 mv; 0.15 mv was added to compensate for thermocouple cold junction at room temperature. The temperature for 6.00 mv is 676°C; at this temperature the thermoelectric sensitivity of Pt vs Pt-10% Rh is 0.0103 mv. Dividing 0.0103 mv into 0.079 mv, which was found by taking the difference of potential between recorder points 3 and 4 and dividing by 100, the temperature gradient is found to be 7.7°C. From recorder point 2 the Seebeck emf was found to be -6.45 mv indicating n-type conduction. Dividing -6.45 mv by 7.7°C and multiplying by 1000 gives a Seebeck coefficient of -838 $\mu\text{V}/^\circ\text{C}$ at 676°C.

5. Thermal Conductivity

Thermal conductivity was approximated using a modified form of the Thermal Conductivity Comparator designed by Kenneth Skinner of the Naval Research Laboratories. The major modification was the addition of circuitry to insure uniform heating cycles. A diagram of this circuitry is shown in Figure V. The Leeds and Northrup Speedomax Type G 4-point Recording Potentiometer was used to measure the "hot" and "cold" temperatures of the specimen; the Brown Electronik Recording Potentiometer was used as a furnace control.

In operation, when the furnace is cold, an opposing voltage is fed in series into the Brown furnace control and adjusted so that this voltage plus furnace thermocouple voltage just equals the voltage needed to drive the furnace control to the pre-set maximum temperature. The clock motor of the programmer is then started which decreases the voltage in series with the thermocouple as a linear function of time. The time for a cycle is adjusted by the position of the slide wire before the voltage adjustment. As the opposing voltage decreases, the furnace temperature increases until the thermocouple voltage plus the new opposing voltage shuts off the furnace. This process repeats continually with the furnace increasing in temperature until the opposing voltage is reduced to zero and the thermocouple supplies all the voltage at shut-off temperature. Since the voltage output is approximately a linear function of temperature, the heating cycle is approximately a linear function of time. A linear heating cycle insured reproducibility, whereas a constant input did not.

The results obtained from the Skinner Thermal Comparator are interpreted in the following manner: The Leeds and Northrup Recorder prints two color-coded sets of data for each sample. One set of points represents the temperature of the "hot" side of the specimen and the other set the "cold" side. The temperature gradient in the specimen is obtained by difference, from the raw data, and plotted against the mean temperature. This produces a curve which is a relative indication of the thermal conductivity of the specimen; that is, the smaller the thermal gradient, the higher the thermal conduction. Graphical expression of this relation is shown in Figure VI.

RESULTS

The final data, resulting from measurement of ceramic and electrical properties, are presented either as illustrations or in tables. In both cases the electrical properties are presented as a function of temperature. Electrical properties of the most promising materials, only, are presented graphically; the majority of the results are collected in three tables in an Appendix to this report.

The pertinent ceramic properties of all specimens screened are given in the Appendix; these properties are time and temperature of sintering, bulk density, and porosity. The Seebeck Coefficient and electrical resistivity both at a series of temperatures, and an estimate of the type of conduction mechanism are also given for these materials which are not presented graphically.

Seebeck Coefficients as a function of temperature, for TiO_2 containing several levels of Nb_2O_5 , are given in Figure VII; in Figure VIII are given the electrical resistivities as a function of temperature for the same compositions. Figures IX and X show the temperature dependence of Seebeck Coefficient and electrical resistivity, respectively, of TiO_2 containing several levels of Ta_2O_5 . The materials presented in these four figures are the best thermoelectrics resulting from this work; all are n-type semiconductors. The most favorable composition is TiO_2 containing 2.0^{±0.1}% Nb_2O_5 . This composition has an approximate figure of merit of $7.0 \times 10^{-5}/^\circ\text{C}$.

Table AI in the Appendix contains ceramic and electrical results for compositions based on simple oxides: TiO_2 , ZrO_2 , CeO_2 . In Table AII of the Appendix are contained the ceramic and electrical results for those compositions based on lithium metatitanate, Li_2TiO_3 , and for the analogous Li_2SnO_3 and LiAlO_2 . The ceramic and electrical results listed in Table AIII of the Appendix are for compositions based on multiple oxides: BaTiO_3 , LaCrO_3 , YCrO_3 , PbNb_2O_6 and $\text{Pb}_2\text{Nb}_2\text{O}_7$.

DISCUSSION

Since thermoelectric energy conversion is essentially an electrical phenomenon, only that aspect of the experimental results are covered here. However, the physical state of a test specimen, as regards conventional ceramic properties, constitutes a prior condition on the resultant electrical properties. Chief amongst these ceramic properties is the porosity of the specimen. Since some Standard Ceramic Bodies were not sintered to zero porosity, the electrical effects of pores should be pointed out. For porosity no greater than a few percent, electrical resistivity increases directly with porosity; at larger porosities, the resistivity of the pore contents enters as that of the second phase of a mixture on a volume basis. The effect of pores on the Seebeck coefficient, that is, the nature of the temperature coefficient of the Fermi level for pores and pore-solid interfaces, is not known.

Observation of Data

The actual recording of the raw electrical data, that is, the instrumental response of the Leeds and Northrup Recording Potentiometer, served as the basis of interpreting analysis of the results. Since neither Hall effect nor diffusion effects were measured, only an estimate could be made, as described below, as to the nature of the conduction mechanism.

The algebraic sign of the Seebeck coefficient, S , was taken as a partial indication of carrier type: for $S > 0$ the net carrier effect was assumed to be due to holes, or direct diffusing cations, or anion vacancies; for $S < 0$ the net carrier effect was assumed to be due to electrons, or direct diffusing anion, or cation vacancies. Two supplementary criteria were available to aid in the estimation of carrier type. A firm, steady print of resistance, by the Leeds and Northrup Recording Potentiometer, was taken to indicate electron or hole conduction; a slow, continuous drift of the resistance print during the 10 record print interval was taken to indicate conduction by ions, either direct or through vacancy mechanism. Alternate high and low print of resistance, upon reversal of direction of external current, was also taken as an indication of ionic conduction, although rectification and thermal gradient effect are both possible explanations of this instrumental response. Combined with drift, this alternation of resistance value was taken as certain indication of ionic conduction; this effect was observed in many materials and was estimated to occur in many other materials, the resistivities of which were too great to respond to instrumental limits. These latter materials are indicated "ionic uncertain" in the tables in the Appendix. However, the thermal gradient and externally applied electric field alternately reinforce and oppose each other, thus confounding the above "uncertainty".

The electrical data alone furnished a criterion of usefulness in that the S^2/ρ quotient must be equal to or greater than 10^{-5} watt/cm $(^\circ\text{C})^2$ in order to give $Z = 10^{-3}/^\circ\text{C}$. Hence, electrical evaluation determined whether thermal conductivity needed to be measured; none of the materials measured electrically warranted determination of thermal conductivity.

Simple Oxides

Amongst these compositions the only materials that produced a thermoelectric effect were those based on either rutile or fluorite structure; and, indeed, rutile itself is the most favorable material of all those examined. From Figures VII and VIII it is seen that 1.0, 2.0, and 5.0^{mol}% Nb_2O_5 additions to TiO_2 produce moderate thermoelectric semiconductors in the temperature range from 600 to 1200 $^\circ\text{C}$; specifically, TiO_2 plus 2.0^{mol}% Nb_2O_5 has a Seebeck coefficient of $-400 \mu\text{V}/^\circ\text{C}$ and 0.1 ohm-cm resistivity. The same levels of additions of Ta_2O_5 to TiO_2 , illustrated in Figures IX and X, produce the same results with the important difference that Ta_2O_5 does not lower the resistivity of TiO_2 as much as does Nb_2O_5 . All of these compositions are typical n-type, controlled-valency semiconductors with the site-to-site conduction mechanism characteristic of such materials. Since the Seebeck coefficient is the same for Nb_2O_5 -doped TiO_2 and Ta_2O_5 -doped

TiO₂, then the energy of the electrons in excess of the chemical potential is the same, though the electrical resistivity is different. It should be noted that although stoichiometric imbalance could exist in these compositions, the experimental evidence did not indicate ionic conduction.

It is to be expected that smaller numbers of carriers would mean higher values of Seebeck coefficient and resistivity. Evidence of this is seen in Table AI for the composition TiO₂ plus 0.2ⁱⁿ% MoO₃: -1100 μV/°C and resistivity greater than instrumental limits of 5 ohm-cm. The raw data for this composition are not sufficient, however, to state with certainty that this is an n-type electronic conductor

Amongst fluorite structures, the only noteworthy electronic semiconductor is CeO₂ plus 4ⁱⁿ% Nb₂O₅: -500 μV/°C and 1.5 ohm-cm over the temperature range of 700 to 1200°C, shown in Table AI. This composition is similar to that of TiO₂ doped with Nb₂O₅. Apparent ionic conduction is found in the fluorite structure ZrO₂-7ⁱⁿ% Y₂O₃ cubic solid solution. Although experimental evidence was not obtained here, it is well established that the conduction mechanism in ZrO₂ is exclusively ionic, via vacancies in the oxygen sublattice. In Table AI it is seen that addition of 10ⁱⁿ% La₂O₃ to this ZrO₂-based composition resulted in a Seebeck coefficient ranging from +1000 μV/°C to +3000 μV/°C as the temperature increased from 900 to 1100°C; relaxation of atoms around an anion vacancy results in a net positive charge and hence a positive Seebeck coefficient. Containing 17ⁱⁿ% sesquioxide, large numbers of oxygen vacancies exist in this composition; the large Seebeck coefficient is attributable to the temperature coefficient of the electrochemical potential of these vacancies. The higher resistivity accompanying the large Seebeck coefficient is expected, but may also be due to small transference numbers for oxygen ions and this in turn to diffusion effects in a thermal gradient and an electric field.

Addition of 10ⁱⁿ% Nb₂O₅ to ZrO₂-7ⁱⁿ% Y₂O₃ cubic solid solution, shown in Table AI, produced a Seebeck coefficient of +1000 to +1600 μV/°C as the temperature ranged from 800 to 1100°C. Stoichiometrically, this composition is unbalanced in the opposite direction to that discussed above; the Y₂O₃ is more than compensated for by the Nb₂O₅ and the net effect is 3ⁱⁿ% excess of pentavalent oxide. It was to be expected that the Seebeck coefficient would decrease in magnitude upon stoichiometric compensation, but not that the Seebeck coefficient would remain positive upon over-compensation. It thus appears that the ionic mechanism of conduction in all ZrO₂-based compositions is an intrinsic property of ZrO₂.

Lithium Metatitanate

Of all those Li₂TiO₃-based compositions listed in Table AII, only two are of sufficient consistency of behavior to warrant discussion. Li₂TiO₃ has an MgO-type structure, with a random cation lattice, and undergoes an order-disorder transformation at about 1025°C. The undoped compound appears to be a strong ionic conductor, but the conduction process is quite erratic and is complicated by the order-disorder transformation. The nature of the conduction process may be attributed, in part, to the large difference in charge of the two similar-sized cations. Another contributing factor is a possible metastability of Li₂TiO₃ indicated by the ease of loss of Li₂O through volatilization. Hence, practically all Li₂TiO₃-based compositions exhibited large seebeck coefficients which varied widely with temperature; either a change in sign or a maximum or minimum occurred. None of these compositions exhibited an electrical resistivity small enough to respond to instrumental limits.

Li_2TiO_3 plus 0.5^m/o NiO , Table AII, had a Seebeck coefficient increasing from +1000 $\mu\text{V}/^\circ\text{C}$ at 700 $^\circ\text{C}$ to +1500 $\mu\text{V}/^\circ\text{C}$ at 1150 $^\circ\text{C}$. A negative Seebeck coefficient should result if the Ni(II) replaces Li(I) ; but if the Ti(IV) is replaced, a p-type semiconductor should result. Since the cation sublattice is randomly occupied by Li(I) and Ti(IV) , and Ni(II) is of the same size as both cations of the host lattice, then both substitutions can occur together. Now the electrical resistivity did not record, so the ionic mechanism of conduction remains uncertain. However, a hole, and/or an electron, contribution to the conduction process may account for the steady, but increasing, value of the Seebeck coefficient over the temperature range of measurement.

Li_2TiO_3 plus 2.0^m/o ThO_2 had a Seebeck coefficient decreasing from -850 $\mu\text{V}/^\circ\text{C}$ at 800 $^\circ\text{C}$ to -1200 $\mu\text{V}/^\circ\text{C}$ at 1225 $^\circ\text{C}$. Considered an uncertain electronic conductor, this composition is the only Li_2TiO_3 -based material which exhibited a consistent negative Seebeck coefficient. Since Th(IV) is so much larger than the cations of the host lattice, it is difficult to understand how the foreign cation enters the lattice. Also, explanation of the conduction mechanism is not possible with the limited data available.

Multiple Oxides

Structurally, the base compounds of these compositions are all perovskite-like, containing a transition metal ion surrounded by an octohedron of six oxygen atoms. The alignment of these octohedra, however, and their relation to the other cation of the compound, differ in each case. It is significant that the majority of compositions discussed here are apparent ionic conductors.

Barium titanate, a tetragonal perovskite, developed interesting thermoelectric properties when doped with 0.5^m/o Nb_2O_5 as shown in Table AIII. Although the resistivity was greater than instrumental limits of 5 ohm-cm, it is rather certain that this composition is an electronic conductor. The Seebeck coefficient ranged from -1700 $\mu\text{V}/^\circ\text{C}$ at 750 $^\circ\text{C}$ to -3000 $\mu\text{V}/^\circ\text{C}$ at 1225 $^\circ\text{C}$, an n-type thermoelectric being produced by substitution of Nb(V) for Ti(IV) . The negative sign and increasing magnitude of the Seebeck coefficient indicate that the material is becoming an intrinsic-type semiconductor as the temperature increases. The relatively large Seebeck coefficient may be attributed to two factors. As in the case of TiO_2 , the controlled-valency effect is manifest, though the resistivity is not as low. Here, again, the carriers have considerable energy in excess of the chemical potential of the host lattice. The second factor is the large dielectric constant of BaTiO_3 . When materials which conduct by the site-to-site mechanism are doped at the levels of this composition, the carriers observe the macroscopic dielectric constant of the host rather than the electronic structure of the host lattice. Hence, high dielectric constant insulators are readily modified to semiconductors of substantial Seebeck coefficient by an increase in both dielectric constant and loss factor, the latter ultimately exceeding 100%. Although such a composition has a large number of non-degenerate carriers, the site-to-site conduction mechanism is not effective enough to use such materials for energy conversion.

Lead metaniobate, PbNb_2O_6 , a ferroelectric with a moderately high dielectric constant, while not a distorted perovskite, does contain discrete NbO_6 octahedra. Addition of 0.5^m/o Bi_2O_3 to PbNb_2O_6 , see Table AIII, resulted in a thermoelectric material somewhat similar to the above BaTiO_3 composition. The Seebeck coefficient

ranged from $-700\mu\text{v}/^\circ\text{C}$ at 700°C to $-2100\mu\text{v}/^\circ\text{C}$ at 1100°C with a pronounced minimum of $-3300\mu\text{v}/^\circ\text{C}$ at 1015°C . The electrical resistivity, measured manually under static conditions, dropped from 70,000 ohm-cm at 700°C to 66 ohm-cm at 1200°C , exhibiting the negative temperature coefficient peculiar to oxide ceramic semiconductors.

Since Bi(III) is intermediate in size between Pb(II) and Nb(V), a definite site of substitution cannot be assigned; on the basis of electronegativity, however, Bi(III) should substitute for Pb(II). The thermoelectric semiconduction could arise as a consequence of the same effects ascribed to the BaTiO_3 composition above, since both lead and bismuth can exist in other oxidation states. The negative temperature coefficient of both resistivity and Seebeck coefficient indicate that this composition also tends to become an intrinsic semiconductor at high temperature. The decrease in magnitude of the Seebeck coefficient at temperatures above 1015°C might be attributed to the onset of ionic conduction due to thermal agitation since PbNb_2O_6 melts in the vicinity of 1200°C . It is of interest that just as Nb(V) is effective as a dope in producing thermoelectric semiconductors, so also, a niobate compound can be converted to the same condition by doping.

The orthochromites of some of the Lanthanum elements are perovskite-like compounds, actually having the garnet structure. The compounds, however, do not have the high dielectric constant of ferroelectrics. Compositions based on LaCrO_3 and YCrO_3 exhibited moderate Seebeck coefficients; all are ionic conductors. The data on the five most noteworthy of these are summarized from Table AIII below.

<u>Composition</u>	<u>Seebeck Coefficient</u>	<u>Electrical Resistivity</u>	<u>Temperature Range</u>	<u>Conduction Mechanism</u>
$\text{LaCrO}_3 + 5.0^{\text{m}}/\text{o TiO}_2$	$+500\mu\text{v}/^\circ\text{C}$	2-3 ohm-cm	600 to 1100°C	ionic
$\text{LaCrO}_3 + 1.0^{\text{m}}/\text{o ZrO}_2$	+500 to +450	1	600 to 1200	ionic
$\text{LaCrO}_3 + 5.0^{\text{m}}/\text{o SnO}_2$	+575	2	600 to 1200	ionic
$\text{YCrO}_3 + 5.0^{\text{m}}/\text{o TiO}_2$	+850	> 5	370 to 1170	ionic, uncertain
$\text{YCrO}_3 + 0.5^{\text{m}}/\text{o ZrO}_2$	+1100	> 5	700 to 1200	ionic, uncertain

All compositions based on LaCrO_3 and YCrO_3 were quite refractory and very difficult to sinter; and not all of them resulted in satisfactory ceramic specimens. In all sintering trials, a dark greenish-grey furnace-like deposit was observed on the interior of the sintering container. This indicates vaporization of chromium as some form of oxide. Hence, the stoichiometry of the base compound may be sufficiently out of balance to determine all the observed effects. If sufficient loss of chromium occurred, the number of vacancies in the above compositions may be of the same order of magnitude as in heavily doped ZrO_2 discussed before. The description of the observed effects may then be that the Seebeck coefficient is due to the temperature coefficient of the chemical potential of vacancies, the conductivity due to diffusion of ions in the oxygen sublattice via the vacancy mechanism. However, compensation by the added tetravalent oxide very likely occurred.

Referring to the above tabulation, certain general effects are to be noted. Doped YCrO_3 and doped LaCrO_3 are moderate ionic semiconductors with moderate Seebeck coefficients. A higher Seebeck coefficient and higher resistivity, as a consequence of a smaller number of carriers, are found in YCrO_3 than in LaCrO_3 . The level of doping with tetravalent oxide, does not appear to be too significant, and indeed may not even be necessary. Finally, the orthochromite grouping alone may be the determining factor in the thermoelectric effects noted. These observations, however, depend greatly on the extent of sintering. The orthochromites of yttrium and lanthanum thus appear to be similar to ZrO_2 as regards an inherent ionic conduction process at high temperature.

Positive Seebeck Coefficient Semiconductors

Since all the compositions with positive Seebeck coefficients that are discussed above are ionic conductors, p-type electronic materials should be given separate attention. High temperature p-type semiconduction is virtually impossible to achieve in any material. Experience has shown that the number of thermally energized electrons overwhelms the number of controlled-valency-produced holes with resultant intrinsic semiconduction at high temperature. Numerous examples of this phenomenon are to be found in Tables AI and AIII. Compositions with positive Seebeck coefficients at lower temperatures are seen to undergo considerable change with increasing temperature, the Seebeck coefficient falling through zero to sizeable negative values. Lead metaniobate and lead pyroniobate, each without any addition, are examples of this, as is PbNb_2O_6 plus 1.0^m/o MoO_3 . Other compositions are seen to exhibit a maximum or a minimum in Seebeck coefficient as a function of temperature, some with and some without changing sign. Examples of this behavior are shown by TiO_2 plus 5.0^m/o SnO_2 , CeO_2 +0.2^m/o La_2O_3 , $\text{Pb}_2\text{Nb}_2\text{O}_7$ plus 1.0^m/o Sb_2O_3 , and PbNb_2O_6 +0.2 Sb_2O_3 . Thus a fundamental characteristic of semiconduction, hindering the development of high temperature p-type thermoelectrics, presents the major obstacle to the production of an efficient thermocouple operating over the temperature range of 700 to 1200°C.

TABLE IIdentification of Raw Materials

<u>Compound</u>	<u>Source</u>	<u>Purity</u>
Antimony (ous) oxide, Sb_2O_3	Fisher Scientific Co., A-860	99.7%
Antimony (ic) oxide, Sb_2O_5	" " " A-857	Technical
Bismuth trioxide, Bi_2O_3	" " " B-339	99.7%
Chromium(ic) oxide, Cr_2O_3	" " " B-334	99.4
Ferric oxide, Fe_2O_3	" " " I-116	99.7
Lead dioxide, PbO_2	" " " L-101	"Special Micro"
Magnesium oxide, MgO	" " " M-51	99.8
Molybdic anhydride, MoO_3	" " " A-174	99.5
Stannic oxide, SnO_2	" " " T-148	99.4
Stannous oxide, SnO	" " " T-150	99.9
Thallium (ic) oxide, Tl_2O_3	" " " T-86	Purified
Tungstic anhydride, WO_3	" " " A-325	Purified
Lanthanum oxide, La_2O_3	Lindsay Chemical Div. American Potash and Chemical Corp., 528	99.99%
Neodymium oxide, Nd_2O_3	" " " 629.9	99.9
Thorium oxide, ThO_2	" " " 112	99.9
Cerium oxide, CeO_2	" " " 217	99.9+
Yttrium oxide, Y_2O_3	" " " 1115	99.9
Lithium carbonate, Li_2CO_3	American Potash and Chemical Corp.	Technical
Nickelous oxide, NiO	Baker Chemical Co., 2796	99.0

TABLE 1 (continued)
Identification of Raw Materials

<u>Compound</u>	<u>Source</u>	<u>Purity</u>
Niobium oxide, Nb_2O_5	Fansteel Metallurgical Co., 721	99.5
Tantalum oxide, Ta_2O_5	" " 521	99.5
Titanium dioxide, TiO_2	TAM Div., National Lead Co., Vapor Phase	98.4
Zirconium dioxide, ZrO_2	TAM Div., National Lead Co., 608	99.3
Barium titanate, BaTiO_3	TAM Div., National Lead Co., 510	99.9

TABLE II

Identification of Compounds Prepared

<u>Name of Compound or Solid Solution</u>	<u>Formula</u>	<u>Raw Materials</u>	<u>Synthesis Conditions</u>	
			<u>Temp.</u>	<u>Time</u>
Zirconia-yttria Solid Solution	$Zr_{0.93}Y_{0.07}O_{1.965}$	ZrO_2, Y_2O_3	2300°F	3 hrs
Zirconia-calcia Solid Solution	$Zr_{0.85}Ca_{0.15}O_{1.85}$	$ZrO_2, CaCO_3$	2300	3
Zirconia-ceria Solid Solution	$Zr_{0.83}Ce_{0.17}O_2$	ZrO_2, CeO_2	2300	3
Lithium metatitanate	Li_2TiO_3	Li_2CO_3, TiO_2	1800	3
Lithium Zirconate	Li_2ZrO_3	Li_2CO_3, ZrO_2	2200	2
Lithium aluminate	$LiAlO_2$	Li_2CO_3, Al_2O_3	1700	2
Lithium stannate	Li_2SnO_3	Li_2CO_3, SnO_2	1600	2
Lead metaniobate	$PbNb_2O_6$	$PbCO_3, Nb_2O_5$	1900	3
Lead pyroniobate	$Pb_2Nb_2O_7$	$2PbCO_3, Nb_2O_5$	1900	3
Yttrium orthochromite	$YCrO_3$	Y_2O_3, Cr_2O_3	2300	3
Lanthanum orthochromite	$LaCrO_3$	La_2O_3, Cr_2O_3	2400	3

FIGURE 1
AUXILIARY CIRCUITRY FOR ELECTRICAL MEASUREMENTS

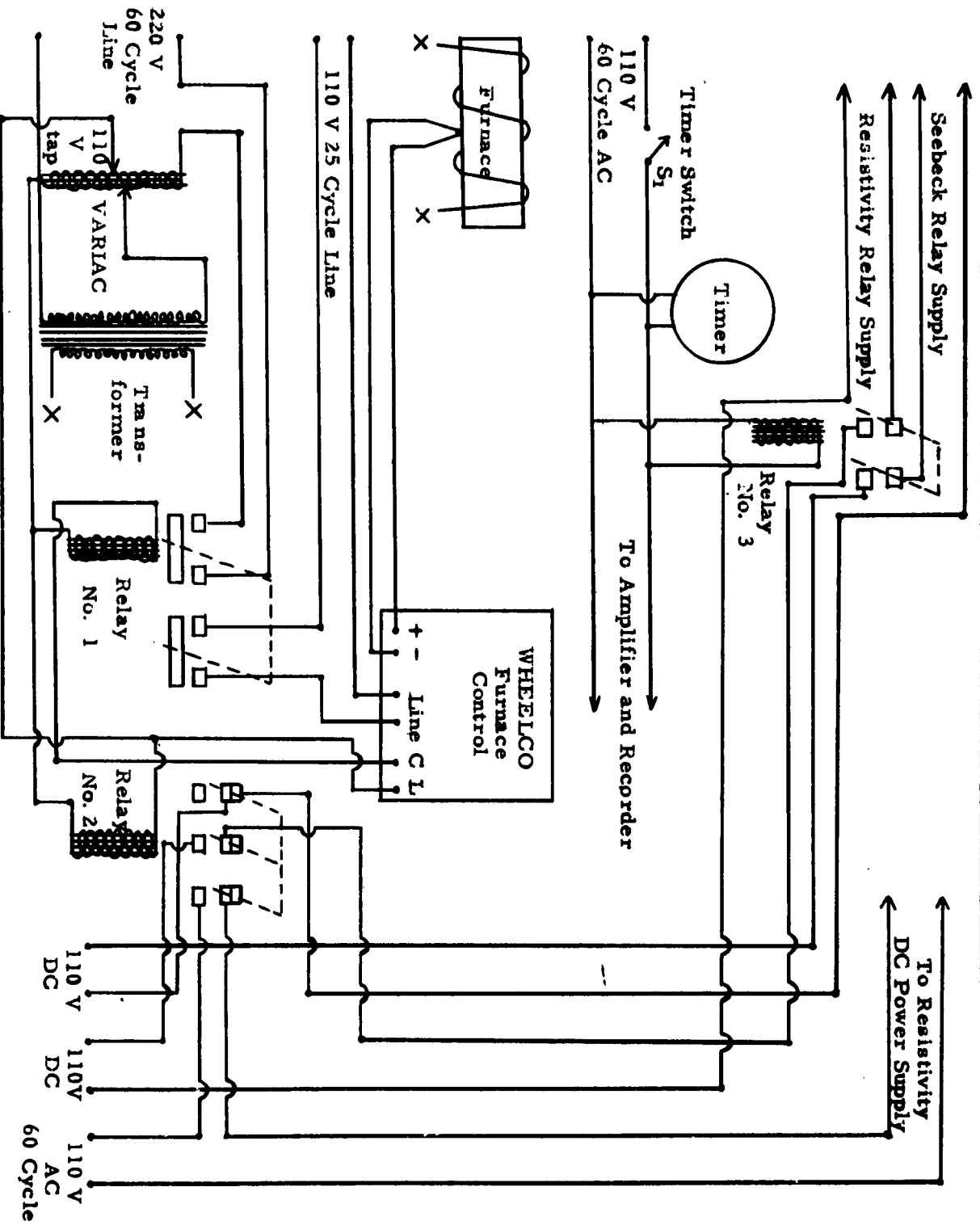
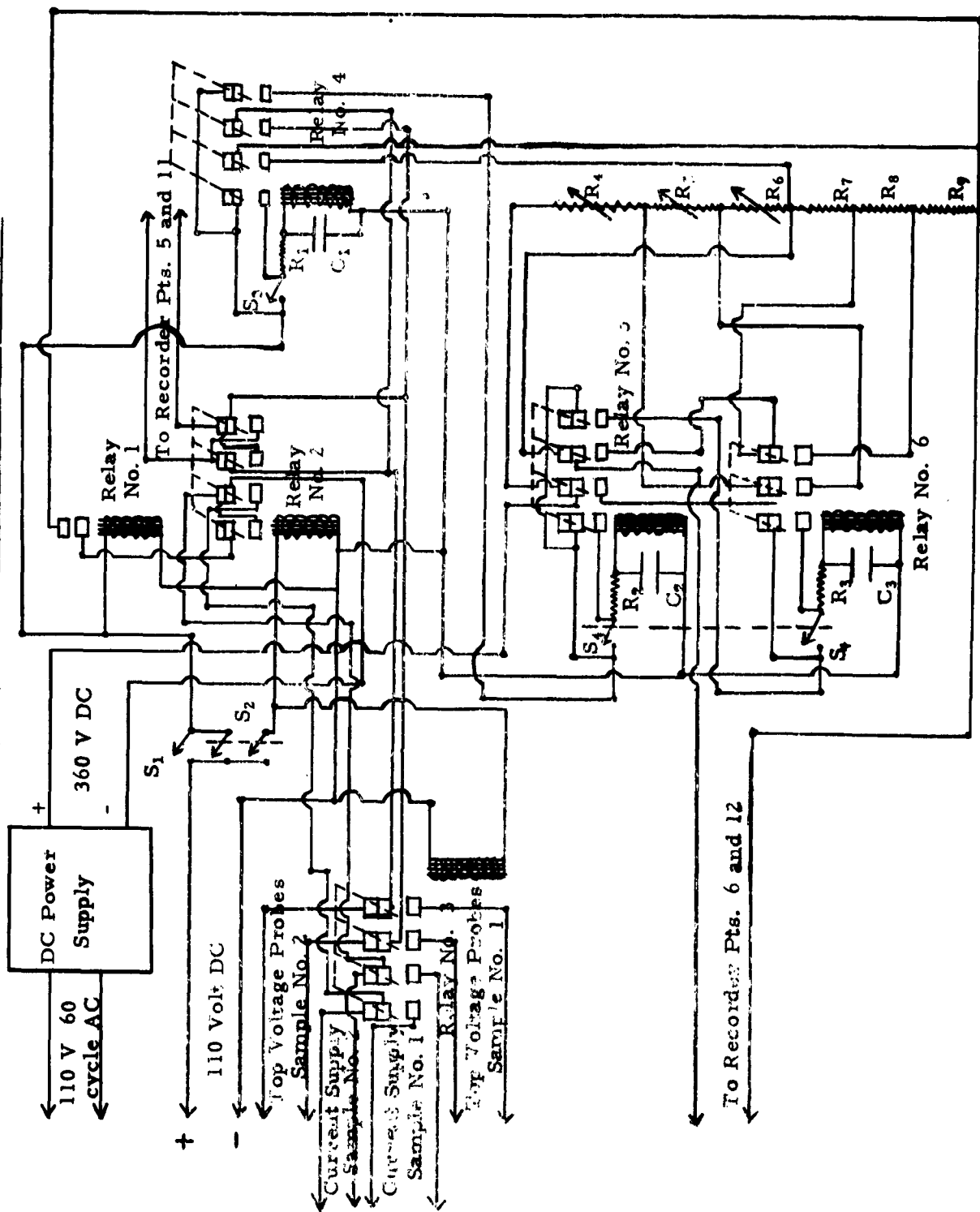


FIGURE II

AUTOMATIC RESISTANCE RANGE SWITCHING OPERATION



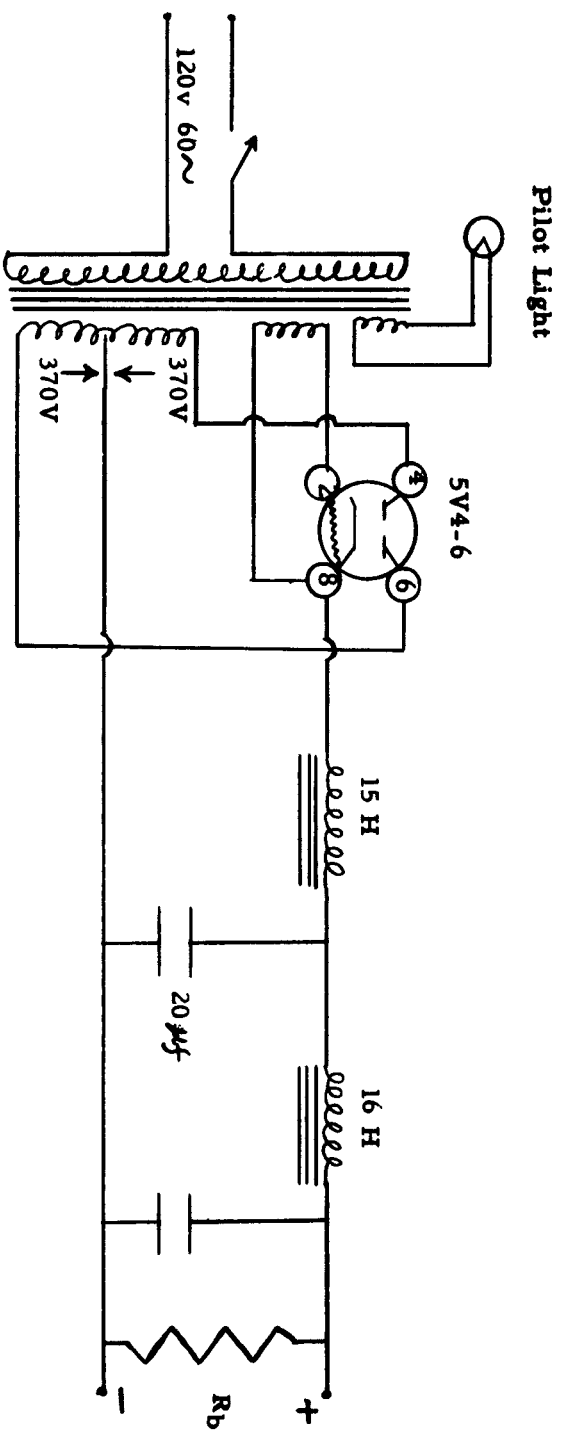


FIGURE II (Supplement)
DC CURRENT SUPPLY
For ARRSO

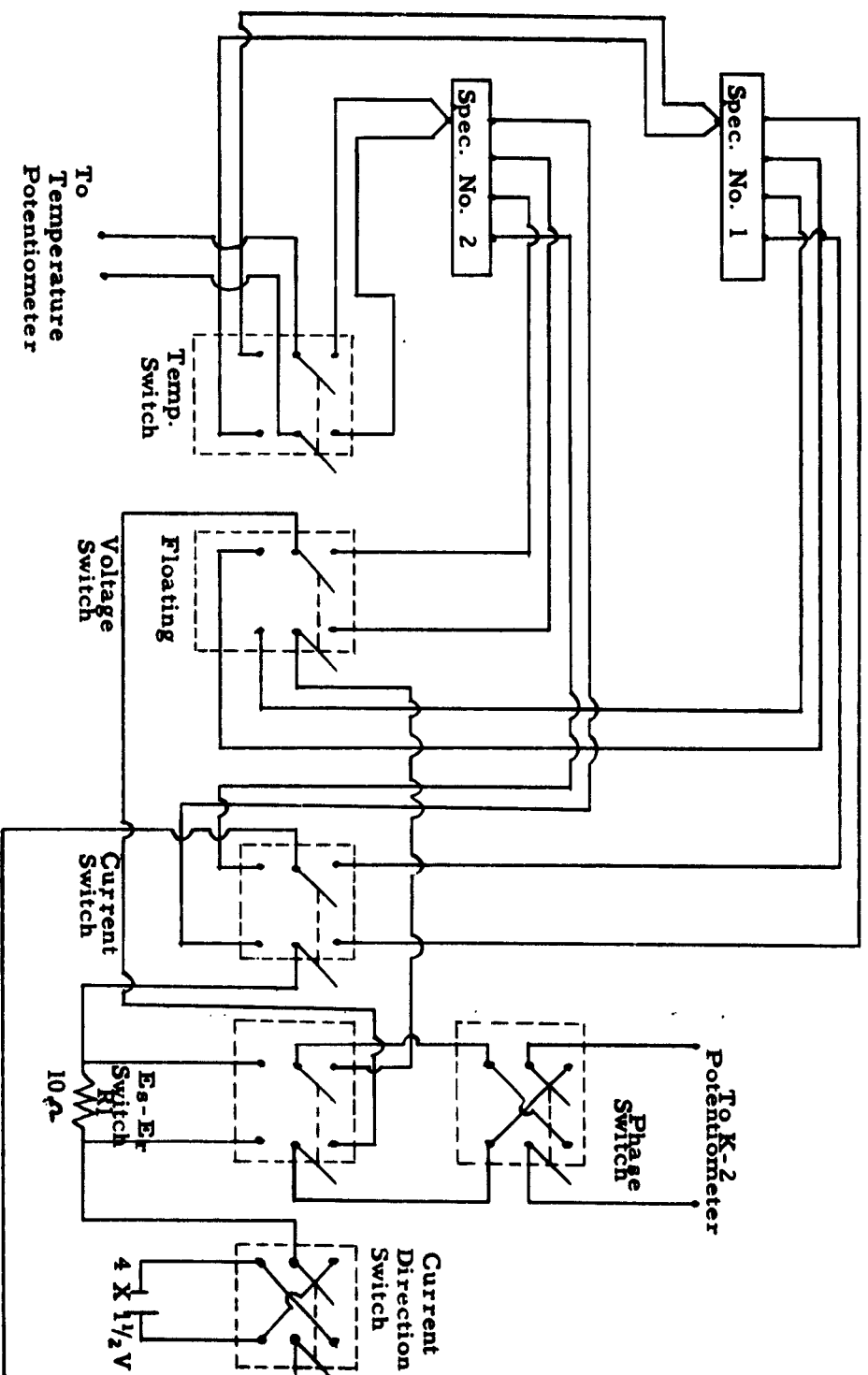


FIGURE III
CIRCUITRY FOR MANUAL MEASUREMENT OF RESISTIVITY

FIGURE IV
AUTOMATIC SEEBECK COEFFICIENT MEASURING APPARATUS

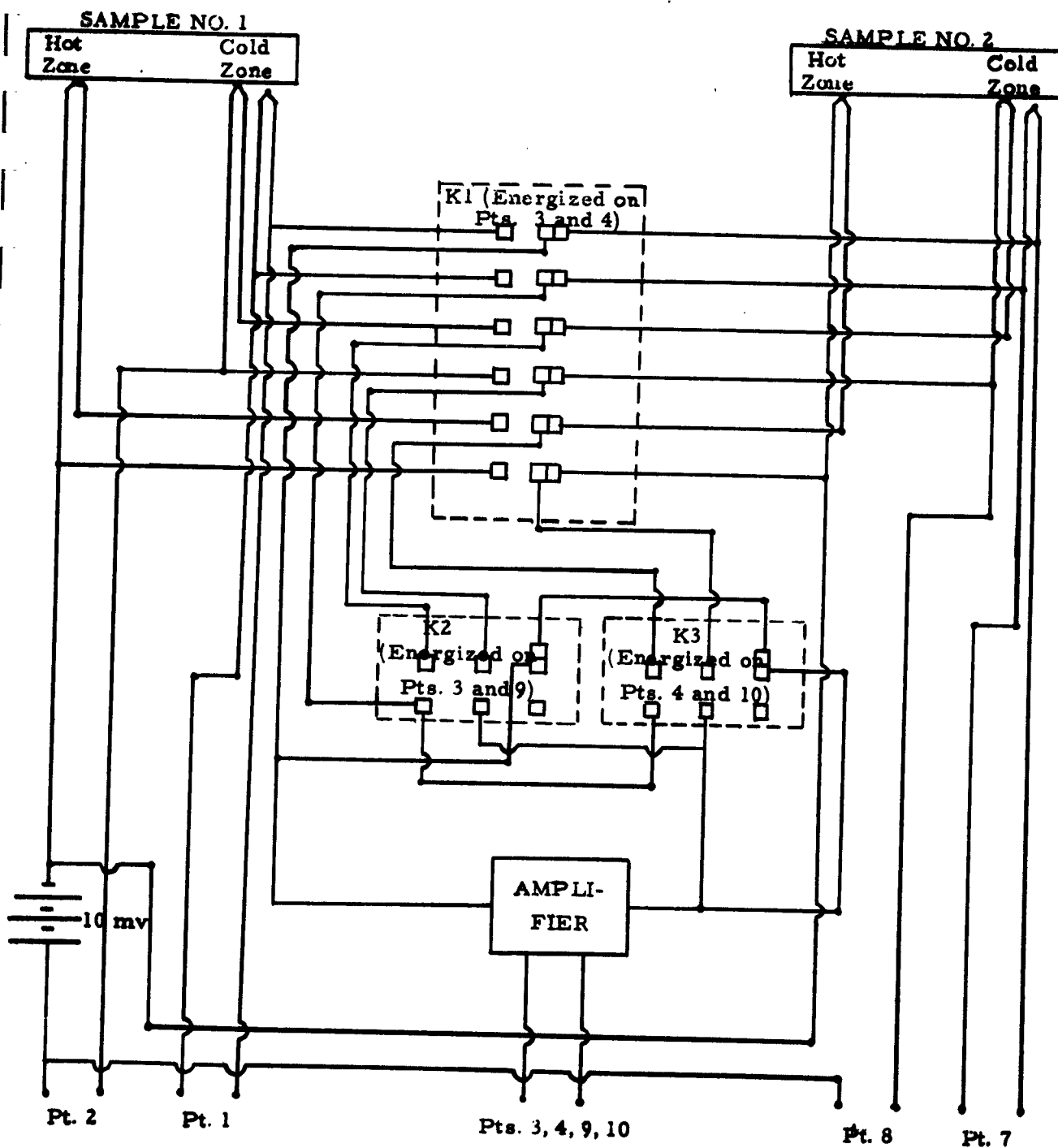
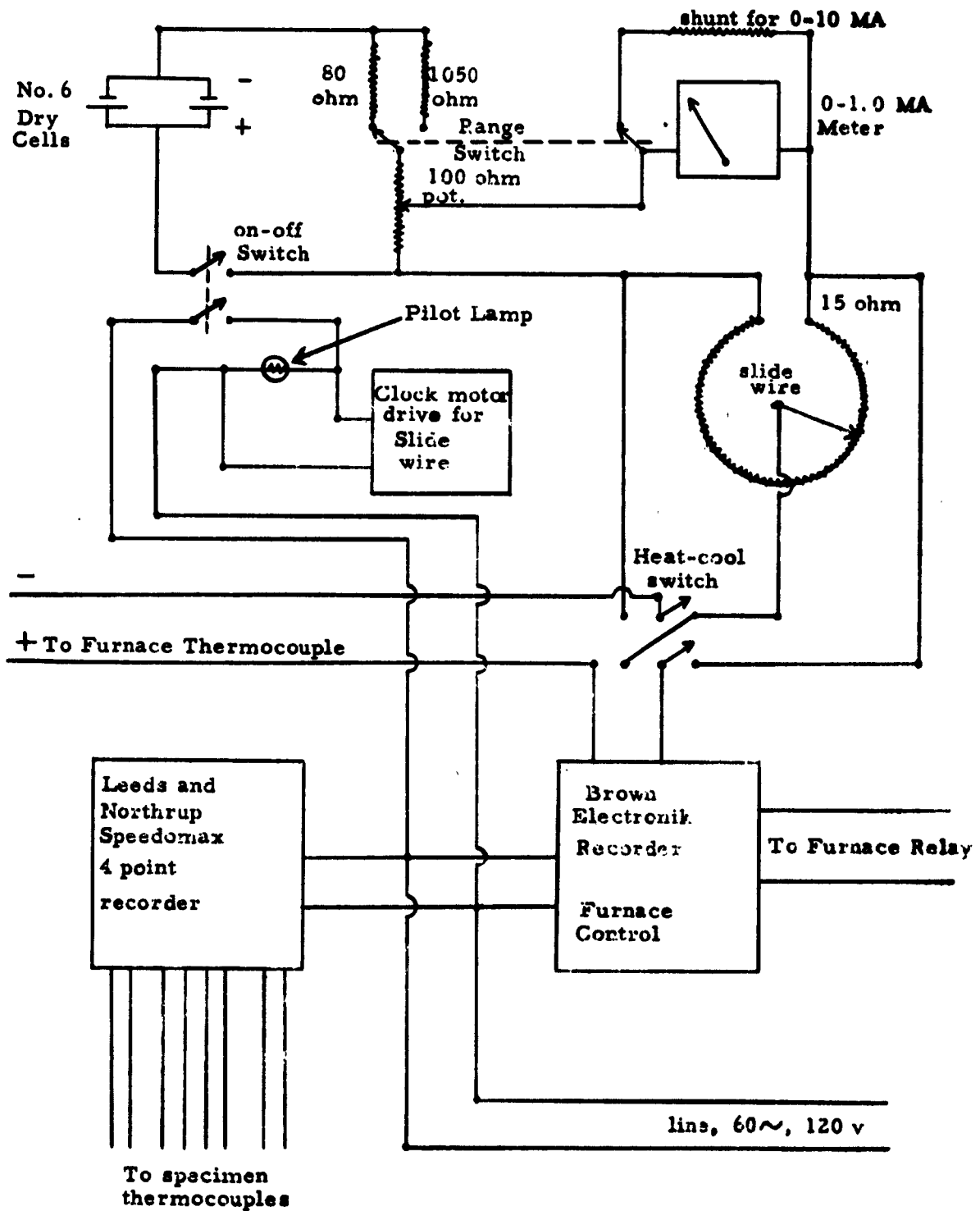
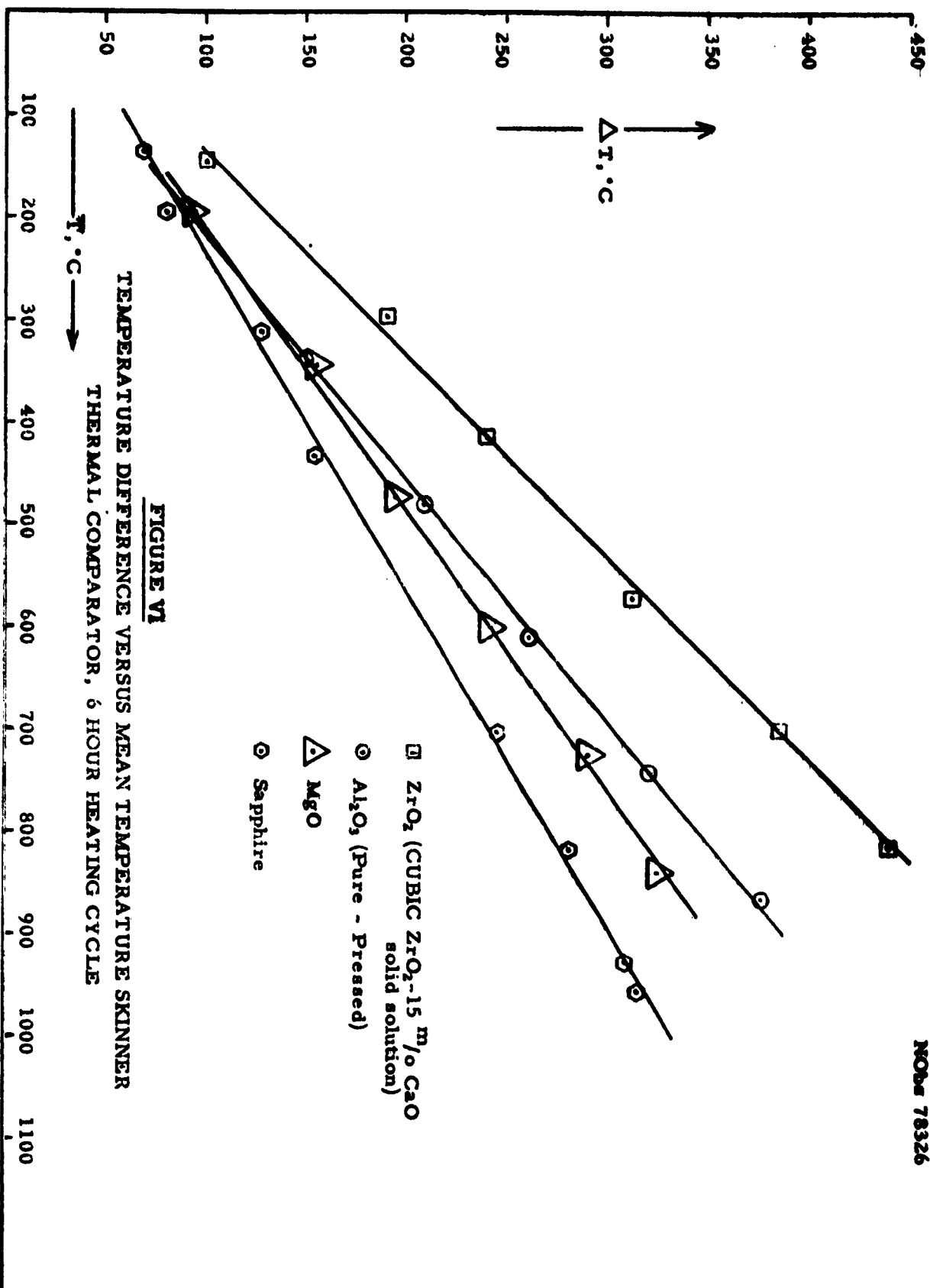


FIGURE V

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MODIFIED CIRCUITRY FOR SKINNER THERMAL COMPARATOR





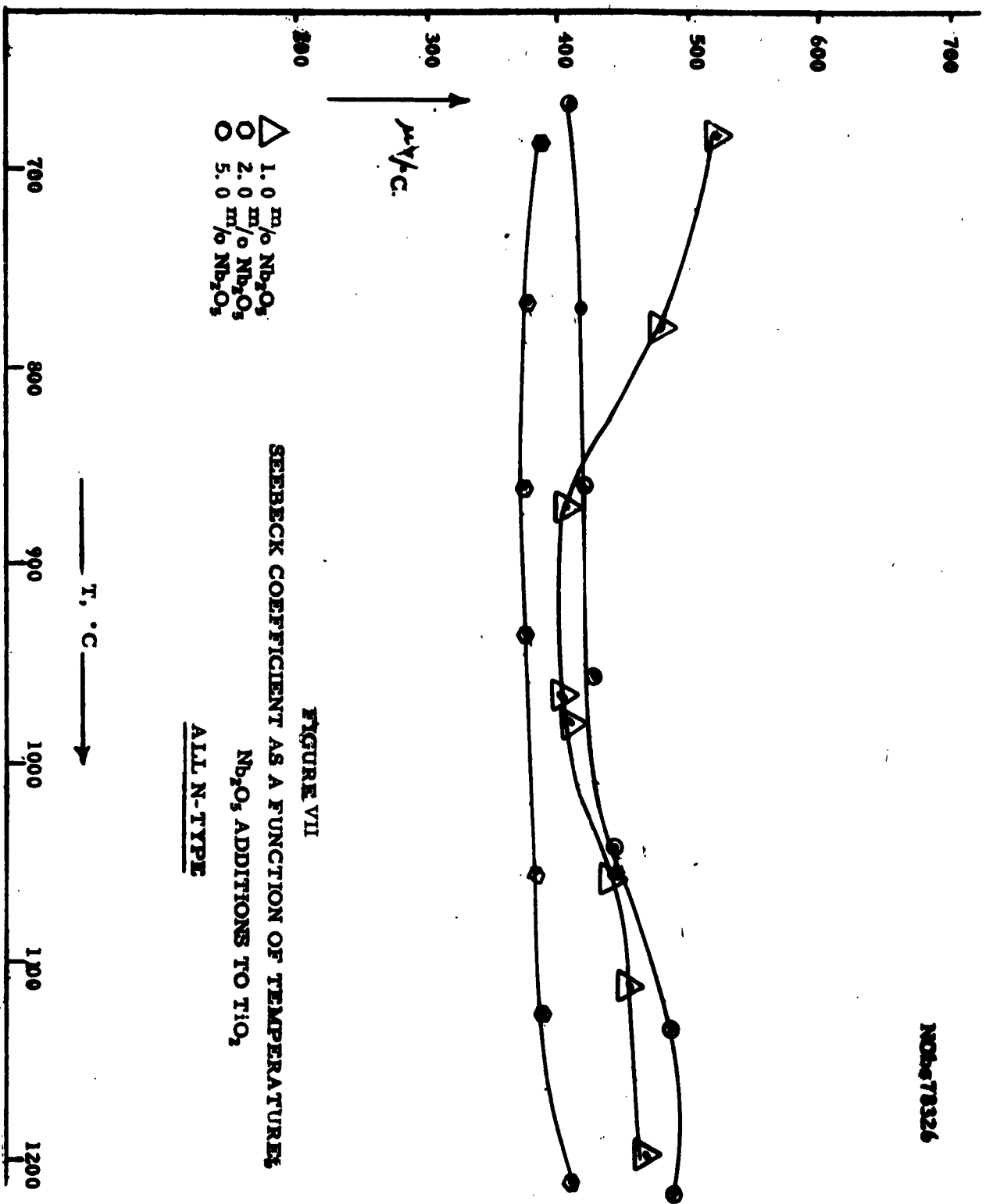
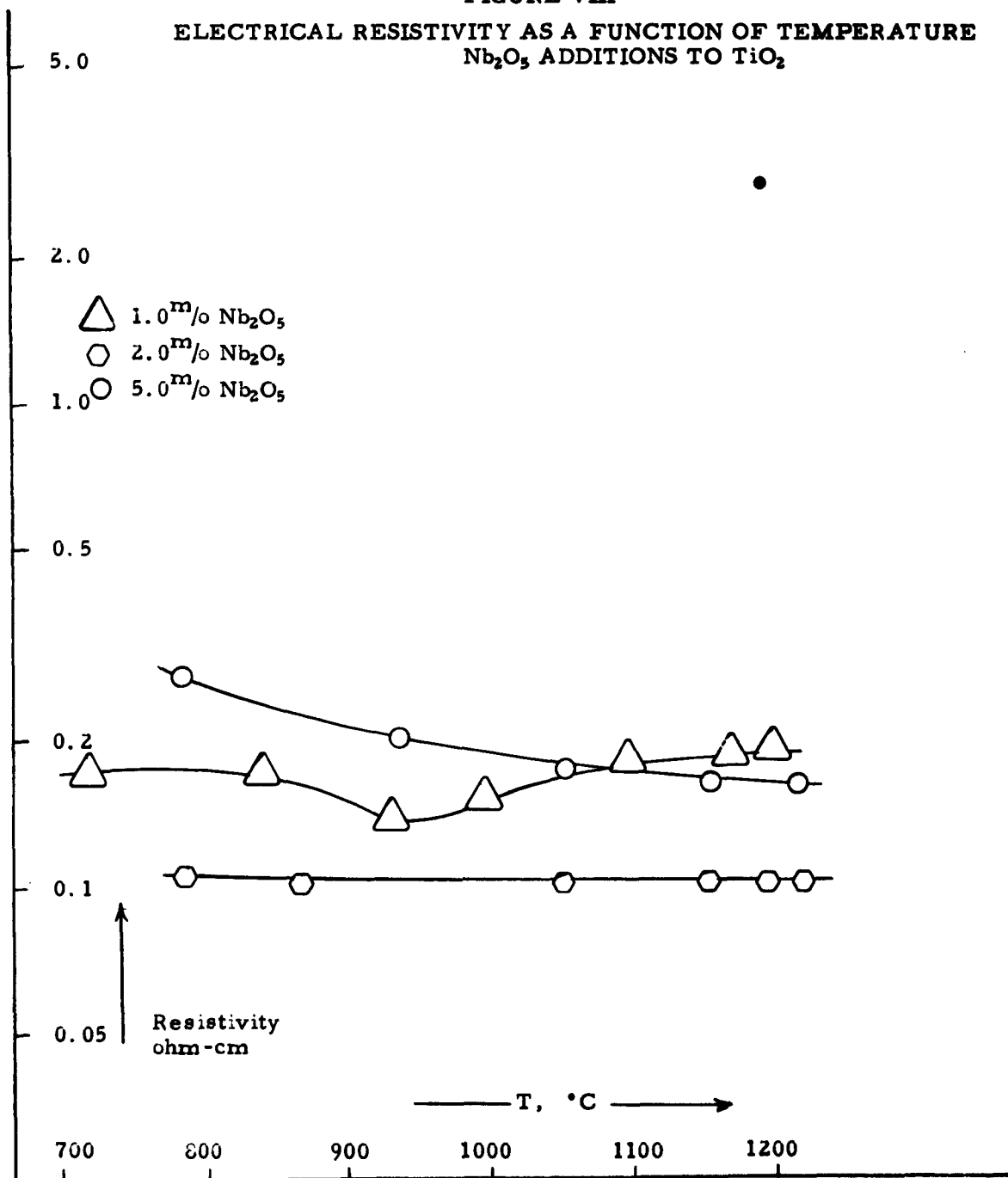


FIGURE VII
SEEBECK COEFFICIENT AS A FUNCTION OF TEMPERATURE,
 Nb_2O_5 ADDITIONS TO TiO_2

ALL N-TYPE

FIGURE VIII

ELECTRICAL RESISTIVITY AS A FUNCTION OF TEMPERATURE
Nb₂O₅ ADDITIONS TO TiO₂

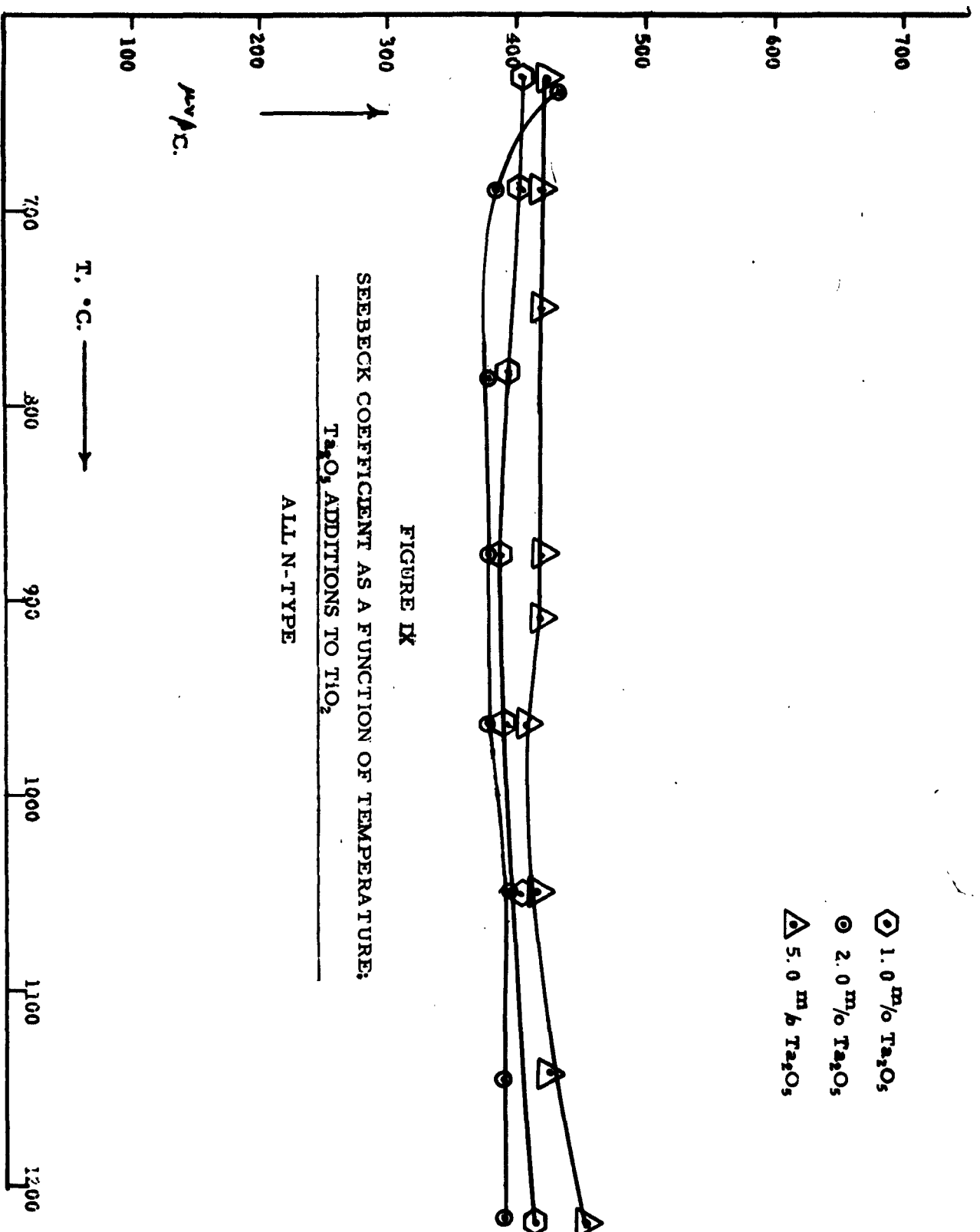
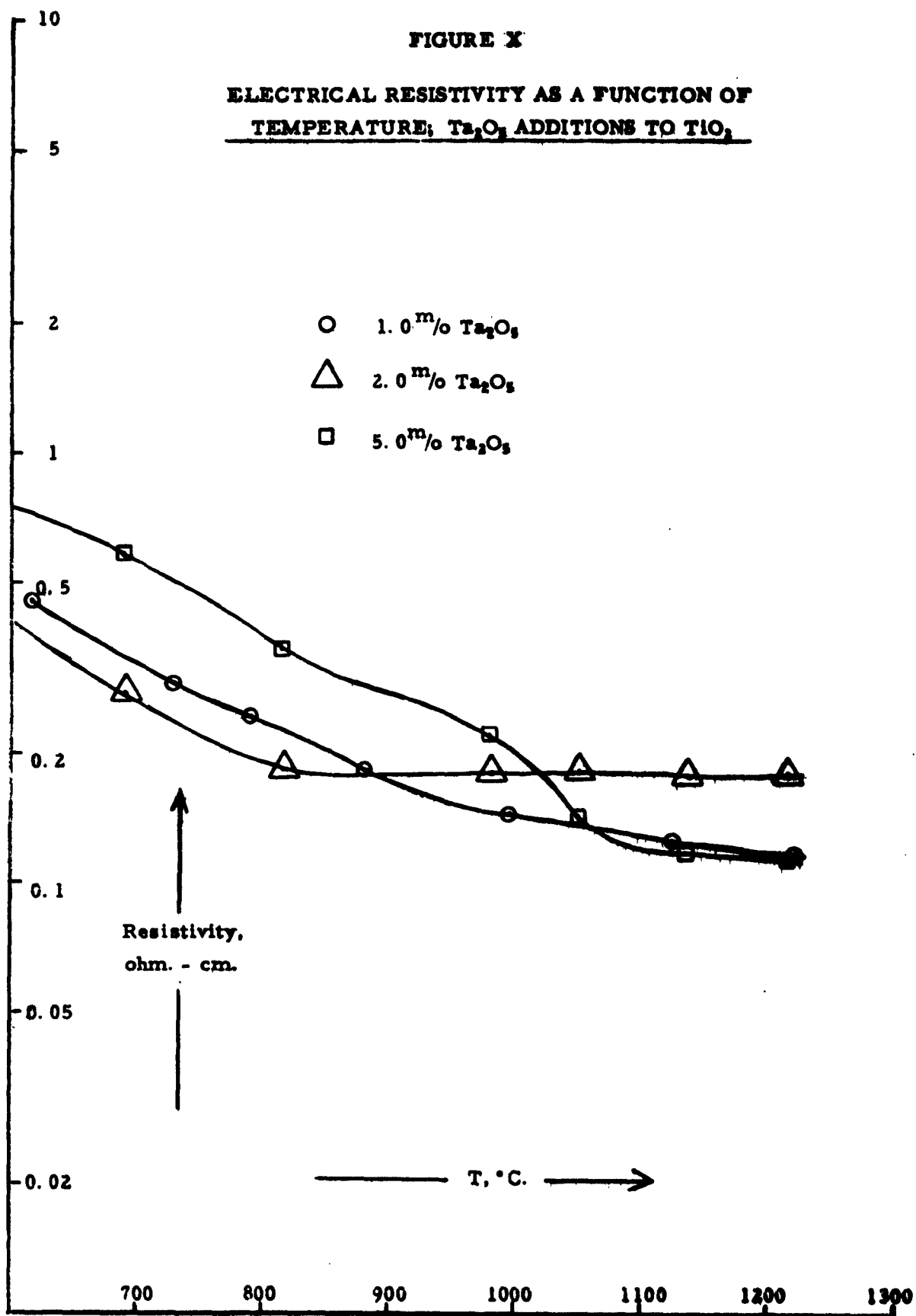


FIGURE IX
 SEEBECK COEFFICIENT AS A FUNCTION OF TEMPERATURE;
 Ta_2O_5 ADDITIONS TO TiO_2

ALL N-TYPE

FIGURE X

ELECTRICAL RESISTIVITY AS A FUNCTION OF
TEMPERATURE; Ta₂O₅ ADDITIONS TO TiO₂



APPENDIX TABLE AI

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp. Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
TiO ₂	0.1 ^m % Sb ₂ O ₃	2600°F 3 hrs	4.05 g/cm ³	0.096%	1218°C 960 852 816	-55 μV/°C -134 0 +100	> 5 ohm-cm	electronic uncertain
	0.2 ^m % Sb ₂ O ₃	2600°F 3 hrs	4.19	0.000	to 700 870 1054 1200	erratic, + +825 0 -550	> 5	electronic uncertain
	0.5 ^m % Sb ₂ O ₃	2600°F 3 hrs	4.17	0.015	704 870 1182	-457 -435 -370	75	electronic uncertain
	1.0 ^m % Sb ₂ O ₃	2600°F 3 hrs	4.12	0.11	690 968 1122 1244	-627 -608 -605 -609	0.74	electronic
	2.0 ^m % Sb ₂ O ₃	2600°F 3 hrs	3.57	12.25	690 880 1050 1244	-482 -491 -489 -480	0.26	electronic
5.0 ^m % Sb ₂ O ₃	2600°F 3 hrs	3.80	9.21		732 934 946 1100 1106 1220	-815 -550 -250	2.35 0.78 0.39	electronic
					694 906 980 1050 1072 1236	-671 -531 -450	1.12 0.69 0.38	electronic

APPENDIX

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TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck			
		Temp.	Time				Coefficient	Resistivity	Conduction	
TiO ₂	0.1 ^m % La ₂ O ₃	2400°F	3 hrs	4.39	0.031	874	0	electronic uncertain		
						928	+1018			
						1100	0			
						1220	-380		> 5	
	0.2 ^m % La ₂ O ₃	2400°F	3 hrs	4.42	0.018	1040	0	electronic uncertain		
						1220	-550		> 5	
						766	0		electronic uncertain	
						946	+605			
	0.5 ^m % La ₂ O ₃	2400°F	3 hrs	4.46	0.028	1118	0	electronic uncertain		
						1220	-213		> 5	
						765	0		electronic uncertain	
						829	+1680			
	1.0 ^m % La ₂ O ₃	2400°F	3 hrs	4.52	0.034	1050	0	electronic uncertain		
						1220	-540		> 5	
						928	+1060		electronic uncertain	
						1082	0			
	2.0 ^m % La ₂ O ₃	2500°F	3 hrs	4.29	0.007	1220	-540	> 5	electronic uncertain	
						820	0	electronic uncertain		
						910	+820			
						1050	0			
	5.0 ^m % La ₂ O ₃	2600°F	3 hrs	4.45	0.000	1220	-400	> 5	electronic uncertain	
						1216	-500	> 5		electronic uncertain
						1054	0			
						1038	+116	+844		
	0.1 ^m % SnO ₂	2600°F	1¾ hrs	4.05	0.000	942		electronic uncertain		
						910	0		electronic uncertain	
						964	+266			
						1102	0		-360	> 5
						1220				

APPENDIX
TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp. Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	0.2 ^m /o SnO ₂	2600°F 1 1/2 hrs	4.03	0.007	964 1050 1220	+565 0 -370	>5	electronic uncertain
	0.5 ^m /o SnO ₂	2600°F 1 1/2 hrs	4.03	0.033	893 938 1050 1236	0 +348 0 -540	>5	electronic uncertain
	1.0 ^m /o SnO ₂	2600°F 1 1/2 hrs	4.09	0.016	710 928 1050 1220	0 +930 0 -425	>5	electronic uncertain
	2.0 ^m /o SnO ₂	2600°F 1 1/2 hrs	3.98	0.90	820 928 1033 1220	0 +620 0 -495	>5	electronic uncertain
	5.0 ^m /o SnO ₂	2600°F 1 1/2 hrs	4.07	0.54	746 765 910 1043 1220	-780 0 +910 0 -500	>5	electronic uncertain
		2400°F 3 hrs	3.28	6.49	1224 1118 976 880	-484 0 +583 +698	>5	electronic uncertain
	0.1 ^m /o LaPO ₄	2400°F 3 hrs	3.70	2.48	722 -836 880 1050 1220	-692 0 +200 0 -557	>5	electronic uncertain

APPENDIX
TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Temp. Time	Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
TiO ₂	0.2 ^m /o LaPO ₄	2400°F 3 hrs	3.92	5.93	to 600	erratic, neg.		electronic
					695	0		uncertain
					914	+1253		
					1156	0		
0.5 ^m /o LaPO ₄	2400°F 3 hrs	3.77	3.92	7.60	1220	-166	>5	
					to 700	erratic, neg.		electronic
					880	+1084		uncertain
					1080	0		
1.0 ^m /o LaPO ₄	2400°F 3 hrs	3.80	3.92	0.161	1200	-410	>5	
					770	-1149		electronic
					906	0		uncertain
					954	+55		
2.0 ^m /o LaPO ₄	2400°F 3 hrs	3.47	3.47	17.41	994	0		
					1200	-532	>5	
					to 600	erratic, neg.		electronic
					685	0		uncertain
5.0 ^m /o LaPO ₄	2450°F 3 hrs	3.65	3.65	13.99	825	+565		
					1054	0		
					1220	-366	>5	
					<825	erratic, +	>5	electronic
0.1 Nb ₂ O ₅	2400°F 3 hrs	3.76	3.76	2.71	825	+571		uncertain
					to 700	erratic		electronic
					880	+400		uncertain
					994	0		
0.2 Nb ₂ O ₅	2400°F 3 hrs	3.55	3.55	1.84	1114	-450	>5	
					to 700	erratic, neg		electronic
					880	+280		uncertain
					994	0		
					1114	-485	>5	

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TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
TiO ₂	0.5 Nb ₂ O ₅	2400°F	3 hrs	3.55	1.49	700 to 896	erratic, neg -606		electronic
						978	-450		uncertain
						1208	-880	> 5	
	1.0 Nb ₂ O ₅	2400°F	3 hrs	3.51	18.2)	See Figures VII, VIII			
	2.0 Nb ₂ O ₅	2400°F	3 hrs	3.73	9.29)				
	5.0 Nb ₂ O ₅	2400°F	3 hrs	3.93	4.49)				
		2600°F	3 hrs	4.15	0.000	1232	-264	> 5	electronic
						1206	0		uncertain
						1046	+1488		
						888	+1640		
	0.1 ^m /o Ta ₂ O ₅	2600°F	3 hrs	4.03	0.000	914	+912		electronic
						1020	0		uncertain
						1208	-648	> 5	
	0.2 ^m /o Ta ₂ O ₅	2600°F	3 hrs	3.93	2.47	914	+505		electronic
						950	0		uncertain
						1208	-653	> 5	
	0.5 ^m /o Ta ₂ O ₅	2600°F	3 hrs	3.76	8.87	< 880	large		electronic
						880	erratic,	> 5	uncertain
						1200	neg.		
						See Figures, IX, X			
	1.0 ^m /o Ta ₂ O ₅	2600°F	3 hrs	4.27	0.000)	1206	-1000	> 5	electronic
	2.0 ^m /o Ta ₂ O ₅	2600°F	3 hrs	4.50	0.000)	< 1206	very erratic		uncertain
	5.0 ^m /o Ta ₂ O ₅	2600°F	3 hrs	4.52	1.65)	732	-1150		electronic
	0.1 MgO ₃	2400°F	3 hrs	4.14	0.29	870	-1170		uncertain
						968	-1170		
						1224	-1070	> 5	
	0.2 MgO ₃	2400°F	3 hrs	3.87	4.65				

APPENDIX
TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions		Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
ZrO ₂ -15 ^m /o CaO Solid Solution	0.5 MoO ₃	2400°F	3 hrs	3.82	8.27	732 870 985 1219	-830 -820 -1110 -830	> 5	electronic uncertain
	1.0 MoO ₃	2500°F	3 hrs	3.96	0.052	802 932 1038 1140	-988 -1093 -1000 -1086	> 5	electronic uncertain
	2.0 MoO ₃	2600°F	3 hrs	3.98	0.000	1206 < 1200	-750 very large neg.	7.8	electronic uncertain
	5.0 MoO ₃	2600°F	3 hrs	4.10	0.000	770 > 770	-927 erratic, neg	> 5	electronic uncertain
		3000°F	2 hrs	4.52	17.50	680 857 950 1080 1230	-584 -565 -529 -313 -161	> 5	ionic, uncertain
	0.1 ^m /o Nb ₂ O ₅	3000°F	2 hrs	4.58	17.36	750 760 880 1240	-458 -170 +820 +508	4.45	ionic
	0.2 ^m /o Nb ₂ O ₅	3000°F	2 hrs	4.59	15.08	732 780 890 1230	-525 0 +1050 +485	4.4	ionic
	0.5 ^m /o Nb ₂ O ₅	3000°F	2 hrs	4.57	16.57	840 890 1230	-530 +1000 +544	4.58	ionic

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TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions		Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
1.0 ^m /o Nb ₂ O ₅		3000°F	2 hrs	4.68	15.29	656	-450		ionic
						732	-120		
						825	+1140		
						1230	+470	3.48	
2.0 ^m /o Nb ₂ O ₅		3000°F	2 hrs	4.88	1.73	656	-1240		ionic uncertain
						732	-79		
						825	+1560		
						1230	+490	>5	
5.0 ^m /o Nb ₂ O ₅		3000°F	2 hrs	5.05	7.97	610	-1060		ionic uncertain
						742	-178		
						960	+1370		
						1230	+1010	>5	
0.1 ^m /o La ₂ O ₃		3000°F	2 hrs	4.60 g/cm ³	15.56	722	-306		ionic
						788	-67		
						840	+750		
						942	+666		
0.2 ^m /o La ₂ O ₃		3000°F	2 hrs	4.58	15.51	1200		4.78	ionic
						722	-454		
						840	-38		
						870	+811		
0.5 ^m /o La ₂ O ₃		3000°F	2 hrs	4.59	15.77	1218	+505	5.56	ionic
						788	erratic, +		
						906	+1542		
						1050	+700		
1.0 ^m /o La ₂ O ₃		3000°F	2 hrs	4.58	16.51	1208	+528	5.2	ionic
						840	-1124		
						850	-54		
						906	+978		
						990	+578		
						1200		5.5	

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TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions		Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
ZrO_2 - 7 M_2O_3 Y_2O_3 Solid Solution	2.0 m/o La_2O_3	3000°F	2 hrs	4.66	16.04	650 728 1190	-323 -29 +554		ionic
	5.0 m/o La_2O_3	3000°F	2 hrs	4.32	20.39	656 765 980	-610 -32 +560	5.65	ionic uncertain
	0.1 m/o La_2O_3	3000°F	2 hrs	4.86	15.28	760 860 964 1100 1206	+1106 +1901 +641 +866 +695	>5	ionic
	0.2 m/o La_2O_3	3000°F	2 hrs	4.85	15.15	964 1020 1100 1140 1206	-3333 -3040 -1264 -13 +181	4.03 ohm-cm	ionic
	0.5 m/o La_2O_3	3000°F	2 hrs	4.92	14.85	856 892 1000 1080 1156	-1290 0 +490 +516 +521	4.5	ionic
	1.0 m/o La_2O_3	3000°F	2 hrs	4.96	14.52	820 856 892 1000 1156	+1315 +961 +690 +590 +544	>5	ionic uncertain
	2.0 m/o La_2O_3	3000°F	2 hrs	5.14	12.91	806 834 860 960 1198	-1164 -11 +324 +465 +550	>5	ionic
								4.65	

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TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions		Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
5.0 ^m /o La ₂ O ₃		3000°F	2 hrs	5.09	9.54	834	+816	4.17	ionic
						860	+910		
						960	+582		
						1200			
4 ^m /o La ₂ O ₃		3000°F	2 hrs	5.24	7.0	<843	erratic, neg	> 5	ionic uncertain
						924	0		
						950	+1410		
						1140	> +1720		
7 ^m /o La ₂ O ₃		3000°F	2 hrs	5.33	3.8	870	> +2000	> 5	ionic uncertain
						950	+861		
						1046	+1500		
						1122	+2700		
10 ^m /o La ₂ O ₃		3000°F	2 hrs	5.55	0.6	<797	erratic, neg	> 5	ionic uncertain
						906	+1000		
						994	+1180		
						1097	+3070		
0.1 ^m /o Nb ₂ O ₅		3000°F	2 hrs	4.96 g/cm ³	12.36	792°C	0 ^m V/°C	> 5	ionic uncertain
						920	+1769		
						1210	+914		
0.2 ^m /o Nb ₂ O ₅		3000°F	2 hrs	4.99	11.51	900 to	erratic, pos	> 5	ionic uncertain
						946	0		
						982	-84		
						1016	0		
0.5 ^m /o Nb ₂ O ₅		3000°F	2 hrs	5.00	11.92	1210	+38	> 5	ionic uncertain
						650	0		
						784	+1209		
1.0 ^m /o Nb ₂ O ₅		3000°F	2 hrs	5.03	11.26	1220	+427	> 5	ionic uncertain
						837	0		
						856	+1117		
						1220	+736	> 5	

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TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions		Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
2.0 ^m /o Nb ₂ O ₅		3000°F	2 hrs	5.21	7.38	838	0		ionic
						874	+700		
						1220	+1095	>5	uncertain
5.0 ^m /o Nb ₂ O ₅		3000°F	2 hrs	5.46	0.013	750	-	2962	ionic
						788	-	2030	
						<800	erratic, neg	-	
						811	0	-	
						898	-	766	
						978	-	420	
						998	> +2300	-	
						1080	-	187	
						1170	-	111	
						1200	-	97.7	
						1220	+213		
4.0 ^m /o Nb ₂ O ₅		3000°F	2 hrs	5.60	0.013	<986	erratic, pos		electronic
						986	0		
						1038	-950		
						1156	> -147	1.78	
7.0 ^m /o Nb ₂ O ₅		3000°F	2 hrs	4.85	14.7	<924	erratic, neg		ionic
						924	0		
						950	+355		
						1097	> +1785	>5	
10.0 ^m /o Nb ₂ O ₅		3000°F	2 hrs	4.97	13.4	<770	erratic, neg		ionic
						770	0		
						825	+1064		
						880	> +1176		
						1002	> +1538		
						1140	> +1612	>5	uncertain

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TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp. Time	Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
ZrO_2 - 17 $m\%$ CeO_2 Solid Solution	0.1 $m\%$ La_2O_3	3000°F 2 hrs	5.70	3.61	722 770 890 1240	-1106 0 +3225 +9000	> 5	ionic uncertain
	0.2 $m\%$ La_2O_3	3000°F 2 hrs	5.56	4.99	erratic results thru out			unknown
	0.5 $m\%$ La_2O_3	3000°F 2 hrs	5.69	3.26	790 924 1250	0 +2044 +630	> 5	ionic uncertain
	1.0 $m\%$ La_2O_3	3000°F 2 hrs	5.64	3.57	915 1250	+639 +664	> 5	ionic uncertain
5.0 $m\%$ La_2O_3	2.0 $m\%$ La_2O_3	3000°F 2 hrs	5.44	3.81	915 1250	+2631 +630	> 5	ionic uncertain
	5.0 $m\%$ La_2O_3	3000°F 2 hrs	5.47	4.06	860 1250	+1470 +370	> 5	ionic uncertain
	0.1 $m\%$ Nb_2O_5	3000°F 2 hrs	5.58	3.58	798 968 1093 1190	-213 > +3600 +1153 -1800	> 5	ionic uncertain
	0.2 $m\%$ Nb_2O_5	3000°F 2 hrs	5.52	4.08	< 1100 1118 1182	very large neg -3800 -1300	> 5	electronic uncertain
0.5 $m\%$ Nb_2O_5	0.5 $m\%$ Nb_2O_5	3000°F 2 hrs	5.60	4.37	< 732 852 976 1114	erratic, neg > -787 > -877 > -1000	> 5	electronic uncertain
	1.0 $m\%$ Nb_2O_5	3000°F 2 hrs	5.42	8.2	906 1034 1150 1223	-589 -882 -833 -545	> 5	electronic uncertain

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TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions		Density	Porosity	Temperature °C	Seebeck		Resistivity	Conduction
		Temp.	Time				Coefficient	Resistance		
	2.0 ^m /o Nb ₂ O ₅	Failed								
	5.0 ^m /o Nb ₂ O ₅	Failed								
ZrO ₂	55 ^m /o ZrH _{1.33}	2200°F	4 hrs	argon	8.85%	784 960 1140 1219	erratic, AT too large	0.008 ohms 0.012 0.011 0.007		
		2200°F	4 hrs	argon	9.10	646 714 806 875 1050 1219	+12.7 +16.4 +11.4	0.021 0.017 0.020 0.013		
	45 ^m /o ZrH _{1.33}	2200°F	4 hrs	argon	9.60	1218	unreliable specimen oxidized	0.006		
	40 ^m /o ZrH _{1.33}	2200°F	4 hrs	argon	9.60		specimen oxidized			

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TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp	Time						
CeO ₂		3000°F	2 hrs	6.56	0	<814	erratic, [†]		
						814	0		uncertain
						850	+431		
						938	0		
						1086	-489		
						1220	-575	>5.00	
	0.1 ^m /o Nb ₂ O ₅	2900°F	2 hrs	7.14	28.17	596	-780		electronic
						692	-786		uncertain
						878	-796		
						1054	-729		
						1214	-669	~5	
	0.2 ^m /o Nb ₂ O ₅	2900°F	2 hrs	6.98	17.59	694	-700		electronic
						878	-760		uncertain
						1010	-615		
						1205	-710	>5	
	0.5 ^m /o Nb ₂ O ₅	2900°F	2 hrs	5.87	16.57	606	-625		electronic
						786	-604		
						931	-647		
						1205	-717	3.05	
	1.0 ^m /o Nb ₂ O ₅	2900°F	2 hrs	5.90	14.82	596	-625		electronic
						786	-588		
						913	-587		
						1188	-595	1.66	
	2.0 ^m /o Nb ₂ O ₅	2900°F	2 hrs	5.98	10.66	596	-457		electronic
						692	-456		
						878	-496		
						1054	-504		
							< -527	1.24 0.73	

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TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp. Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
5. 6 ^m % Nb ₂ O ₅		2900°F 2 hrs	6. 10	1. 69	616	-455		electronic
					730	-450		
					817	-433		
					958	-466		
					1153		1. 13	
3 ^m % Nb ₂ O ₅		3000°F 2 hrs	6. 07	1. 40	1205	-482		electronic
					728	-450		
					760		5. 05	
					806	-438		
					950		1. 55	
					960	-424		
					1050		0. 90	
4. 6 ^m % Nb ₂ O ₅		2900°F 2 hrs	5. 79	5. 42	1097	-500		electronic
					1173		0. 69	
					732	-515		
					806	-504		
					880	-512		
					986		1. 56	
					1004	-523		
CeO ₂	0. 1 ^m % La ₂ O ₃	2900°F 2 hrs	5. 88	16. 85	1080		1. 32	mixed uncertain
					1120	-522		
					1198		1. 13	
					740	0		
					795	+3		
					859	0		
					904	+188		
					1013	0		
					1053	-129		
					1220	-529	> 5	

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TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
0.2 ^m % La ₂ O ₃		2800°F	2 hrs	4.90	16.21	740	-800		mixed uncertain
						805	0		
						878	+940		
						940	+614		
						1112	0		
						1172	-277	> 5	
0.5 ^m % La ₂ O ₃		2900°F	2 hrs	6.25	8.47	654	-120		mixed uncertain
						692	-416		
						786	0		
						823	+168		
						913	+412		
						1019	+427		
1.0 ^m % La ₂ O ₃		2900°F	2 hrs	5.86	17.66	1171	0		mixed uncertain
						1208	> -109	> 5	
						692	-189		
						823	0		
						913	+374		
						1035	+311		
2.0 ^m % La ₂ O ₃		2900°F	2 hrs	5.62	24.39	1188	0		mixed uncertain
						1208	-30	> 5	
						832	0		
						841	+303		
						1101	+386		
						1104	+333		
5.0 ^m % La ₂ O ₃		2900°F	2 hrs	4.80	46.38	1238	< +159	> 5	ionic uncertain
						832	0		
						841	+466		
						1101	+423		
						1104	+584		
						1238	< +691	> 5	

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TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction	
		Temp.	Time							
CeO ₂	0.1 ^m % Y ₂ O ₃	2900°F	2 hrs	6.01	12.59	694	-361		mixed uncertain	
						820	0			
						860	+281			
						1018	+143			
						1053	0			
								</		

APPENDIX

TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
CeO ₂	7 ^m /o Y ₂ O ₃	3000°F	2 hrs	5.64	15.5	942 1020 1140 1223	+366 +263 +375 +331		ionic
	10 ^m /o Y ₂ O ₃	3000°F	2 hrs	5.19	20.7	960 1084 1140 1198 1223	+519 -61 +41 +294	5.1	ionic
	0.1 ^m /o UO ₂	2200°F	2 hrs	argon	0.65	all temps	very large and erratic	> 5	
	0.2 ^m /o UO ₂	2200°F	2 hrs	argon	0.65	all temps	very large and erratic	> 5	
	0.5 ^m /o UO ₂	2200°F	2 hrs	argon	0.45	all temps	very large and erratic	> 5	
	1.0 ^m /o UO ₂	2200°F	2 hrs	argon	0.5	all temps	very large and erratic	> 5	
	2.0 ^m /o UO ₂	2200°F	2 hrs	argon	0.7	all temps	very large and erratic	> 5	
	5.0 ^m /o UO ₂	2200°F	2 hrs	argon	0.7	508°C only reading that could be obtained	+361	> 5	
Base Material	Addition	Firing Conditions		Atmosphere	Shrinkage	Temp °C	Seebeck Coefficient	Resistivity ohm-cm	
		Temp.	Time						
CeO ₂	0.1 ^m /o UO ₂	2200°F	2 hrs	argon	0.65	all temps	very large and erratic	> 5	
	0.2 ^m /o UO ₂	2200°F	2 hrs	argon	0.65	all temps	very large and erratic	> 5	
	0.5 ^m /o UO ₂	2200°F	2 hrs	argon	0.45	all temps	very large and erratic	> 5	
	1.0 ^m /o UO ₂	2200°F	2 hrs	argon	0.5	all temps	very large and erratic	> 5	
	2.0 ^m /o UO ₂	2200°F	2 hrs	argon	0.7	all temps	very large and erratic	> 5	
	5.0 ^m /o UO ₂	2200°F	2 hrs	argon	0.7	508°C only reading that could be obtained	+361	> 5	

APPENDIX

TABLE AII

Summary of Ceramic and Electrical Properties of
Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
Li ₂ TiO ₃		2400°F	3 hrs	3.86 g/cm ³	3.27%	<800°C 950 1050 1215	erratic, neg. +2173 μ V/°C +2514 +1459	> 5 ohm-cm	ionic, uncertain
	0.1 ^m % ZnO	2400°F	3 hrs	2.82	14.7	<800 950 981 1135 1215	erratic, neg. +2040 0 -588 -1172		mixed, uncertain
	0.2 ^m % ZnO	2400°F	3 hrs	2.85	15.1	<800 950 1215	erratic, neg. +1639 +326	> 5	ionic uncertain
	0.5 ^m % ZnO	2400°F	3 hrs	2.85	13.4	700 978 1215	erratic, neg. +2000 +87	> 5	ionic uncertain
	1.0 ^m % ZnO	2400°F	3 hrs	2.87	13.7	700 980 1215	erratic, neg. +1100 +1300	> 5	ionic uncertain
	2.0 ^m % ZnO	2400°F	3 hrs	2.90	11.8	(~700 ((~1000 ((~1200 (erratic, large neg. erratic, large pos. erratic, large neg.	> 5	unknown
	5.0 ^m % ZnO	2400°F	3 hrs	2.93	12.3				
	0.1 ^m % MgO	2400°F	3 hrs	3.03	12.7	<950 950 1012 1152	erratic, pos. 0 +779 +897	> 5	ionic, uncertain

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TABLE AII (continued)

Summary of Ceramic and Electrical Properties of
Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions		Bulk Density g/cm ³	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
Li ₂ TiO ₃	0.2 ^m % MgO	2400°F	3 hrs	2.85	13.2	<870	erratic, neg.		mixed, uncertain
						870	0		
						916	>+775		
	0.5 ^m % MgO	2400°F	3 hrs	3.15	11.3	1190	>+1490	> 5 ohm-cm	ionic, uncertain
						<914	erratic, pos.		
						914	>+1470		
	1.0 ^m % MgO	2400°F	3 hrs	2.88	10.2	986	>+770		mixed, uncertain
						1080	+1085	> 5	
						<968	erratic, neg.		
	2.0 ^m % MgO	2400°F	3 hrs	2.87	11.3	968	0		mixed, uncertain
						1140	+1094	> 5	
						<704	erratic, neg.		
	5.0 ^m % MgO	2400°F	3 hrs	2.88	12.3	704	0		ionic uncertain
						820	+456		
						942	>+825	> 5	
	0.1 ^m % SnO	2400°F	3 hrs	2.83	15.2	1206	>+925		electronic, uncertain
						<723	erratic, pos.		
						723	>+943		
	0.2 ^m %	2400°F	3 hrs	2.83	13.4	924	>+1100		ionic uncertain
						1122	+1017	> 5	
						<852	erratic, neg.		
	0.1 ^m % SnO	2400°F	3 hrs	2.83	15.2	852	-1175		electronic, uncertain
						1046	-1130		
						1173	-24	> 5	
	0.2 ^m %	2400°F	3 hrs	2.83	13.4	<746	erratic, neg.		ionic uncertain
						746	0		
						861	>+1220		
	0.2 ^m %	2400°F	3 hrs	2.83	13.4	1028	>+1785		ionic uncertain
						1164	>+1960	> 5	

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TABLE AII (continued)

Summary of Ceramic and Electrical Properties of
Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions Temp. Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li ₂ TiO ₃	0.5 ^m /o SnO	2400°F 3 hrs	2.86	12.6	<788	erratic +		
					893	>+1350-		ionic
					1020	>+2222		uncertain
					1168	>+1695	> 5 ohm-cm	
	1.0 ^m /o SnO	2400°F 3 hrs	2.89	11.3	<843	erratic, neg		electronic,
					843	>-1315		uncertain
					959	-3480		
					1207	-253	> 5	
	2.0 ^m /o SnO	2400°F 3 hrs	2.95	8.5	<843	erratic, neg		ionic,
					843	>+2600		uncertain
					888	>+2440		
					1046	>+1200		
	5.0 ^m /o SnO	2400°F 3 hrs	3.04	5.1	1198	>+952	> 5	
					742	-282		electronic,
					870	-297		uncertain
					981	-276		
	0.1 ^m /o NiO	2400°F 3 hrs	2.83	14.6	1063	-277		
					1164	-305	> 5	
					820	erratic, neg.		ionic
					843	>+1043		uncertain
	0.2 ^m /o NiO	2400°F 3 hrs	2.83	14.4	875	>+1000	> 5	
					816	erratic, +		ionic
					875	>+1470		uncertain
					1003	>+2220		
	0.5 ^m /o NiO	2400°F 3 hrs	2.83	14.5	1164	>+5000		
					<676	erratic, neg.		ionic
					732	>+1053		uncertain
					932	>+1265		
					1046	>+1493		
					1156	>+1515	> 5	

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TABLE AII (continued)

Summary of Ceramic and Electrical Properties of
Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density g/cm ³	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li ₂ TiO ₃	1.0 ^m /o NiO	2400°F	3 hrs	2.84	14.5	820 895 976 1173	erratic, neg. +1077 0 -536	> 5 ohm-cm	mixed, uncertain
	2.0 ^m /o NiO	2400°F	3 hrs	2.83	15.6	<816 976 1182	erratic, neg. +1960 +2630	> 5	ionic, uncertain
	5.0 ^m /o NiO	2400°F	3 hrs	2.83	16.5	<816 932 1046 1063 1190	erratic, neg. +2100 0 -1667 -311	> 5	mixed, uncertain
0.1 ^m /o Bi ₂ O ₃	0.1 ^m /o Bi ₂ O ₃	2200°F	2 hrs	2.99	2.63	<916 916 1124	erratic, neg. -980 0	> 5	mixed, uncertain
	0.2 ^m /o Bi ₂ O ₃	2200°F	2 hrs	2.97	3.56	842 1028	erratic, + +901	> 5	ionic, uncertain
	0.5 ^m /o Bi ₂ O ₃	2200°F	2 hrs	2.92	4.53	709 860 1028	erratic, neg. +530 +750	> 5	ionic, uncertain
1.0 ^m /o Bi ₂ O ₃	1.0 ^m /o Bi ₂ O ₃	2200°F	2 hrs	2.91	8.28	<770 770 916 1028	erratic, neg. -267 0 +1333	> 5	mixed, uncertain
	2.0 ^m /o Bi ₂ O ₃	2200°F	2 hrs	2.92	7.07	<994 994 1012 1080	erratic, neg. -372 0 +892	> 5	mixed, uncertain
	5.0 ^m /o Bi ₂ O ₃	(Unavailable)			4-20	<916 916 1050	erratic, pos. +224 +1449	> 5	ionic, uncertain

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TABLE AII (continued)

Summary of Ceramic and Electric Properties of
Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density g/cm ³	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li ₂ TiO ₃	0.1 ^m % ZrO ₂	2400°F	3 hrs.	2.83	14.7	<700	erratic, neg.		
						920	0		ionic, uncertain
						1016	+844		
						1122	+1200		
						1135	+1215		
	0.2 ^m % ZrO ₂	2400°F	3 hrs	2.85	12.8	1164	+1164		
						1220	+932	> 5 ohm-cm	
						<700	erratic, neg.		electronic, uncertain
						950	0		
						1140	-1246		
	0.5 ^m % ZrO ₂	2400°F	3 hrs	2.87	12.7	1215	-412	> 5	
						<700	erratic, neg.		ionic, uncertain
						788	+1000		
						950	+438		
						1215	+885	> 5	
	1.0 ^m % ZrO ₂	2400°F	3 hrs	2.90	10.1	<700	erratic, neg.		mixed, uncertain
						778	0		
						994	+1400		
						1122	0		
						1206	-700	> 5	
	2.0 ^m % ZrO ₂	2400°F	3 hrs	2.94	6.4	<700	erratic, neg.		ionic, uncertain
						994	>+2700		
						1206	+1400	> 5	
	5.0 ^m % ZrO ₂	2400°F	3 hrs	3.04	4.2	<700	erratic, neg.		mixed, uncertain
						906	>+2100		
						976	0		
						1004	-1910		
						1215	-1391	> 5	
	0.1 ^m % CeO ₂	2400°F	3 hrs	2.86	14.0	<700	erratic, neg.		ionic, uncertain
						960	+1800		
						1164	+714	> 5	

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TABLE AII (continued)

Summary of Ceramic and Electric Properties of
Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions Temp. Time	Bulk Density g/cm ³	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li ₂ TiO ₃	0.2 ^m /o CeO ₂	2400°F 3 hrs	2.86	13.1	< 700	erratic, neg.		
					826	+3000		unknown
					960	0		
					1012	-634		
					1088	0		
	0.5 ^m /o CeO ₂	2400°F 3 hrs	2.91	9.8	1215	+1258	> 5 ohm-cm	
					< 700	erratic, neg.		ionic, uncertain
					960	+2000		
					1200	+1105	> 5	
	1.0 ^m /o CeO ₂	2400°F 3 hrs	2.90	10.9	< 700	erratic, neg.		ionic, uncertain
					960	+2000		
					1200	+927	> 5	
	2.0 ^m /o CeO ₂	2400°F 3 hrs	2.93	10.8	< 700	erratic, neg.		ionic, uncertain
					960	+1700		
					1215	+895	> 5	
	5.0 ^m /o CeO ₂	2400°F 3 hrs	3.03	10.4	< 700	erratic, neg.		ionic
					750	-	628	
					898	-	63.2	
					960	+1800	-	
					978	-	19.6	
	4 ^m /o CeO ₂	2400°F 2 hrs.	3.13	4.62	1080	-	25.5	
					1090	+957	-	
					1170	-	23.4	
					1200	-	25.7	
					1215	+1400	-	
	7 ^m /o CeO ₂	2400°F 2 hrs	3.25	4.70	842	> -1450		electronic, uncertain
					986	> -2040		
					1080	> -3125		
					1206	-663	> 5 ohm-cm	
			A-22		843	> +1410		ionic, uncertain
					1046	> +2080		
					1164	> +1205	> 5	

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TABLE AII (continued)

Summary of Ceramic and Electric Properties of
Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Condition Temp. Time	Bulk Density g/cm ³	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li ₂ TiO ₃	10 ^{mol} % CeO ₂	2400°F 2 hrs	3.38	4.23	<850	erratic, neg.		
					950	+1180		Mixed, uncertain
					1106	0		
	2400°F 2 hrs	2400°F 2 hrs	2.81	14.99	1182	-2250	> 5 ohm-cm	
					<784	erratic, neg		ionic, uncertain
					784	0		
					964	+2666		
					1220	+1160	> 5	
	0.1 ^{mol} % ThO ₂	2400°F 2 hrs	2.79	16.37	<802	erratic, neg.		ionic, uncertain
					802	0		
					876	+1424		
0.2 ^{mol} % ThO ₂	2400°F 2 hrs.	2400°F 2 hrs.	2.79	17.13	1016	+127	> 5	
					<765	erratic, neg.		ionic, uncertain
					765	0		
	2400°F 2 hrs	2400°F 2 hrs	2.87	13.53	839	+1700		
					1016	+3000		
					1220	+1000	> 5	
					<764	erratic, neg.		ionic or mixed, uncertain
					764	0		
					829	+1118		
					875	+464		
0.5 ^{mol} % ThO ₂	2400°F 2 hrs	2400°F 2 hrs	2.87	14.98	1050	+87	> 5	
					<820	erratic, neg.		ionic, uncertain
					820	0		
	2400°F 2 hrs	2400°F 2 hrs	2.88	16.11	937	+893		
					1220	+1643	> 5	
					<790	erratic, neg.		electronic, uncertain
					793	-860		
					937	-1099		
					1220	-1200	> 5	
2.0 ^{mol} % ThO ₂	2400°F 2 hrs	2400°F 2 hrs	2.51	30.90	<820	erratic, neg.		mixed uncertain
					821	-1342		
					972	0		
	5.0 ^{mol} % ThO ₂	2400°F 2 hrs		A-23	1916	+1310	> 5	

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TABLE AII (continued)

Summary of Ceramic and Electric Properties of
Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Condition Temp. Time	Bulk Density g/cm ³	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li ₂ TiO ₃	0.1 ^m /o Nb ₂ O ₅	2400°F 3 hrs	2.91	14.5	<700	erratic, neg.		
					964	+1900		ionic, uncertain
					1050	+705		
					1215	+113	> 5 ohm-cm	
	0.2 ^m /o Nb ₂ O ₅	2400°F 3 hrs	2.94	11.7	<700	erratic, neg.		ionic, uncertain
					970	+1700		
					1070	0		
					1215	+241	> 5	
	0.5 ^m /o Nb ₂ O ₅	2400°F 3 hrs	3.00	4.1	<700	erratic, neg.		ionic, uncertain
					950	+1600		
					1070	+1135	> 5	
					1215	+787		
	1.0 ^m /o Nb ₂ O ₅	2400°F 3 hrs	3.03	3.3	<700	erratic, neg.		ionic, uncertain
					852	+3000		
					950	+1500	> 5	
					1215	+577		
	2.0 ^m /o Nb ₂ O ₅	2400°F 3 hrs	3.09	2.9	<700	erratic, neg.		ionic, uncertain
					850	+4000		
					950	+1250	> 5	
					1215	+650		
	5.0 ^m /o Nb ₂ O ₅	2400°F 3 hrs	3.24	2.8	<700	erratic, neg.		ionic, uncertain
					950	+1500	> 5	
					1215	+370		
	0.1 ^m /o Ta ₂ O ₅	2400°F 3 hrs	2.98	8.9	<700	erratic, neg.		mixed, uncertain
					900-1000	+2300		
					1050	0	> 5	
					1200	+1000		
	0.2 ^m /o Ta ₂ O ₅	2400°F 3 hrs	2.95	7.3	<700	erratic, neg.		mixed, uncertain
					850	0		
					1000	-1000		
					1050	0	> 5	
				A-24	1200	+500		

APPENDIX

TABLE AII (continued)

Summary of Ceramic and Electric Properties of
Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions		Bulk Density g/cm ³	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
Li ₂ TiO ₃	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	<700	erratic, neg.		mixed, uncertain
						1050	>+2300		
						1190	0		
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	1200	+323	> 5 ohm-cm	mixed, uncertain
						924	> -1700		
986						0			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1030	+537		mixed
						1056	0		
						1114	-415		
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	1198	-73	> 5	ionic,
						942	erratic, neg.		
960						+1900			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1050	>+2300		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.12	3.2	924	> -1700		mixed, uncertain
						986	0		
1030						+537			
Li ₂ SnO ₃	2.0 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.17	4.6	1056	0		mixed
						1114	-415		
						1198	-73	> 5	
	5.0 ^m % Ta ₂ O ₅	2300°F	2 hrs	4.36	13.2	942	erratic, neg.		ionic,
						960	+1900		
1050						0			
LiAlO ₂	0.5 ^m % Ta ₂ O ₅	2400°F	3 hrs	3.06	3.7	1122	-473		mixed, uncertain
						1190	0		
						1200	+323	> 5 ohm-cm	
	1.0 ^m % Ta ₂ O ₅	2400°F	3 hrs						

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TABLE AIII

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp. Time	Bulk Density g/cm ³	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
BaTiO ₃		2500°F 2 hrs	5.67	5.16%	1232°C 1106 986 888 770 <770	+439 μ V/°C +628 +962 +1098 +672 erratic +	>5 ohm-cm	unknown
	0.1 ^m % La ₂ O ₃	2400°F 0 hrs	5.54	7.28	742 915 1236 750 980 1219	-638 -958 -566 -929 -742 -628	>5	electronic, uncertain
	0.2 ^m % La ₂ O ₃	2400°F 0 hrs	5.84	0.047	<960 960 1174 1256	erratic, neg -1328 -1171 -1203	>5	electronic uncertain
	0.5 ^m % La ₂ O ₃	2500°F 2 hrs	5.34	7.49	<915 915 1030 1174	erratic, neg -969 -860 -1087	>5	electronic uncertain
	1.0 ^m % La ₂ O ₃	2700°F 2 hrs	5.54	0.14				
	2.0 ^m % La ₂ O ₃) 5.0 ^m % La ₂ O ₃)	Failed						
	0.1 ^m % Nb ₂ O ₅	2500°F 2 hrs	Unavailable		<906 906 942 1100	erratic, neg -981 0 -676	>5	electronic uncertain
	0.2 ^m % Nb ₂ O ₅	Failed						
	0.5 ^m % Nb ₂ O ₅	2600°F 2 hrs	5.42	4.66	<745 745 946 1220	erratic, neg -1754 -1951 -2976	>5	electronic uncertain

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
	1. 0 ^m /o Nb ₂ O ₅	2500°F	2 hrs	5. 22	7. 32	<788 788 862 >862	erratic, neg -610 -1224 very large, >5 neg		electronic uncertain
	2. 0 ^m /o Nb ₂ O ₅	2500°F	2 hrs	5. 50	0. 0	<750 750 824 950 >950 <836 836 1046 1206	erratic, neg -764 -763 -328 erratic, - erratic, pos. +980 0 +221		electronic uncertain
	5. 0 ^m /o Nb ₂ O ₅	2700°F	2 hrs	5. 17	8. 06	960 780 960	>5 erratic, pos. +980 0 +221		ionic uncertain
	BaTiO ₃	2400°F	0 hrs	5. 73	0. 73	<780 780 960	erratic, neg -139 -425		electronic uncertain
	0. 2 ^m /o Sb ₂ O ₃	2400°F	0 hrs	5. 69	1. 05	<960 960 1164	erratic, neg -778 -767		electronic uncertain
	0. 5 ^m /o Sb ₂ O ₃	2500°F	2 hrs	5. 52	0. 65	<1050 1050 1240	erratic, neg -757 -651		electronic uncertain
	1. 0 ^m /o Sb ₂ O ₃	2500°F	2 hrs	5. 66	0. 00	<1050 1050 1240	erratic, neg -827 -807		electronic uncertain
	2. 0 ^m /o Sb ₂ O ₃	2500°F	2 hrs	5. 23	0. 00	750 870 1002 1206	-133 -647 -1090 -800		electronic uncertain
								>5	

APPENDIX

TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
BaTiO ₃	5.0 ^m /o Sb ₂ O ₃	2500°F	2 hrs	5.62	0.00	<600 825 >825	erratic, neg -770 very large neg.	>5	electronic uncertain
	0.1 ^m /o CeO ₂	2500°F	2 hrs	5.31 g/cm ³	3.33	<714 950 1140 1240	erratic, neg +395 0 -519	>5	unknown
	0.2 ^m /o CeO ₂	2500°F	2 hrs	5.34	3.34	<679 852 1198 1240	erratic, neg +934 0 +107	>5	unknown
	0.5 ^m /o CeO ₂	2500°F	2 hrs	5.27	6.22	1012 1050 1215	erratic, neg -767 -861	>5	electronic uncertain
	1.0 ^m /o CeO ₂	2600°F	2 hrs	5.38	6.20	1012 1050 1215	erratic, neg -780 -738	>5	electronic uncertain
LaCrO ₃	2.0 ^m /o CeO ₂	2600°F	2 hrs	5.41	4.31	986 1038 1215	erratic, neg -381 -833	>5	electronic uncertain
	5.0 ^m /o CeO ₂	2600°F	2 hrs	5.36	6.67	1038 1172 1215	erratic, neg -850 -772	>5	electronic uncertain
	3000°F	2 hrs		6.46 g/cm ³	0.0%	582°C 650 819 906 967 1032	+634 ₁₁ v/°C +629 +288 +640 +650 +695	4.32 ohm-cm 3.59 3.26	ionic

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
0.1 ^m % TiO ₂		3000°F	2 hrs	6.31	0.7	592 708 874 963 1041 1100 1231	+571 +563 +541 558		ionic
0.2 ^m % TiO ₂	Failed to sinter								
0.5 ^m % TiO ₂	Failed to sinter								
1.0 ^m % TiO ₂	Failed to sinter							3.65 1.97	
2.0 ^m % TiO ₂	Failed to sinter								
5.0 ^m % TiO ₂		3000°F	2 hrs	5.52	13.2	570 724 881 998 1134	+532 +522 +541 +554 +565	2.74 2.03	ionic
0.1 ^m % ZrO ₂		3000°F	2 hrs	5.40	17.73	592 810 928 945 1050 1109 1126 1216	+560 +547 + +568 +566 +591	2.38 2.22 1.55	ionic
0.2 ^m % ZrO ₂		3000°F	2 hrs	5.87	8.48	596 810 945 1041 1159	+580 +553 +584 +615 +595		ionic, uncertain

> 5 ohm-cm

APPENDIXTABLE AIII (continued)
Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
0.5 ^m % ZrO ₂		3000°F	2 hrs	5.44	16.85	677	+547		ionic
						777	+533		
						959	+564		
						1030	+555		
						1123	+532		
						1166		2.05	
						1205		3.12	
						1213	+560		
1.0 ^m % ZrO ₂		3000°F	2 hrs	5.94	6.96	594	+491		ionic
						814	+501		
						936	+509		
						1020	+516		
						1056		0.98	
						1112	+449		
						1171		1.08	
						1218	+454		
						1240		0.84	
2.0 ^m % ZrO ₂		3000°F	2 hrs	6.34	10.17	684	+543		ionic
						798	+557		
						904	+585		
						1099	+628		
						1216		1.21	
5.0 ^m % ZrO ₂		3000°F	2 hrs	6.20	1.88	670	+529		ionic
						762		1.38	
						768	+530		
						845		1.81	
						866	+532		
						964	+554		
						968		1.33	
						1072	+545		
						1172		1.15	
						1248		1.26	

APPENDIX

TABLE AIII (continued)

Summary of Ceramics and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
0.1 ^m % SnO ₂	0.2 ^m % SnO ₂	Failed to sinter		644	0.22	574	+587	3.61	ionic
		3000°F	2 hrs			668			
0.5 ^m % SnO ₂		3000°F	2 hrs	5.66	10.32	687	+586	2.77	
						760			
						807	+602	2.26	
						859			
						963	+522		
						1072	+637		
						1182	+689		
						633	+138		ionic
						706	+671		
						799	+626		
843	-277								
894	> -833								
943	+667								
1100	+711								
1213	+707								
1.0 ^m % SnO ₂		3000°F	2 hrs	4.46	33.2	770	+525	>5	ionic
						861	+548		
						968	+584		
						1080	+606		
2.0 ^m % SnO ₂		3000°F	2 hrs	6.38	0.11	1140	+663	1.9	
						1182			
						702	+631	•	ionic
						749			
						826	+658	4.58	
						841			
						942	+647	4.07	
						1036	+656		
						1053		3.40	
						1143			
1168	+601	2.93							
1235									
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TABLE AIII (continued)
Summary of Ceramics and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp. Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
LaCrO ₃	5.0 ^m % SnO ₂	3000°F 2 hrs	6.40	0.02	594	+568		ionic
					734	+555		
					850	+569		
					963	+574		
					982		2.09	
					1072	+585		
					1095		2.09	
					1185		1.91	
					1200	+577		
					602	+628		
	0.1 ^m % CeO ₂	Failed to sinter	6.47	0	689	+600		ionic
					766	+630		
					938	+684	3.52	
					1013	+652	3.80	
					1166	---	3.38	
					1223	---	3.97	
							3.61	
	0.2 ^m % CeO ₂	Failed to sinter	6.56	0	592	+672		ionic
					792	+667		
					1019	+698		
					1034		4.52	
					1119	+713		
					1226	+705		
					1255		4.03	
	0.5 ^m % CeO ₂	3000°F 2 hrs	6.52	0.05	758	+629		ionic
					957	+661		
					985		5.35	
					1063		5.23	
					1089	+663		
					1154		4.65	
					1193	+679		
					1257		4.08	

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TABLE AIII(continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
1. 0 ^m /oCeO ₂		3000°F	2 hrs	4. 46	33. 30	648		3. 68	ionic
						690	+522		
						790		3. 45	
						810	+512		
						909		2. 89	
						936	+509		
						1030		2. 08	
						1034	+529		
						1117		2. 65	
						1151	+541		
2. 0 ^m /oCeO ₂		3000°F	2 hrs	6. 47	0	1065		2. 24	ionic
						1163		4. 67	
						1230		3. 66	
						1173	+288	3. 98	
						1049	+723		
						958	+691		
						842	+675		
						730	+665		
						570	+708		
						664	+595	5. 76	
5 ^m /oCeO ₂		3000°F	2 hrs	5. 96	6. 62	700			ionic
						762	+588		
						876	+580	2. 47	
						910			
						975	+574	3. 45	
						1048	+545		
						1097	+590		
						1206		2. 37	
						1223			

APPENDIX

TABLE AIII(continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
YCrO ₃		3000°F and	2 hrs	3.82	32.7	< 1002	erratic, pos		ionic
		3100°F	2 hrs			1002	+371		uncertain
						1028	+372		
						1219	+1070	> 5	
	.1 ^m /oCeO ₂	3000°F and	2 hrs	4.34	22.8	806	terratic, pos		ionic
		3100°F	2 hrs			< 806	+831		uncertain
						897	+1000		
						1080	+1551		
						1224	+976	> 5	
	.2 ^m /oCeO ₂	3000°F and	2 hrs	4.03	28.9	< 994	erratic, +		mixed,
		3100°F	2 hrs			994	< -228		uncertain
						1054	0		
						1130	< +367	> 5	
	.5 ^m /oCeO ₂	3000°F and	2 hrs	4.36	22.6	816	erratic, pos		ionic
		3100°F	2 hrs			888	+967		uncertain
						1032	+1428		
						1169	+1108	> 5	
	1 ^m /oCeO ₂	3000°F and	2 hrs	3.98	29.9	< 1008	erratic, pos		mixed
		3100°F	2 hrs			1008	> +2326		uncertain
		3000°F and	2 hrs	3.41	40.1	1206	> -1613	> 5	mixed
	2 ^m /oCeO ₂	3100°F	2 hrs			< 942	large, neg		uncertain
		3000°F and	2 hrs			942	> -1408		
		3100°F	2 hrs			1050	> -1450	> 5	
						1218	+915		
	5 ^m /oCeO ₂	3000°F and	2 hrs	3.33	41.5	< 1008	erratic, neg		mixed
		3100°F	2 hrs			1008	-1605		uncertain
						1218	+1171	> 5	

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
.1 ^m /o TiO ₂		3000°F	2 hrs	4.90	10.2	1218	+1132	>5	ionic uncertain
						942	+906		
						824	+943		
						<824	erratic, pos		
.2 ^m /o TiO ₂		3000°F	2 hrs	4.75	14.0	1218	+970	>5	mixed uncertain
						994	0		
						<994	erratic, +		
.5 ^m /o TiO ₂		3000°F	2 hrs	5.05	8.0	1218	+1113	>5	mixed uncertain
						1072	-1900		
						<1072	very erratic, -	+	
1 ^m /o TiO ₂		3000°F	2 hrs	5.09	5.9	1218	+1160	>5	ionic uncertain
						1164	+2272		
						<1164	erratic, pos		
2 ^m /o TiO ₂		3000°F	2 hrs	5.46	3.2	1218	+128	>5	mixed uncertain
						1172	0		
						1130	-223		
						1012	-903		
5 ^m /o TiO ₂		3000°F	2 hrs	4.41	21.3	<1012	erratic, neg	>5	ionic uncertain
						1173	+867		
						986	+960		
						870	+830		
.1 ^m /o ZrO ₂		3100°F	2 hrs	4.66	17.37	<870	erratic, pos	>5	ionic, uncertain
						1038	>+1220		
						924	>+952		
						842	+788		
.2 ^m /o ZrO ₂		3100°F	2 hrs	4.63	17.8	<842	very large, pos.	>5	ionic uncertain
						986	+738		
						897	<+512	+	
						<897	erratic, -		

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	.5 ^m /oZrO ₂	3100°F	2 hrs	4.70	14.5	1198	+1125	>5	ionic uncertain
						1072	+2021		
						942	>+1429		
						824	> +1150		
						714	> +1052		
	zm/oZrO ₂	3100°F	2 hrs	4.06	29.0	<714	erratic, pos	>5	ionic uncertain
						1164	+703		
						1096	+337		
						<1096	erratic ⁺		
	5 ^m /oZrO ₂	3100°F	2 hrs	4.38	23.8	1218	>+787	>5	mixed uncertain
						1106	+1061		
						1012	0		
						942	-950		
						<942	erratic, neg		
PbNb ₂ O ₆		2150°F	2 hrs	6.07	5.48	1218	-1020	>5	mixed uncertain
						1160	-1961		
						1096	0		
						1008	+2375		
						937	+978		
	0.1 ^m /oCdO	2200°F	2 hrs	6.11	4.73	830	> +1587	very large, pos	mixed uncertain
						<830			
						680	-448		
						726	0		
						736	+350		
						838	> +1375	>5	
						998	+812		
						1066	0		
						1143	-519		

APPENDIX

TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
0.2 ^m % CdO		2200°F	2 hrs	6.10	4.32	<726	erratic, neg		mixed uncertain
						792	> -1138		
						902	0		
						910	+428		
						954	0		
0.5 ^m % CdO		2200°F	2 hrs	5.83	7.58	972	-194		electronic uncertain
						1024	-568	> 5	
						<754	erratic, neg		
						754	-411		
						928	> -2061		
1.0 ^m % CdO		2200°F	2 hrs	5.70	10.54	1066	-2500		mixed uncertain
						1168	-1060	> 5	
						<755	erratic, neg		
						755	> -1121		
						892	-1188		
2.0 ^m % CdO		2200°F	2 hrs	5.33	17.41	963	0		electronic
						980	+216		
						1016	0		
						1040	-73		
						1154	-712	> 5	
		2200°F	2 hrs			<736	erratic, neg		electronic
						736	-771		
						797		21, 200	
						801	> -1560		
						892	> -1821		
						897		6, 359	
						1016	-1141		
						1088		399	
						1152	-1121		
						1198		64	

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TABLE AIII(continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp. Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
5 ^m /oCdO		2200°F 2 hrs	4.91	24.8	<726	erratic, neg		
					726	> -1072		electronic
					782	> -1141		uncertain
					864	> -1236		
					1006	> -800		
0.1 ^m /oBi ₂ O ₃		2200°F 2 hrs	6.06	4.86	1118	-708	>5	
					<724	erratic, neg		
					724	-683		electronic
					800	-415		uncertain
					910	-1720		
0.2 ^m /o Bi ₂ O ₃		2200°F 2 hrs	6.09	4.93	1170	-994	>5	
					<718	erratic, neg		
					718	-498		electronic
					792	> -1138		uncertain
					892	> -1228		
0.2 ^m /oBi ₂ O ₃		2200°F 2 hrs	6.09	4.93	1168	-813	>5	
					<718	erratic, neg		
					718	-498		electronic
					792	> -1138		uncertain
					892	> -1228		
0.5 ^m /oBi ₂ O ₃		2200°F 2 hrs	5.74	6.54	1168	-813	>5	
					<715	erratic, neg		
					715	-685		electronic
					732		69,500	
					770	-1143		
					800		23,000	
					856			
					915			
					1015	-3285	3,798	
					1097		766	
					1142	-2098	244	
					1215			
							55	

APPENDIX

TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
	1.0 ^m /oBi ₂ O ₃	2200°F	2 hrs	5.63	9.34	<698	erratic, neg		electronic uncertain
						698	-1090		
						782	>-1290		
						836	>-1397		
						980	-771		
	2.0 ^m /oBi ₂ O ₃	2200°F	2 hrs	5.83	7.59	1168	-780	>5	electronic uncertain
						<762	erratic, neg		
						762	-1215		
						862	>-1724		
						936	-1233		
	5 ^m /oBi ₂ O ₃	2200°F	2 hrs	5.44	15.23	1150	-522	>5	electronic uncertain
						<670	erratic, neg		
						670	-1029		
						845	-745		
						928	-454		
PbNb ₂ O ₆		2150°F	2 hrs	6.06	5.26	1118	-744	>5	mixed uncertain
						1218	-921	>5	
						1192	0		
						1110	+1000		
						1032	+1979		
	0.1Sb ₂ O ₃	2150°F	2 hrs	6.00	5.58	924	+1257		electronic
						866	>+1333		
						<866	erratic, pos.		
						732		84,300	
						793		23,600	
						<800	erratic, neg		
						800	>-1751		
						915		3.699	
						972	>-1705		
						1016		801	
						1100		255	
						1160	>-1930		
						1207		68	

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
0.2 ^m /oSb ₂ O ₃		2150°F	2 hrs	5.91	5.90	<782	erratic, neg		mixed uncertain
						782	-910		
						874	0		
						936	> +1579		
						1058	0		
0.5 ^m /oSb ₂ O ₃		2150°F	2 hrs	5.98	5.20	1142	-641	> 5	electronic uncertain
						<754	erratic, neg		
						754	-279		
						812	-260		
						910	-1154		
1.0 ^m /oSb ₂ O ₃		2150°F	2 hrs	5.58	7.19	1143	-1272	> 5	unknown
						<708	erratic, neg		
						708	> -1040		
						762	0		
						802	+668		
2.0 ^m /oSb ₂ O ₃		Unavailable				846	0		electronic uncertain
						863	-167		
						892	0		
						945	+599		
						1066	0		
						1100	-264	> 5	electronic uncertain
						<782	erratic, neg		
						782	> -1176		
						874	> -1277		
						998	-505		
						1151	< -874	> 5	

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TABLE AIII(continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp. Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
PbNb ₂ O ₆	5.0 ^m /oSb ₂ O ₅	2150°F 2 hrs	6.04	4.44	<891	erratic, neg		electronic uncertain
					891	-909		
					954	-1056		
					1006	-788		
					1151	-791	>5	
	2200°F 2 hrs		6.00	5.69	1214	-980	>5	mixed uncertain
					1156	0		
					1054	+1885		
					<1054	erratic, pos		
					782	> -1494		mixed uncertain
	0.1 ^m /oMoO ₃	2150°F 2 hrs	5.96	5.82	874	> -1666		
					901	0		
					1032	+69		
					1041	0		
					1151	-661	>5	
	0.2 ^m /oMoO ₃	2150°F 2 hrs	5.86	5.72	880	> -1834		electronic uncertain
					1006	-1896		
					1185	-836	>5	
					782	> -1474		electronic uncertain
					874	> -1721		
	0.5 ^m /oMoO ₃	2150°F 2 hrs	5.97	5.82	998	-1585		
					1168	-796	>5	
					820	<+1111		mixed uncertain
					864	<+1165		
					936	0		
	1.0 ^m /oMoO ₃	2150°F 2 hrs	5.22	5.08	962	-486		
					1092	-895	>5	
					<968	erratic, neg		electronic uncertain
					968	-1468		
					981	-1808	>5	

APPENDIX

TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
PbNb ₂ O ₆	5.0 ^m %MoO ₃	2150°F	2 hrs	5.95	6.27	968	-1377		electronic uncertain
						1088	-1400		
						1190	-939	> 5	
		2200°F	2 hrs	6.13	4.98	1218	-852	> 5	ionic uncertain
						1122	-900		
						1002	-1215		
	0.1 ^m %WO ₃	2200°F	2 hrs	6.02	6.92	< 1002	erratic, neg		electronic uncertain
						< 906	erratic, neg		
						906	-304		
						968	-624		
	0.2 ^m %WO ₃	2200°F	2 hrs	5.91	6.79	1061	< -835		electronic uncertain
						1206	-925	> 5	
						< 896	erratic, neg		
	0.5 ^m %WO ₃	2200°F	2 hrs	6.03	3.66	896	-56		electronic uncertain
						960	-539		
						1148	-925	> 5	
	1.0 ^m %WO ₃	2200°F	2 hrs	5.94	5.00	< 694	erratic, neg		electronic uncertain
						942	-855		
						1088	-1100	> 5	
	2.0 ^m %WO ₃	2200°F	2 hrs	5.95	5.71	< 902	erratic, neg		electronic uncertain
						902	-704		
						1028	< -652		
	5.0 ^m %WO ₃	2200°F	2 hrs	6.01	4.20	1140	< -865	> 5	mixed uncertain
						Failed in test			
						< 906	erratic, neg		
		2200°F	2 hrs	6.01	4.20	906	0		mixed uncertain
						1028	> +1050		
						1122	> +1085	> 5	

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
$Pb_3Nb_2O_7$		2300°F	0 hrs	5.65	20.9	<800	erratic, neg		mixed
						800	+1256		uncertain
						844	+2912		
						936	0		
						988	-1600		
0.1 ^m /oCdO						1184	<-1343	>5	
		2300°F	0 hrs	5.61	22.8	<773	erratic, neg		mixed
						773	+632		uncertain
						826	+1077		
						910	0		
0.2 ^m /oCdO						1015	-833		
						1159	-738	>5	
		2300°F	0 hrs	5.70	20.2	<764	erratic, neg		electronic
						764	> -1242		uncertain
						821	> -2645		
0.5 ^m /oCdO						989	-641		
						1143	-692	>5	
		2300°F	0 hrs	5.80	19.8	<736	erratic, neg		electronic
						736	-931		uncertain
						764	> -1092		
1.0 ^m /oCdO						838	> -1176		
						1144	-665	>5	
		2300°F	0 hrs	5.84	20.2	<726	erratic, neg		electronic
						726	-458		uncertain
						764	-221		
						802	0		
						883	-669		
						1143	-717	>5	

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Material	Addition	Temp.	Time	Density	Porosity	Temperature	Coefficient	Resistivity	Conduction				
Pb ₂ Nb ₂ O ₇	2.0 ^m /oCdO	2300°F	0 hrs	6.05	19.7	<726	erratic, neg		electronic uncertain				
						726	-1088						
						874	>-1639						
						954	-340						
						1151	-697	>5					
	5.0 ^m /oCdO	2200°F	2 hrs	5.22	32.04	<719	erratic, neg		electronic uncertain				
						719	-572						
						810	> -1114						
						901	-1132						
						988	-778						
	1151					< -747	>5						
	0.1 ^m /oBi ₂ O ₃					2200°F	2 hrs	5.18	40.89	<708	erratic, neg		mixed uncertain
										708	-395		
										746	-116		
										782	+240		
										856	0		
0.2 ^m /oBi ₂ O ₃	2200°F	2 hrs	5.53	37.0	901					-495	>5	electronic uncertain	
					1126					-722			
					<690					erratic, neg			
					690					-804			
					726					-571			
0.5 ^m /oBi ₂ O ₃					2200°F	2 hrs	5.65	27.3	874	> -1100	>5	electronic uncertain	
									1050	-703			
									<746	erratic, neg			
									746	-224			
									945	-373			
0.5 ^m /oBi ₂ O ₃	2200°F	2 hrs	5.67	26.0					1151	-685	>5	electronic uncertain	
									<724	erratic, neg			
									724	-590			
									792	0			
									810	+790			
0.5 ^m /oBi ₂ O ₃					2200°F	2 hrs	5.67	26.0	838	0		mixed uncertain	
									918	-732	>5		
									1134	< -657			
									A-44				

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient		Resistivity	Conduction
		Temp.	Time				Seebeck Coefficient	Seebeck Coefficient		
1. 0 ^m /oBi ₂ O ₃		2200°F	2 hrs	5. 77	25. 1	<745	erratic, neg		> 5	electronic uncertain
						745	> -1154			
						812	> -1256			
						945	-648			
						1111	-670			
2. 0 ^m /oBi ₂ O ₃		2200°F	2 hrs	5. 76	19. 6	<726	erratic, neg		> 5	mixed uncertain
						726	-319			
						747	0			
						828	+987			
						892	0			
						980	-706			
5. 0 ^m /oBi ₂ O ₃		2200°F	2 hrs	6. 78	6. 21	1151	-697		> 5	electronic uncertain
						612	-786			
						698	> -1200			
						828	> -1300			
						1143	-786			
0. 1 ^m /oSb ₂ O ₅		2200°F	2 hrs	5. 77	22. 9	<755	erratic, +		> 5	mixed uncertain
						755	-35			
						865	+1818			
						910	0			
						1032	-817			
0. 2 ^m /oSb ₂ O ₅		2200°F	2 hrs	6. 03	14. 6	1142	-810		> 5	electronic uncertain
						<968	erratic, neg			
						968	-477			
						1088	-591			
0. 5 ^m /oSb ₂ O ₅		2200°F	2 hrs	5. 78	22. 05	<764	erratic, neg		> 5	electronic uncertain
						764	> -134			
						857	> -153			
						971	-912			
						1126	-775		> 5	

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TABLE AIII(continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides
Sintering Conditions

Base Material	Addition	Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
1.0 ^m %Sb ₂ O ₃		2200°F	2 hrs	5.66	25.5	<629	erratic, neg		mixed uncertain
						629	< -1836		
						708	< -606		
						724	0		
						854	> +218		
2.0 ^m %Sb ₂ O ₃		2200°F	2 hrs	5.91	20.0	918	0		electronic uncertain
						1118	-705	>5	
						<780	erratic, neg		
						780	> +414		
						864	> +642		
5.0 ^m %Sb ₂ O ₃		2200°F	2 hrs	5.70	23.9	984	-651		electronic uncertain
						1202	-609	>5	
						<612	erratic, neg		
						612	-773		
						698	> -137		
0.1 ^m %WO ₃		2200°F	2 hrs	5.6	21.5	828	> -120	>5	electronic uncertain
						1143	-786		
						<792	erratic, neg		
						792	-747		
						837	-385		
0.2 ^m %WO ₃		2200°F	2 hrs	5.79	18.6	901	-681		electronic uncertain
						1032	-881		
						1162	-763	>5	
						<782	erratic, neg		
						782	-676		
		2200°F	2 hrs	5.79	18.6	828	-463		electronic uncertain
						904	-391		
						1015	-741	>5	
		2200°F	2 hrs	5.79	18.6	1151	-721		electronic uncertain

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
	0.5 ^m /oWO ₃	2200°F	2 hrs	5.92	16.6	<810	erratic, neg		mixed uncertain
						810	-257		
						882	+207		
						892	0		
						980	-701		
	1.0 ^m /oWO ₃	2200°F	2 hrs	5.75	19.4	1168	-725	> 5	electronic uncertain
						<810	erratic, neg		
						810	-862		
						864	-812		
						971	-766		
	2.0 ^m /oWO ₃	2200°F	2 hrs	5.37	23.1	1168	-645	> 5	mixed uncertain
						679	-709		
						736	-266		
						845	+124		
						936	-722		
	5.0 ^m /oWO ₃	2200°F	2 hrs	4.87	31.8	1168	< -482	> 5	electronic uncertain
						< 670	erratic, neg		
						670	-425		
						736	> -794		
						835	> -860		
	Pb ₂ Nb ₂ O ₇	2200°F	2 hrs	5.43	24.78	1106	-722	> 5	electronic uncertain
						1169	< -110		
						< 717	erratic, neg		
						717	-675		
						847	> -982		
	0.1 ^m /oMoO ₃	2200°F	2 hrs	5.24	24.9	954	-548	> 5	electronic uncertain
						1100	-662		
						> 801	erratic, neg		
						801	> -1754		
						928	-654	> 5	

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions		Bulk Density	Porosity	Temperature	Seebeck Coefficient		Resistivity	Conduction
		Temp.	Time							
0. 2 ^m /oMoO ₃		2200°F	2 hrs	5. 87	20. 2	< 782	erratic, neg			mixed uncertain
						782	-233			
						805	0			
						838	+ 1109			
						878	0			
0. 5 ^m /oMoO ₃		2200°F	2 hrs	6. 77	27. 3	945	-474			electronic uncertain
						1134	-726		> 5	
						< 764	erratic, neg			
						764	-191			
						856	-74			
1. 0 ^m /oMoO ₃		2200°F	2 hrs	5. 53	23. 2	982	-788			electronic uncertain
						1117	-655		> 5	
						< 773	erratic, neg			
						773	-323			
						874	-614			
2. 0 ^m /oMoO ₃		2200°F	2 hrs	5. 72	20. 4	945	-619			electronic uncertain
						1143	-690		> 5	
						< 764	erratic, neg			
						764	-845			
						819	-598			
5. 0 ^m /oMoO ₃	Failed to sinter					892	-790			
						992	-564			
						1168	-610		> 5	