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HIGH TEMPERATURE
ELECTRICAL RESISTIVITY
OF REFRACTORY OXIDES - Al_2O_3

June 1970

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HIGH TEMPERATURE ELECTRICAL RESISTIVITY
OF REFRACTORY OXIDES - Al_2O_3

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PROGRAM DESCRIPTION

The program is funded in support of the LMFBR Task 4-6.2 entitled, "Electrical Insulators for Sensors and Cables". The purpose of the program is to **determine** the electrical conduction mechanisms and related properties of electrical insulators at high temperatures, and to determine the effects of radiation on these properties so that cable insulation for in-reactor use can be improved. A comprehensive search, compilation and analysis of available data from publications is to be supplemented by experiments and is to be issued in handbook form and periodically updated as more information becomes available. This topical report summarizes published data on the resistivity of Al_2O_3 and emphasizes effects of environment and thermal history on resistivity.

As currently envisioned the insulator handbook will contain necessary **information** and design specifications for electrical insulation requirements for use with LMFBR sensors and cables including:

- a. low-leakage, small-signal, coaxial cables to 1400°F
- b. low-leakage, small-signal, coaxial cables to 1400°F with radiation
- c. electrical wiring including mineral-insulated cables for sodium immersion from 1200-5000°F
- d. large-signal coaxial cables to 1200°F and radiation
- e. magnet wire from 1200 - 1600°F
- f. electrical seals for ion chambers
- g. electrical seals for EM pumps, flowmeters, and sodium systems to 1200°F.

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OF REFRACTORY OXIDES - Al_2O_3

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ABSTRACT

Electrical insulation requirements for cables and seals in a reactor environment are becoming more stringent, and the problem of choosing an adequate insulating material for reactor instrumentation remains a difficult one. This paper **summarizes** a survey of reported results for Al_2O_3 , emphasizing the effects of annealing history and atmosphere on the electrical resistivity. The discrepancies pointed out show the need for careful characterization of samples and for analytical measuring procedures in establishing standard techniques to **determine** the electrical properties of insulating materials.

CONTENTS

LIST OF FIGURES	ix
INTRODUCTION	1
SURVEY OF REPORTED DATA	1
EFFECTS OF ANNEALING HISTORY	1
EFFECTS OF ATMOSPHERE	16
SUMMARY	24
REFERENCES	25

LIST OF FIGURES

1	Composite Graph of Published Results for Alumina	2
2	A Comparison of Single Crystal and Polycrystal Results	3
3	A Comparison of Results Measured in Air and Vacuum	4
4	A Comparison of Results Measured with Four-Probe and Guard-Ring Technique	5
5	Resistivity Changes Noted During Initial Testing	7
6	Changes in Resistivity with Repeated Testing in Air	8
7	Increases in Resistivity with Repeated Testing in Inert and Reducing Atmospheres	10
8	Decreases in Resistivity with Repeated Testing in Reducing Atmosphere	11
9	Inconsistent Changes in Resistivity with Repeated Testing	12
10	Effect of Annealing (Time at Temperature) on Resistivity	13
11	Effects of Grain Size on Resistivity	
12	Effects of Deformation and Strain on Resistivity	
13	Dependence of Resistivity on Oxygen Partial Pressure	19
14	Changes in Resistivity vs Temperature Curves with Oxygen Partial Pressure	20
15	Resistivity vs Temperatures Curves in Varying Atmospheres	21
16	Effect of Humidity on Resistivity	22
17	Resistivity Curves in Various Environments	23

HIGH TEMPERATURE ELECTRICAL RESISTIVITY OF REFRACTORY OXIDES - Al_2O_3

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INTRODUCTION

Much of the tremendous variation in values for the resistance-temperature data reported in the literature for insulators can be explained in terms of the effect of impurities, sample fabrication (including sintering), postfabrication treatment (including annealing), test atmosphere, and method of measurement. While Figure 1 presents a composite graph of $\log \rho$ vs $1/T$ for Al_2O_3 , a valid comparison could only be applied to similar samples in similar environments measured in the same manner. This discrepancy in data on insulator resistivities points out the need for careful characterization of samples and analytical measuring procedures in establishing standard techniques to put meaning into electrical properties determinations of insulating materials.

SURVEY OF REPORTED DATA

The spread in resistivity data and variation in experimental conditions illustrated in Figures 2a through 4b point out the need to specify all of the above parameters when considering data of high resistivity Al_2O_3 insulation. Each of the graphs includes portions of Figure 1. The single crystal and polycrystalline results are separated in Figures 2a and 2b, respectively. Figure 3a shows data measured in vacuum, while data displayed in 3b was taken in air. Measurements reported to have been made with a standard 4-probe technique are given in Figure 4a, while guarded ring technique measurements are compared in Figure 4b. In general, the respective author did not give complete specification of parameters that would affect his measurements, thus making comparisons of the available data difficult and usually meaningless.

EFFECTS OF ANNEALING HISTORY

The effect of sample annealing on the electrical resistivity has been confirmed by many authors. The significance of sample heat treatment of

FIGURE 1. Composite Graph of Published Results for Alumina

FIGURE 2. A Comparison of Single Crystal and Polycrystal Results

FIGURE 3. A Comparison of Results Measured in Air and Vacuum

FIGURE 4. A Comparison of Results Measured with Four-Probe and Guard-Ring Technique

Al_2O_3 was pointed out by E. G. Rochow⁽⁴⁾ when he reported difficulty in reproducing resistivities with heating. Only after heating for several hours at 1200°C could a linear plot of $\ln \rho$ vs $1/T$ be obtained. K. Heldt and G. Haase⁽¹¹⁾ reported results obtained with a sample which was not preannealed. At 700°C , in vacuum, the sample showed a resistance of $1.3 \times 10^9 \Omega$. After 90 minutes at 700°C the resistance rose to $2.5 \times 10^9 \Omega$. After annealing at 1500°C and rapidly cooling to 700°C , the resistance was $1.2 \times 10^{11} \Omega$. J. A. Champion⁽²¹⁾ reported that only after three to four heating and cooling cycles would his resistivity data become reproducible. The initial data displayed non-linearity with peaks in the $\log \rho$ vs $1/T$ curve and transient pulses in the conduction current which started near 400°C . Champion's results are given in Figure 5a in the form $\log \rho$ vs $(1/T)$.

Cohen⁽¹⁾ stated that many investigators have found heat treatment of Al_2O_3 samples at 1500°C was necessary for obtaining reproducibility in measurement. P. J. Harrop and R. H. Creamer⁽²⁸⁾ supported this conclusion by noting that their $\log \rho$ vs $1/T$ curves for a fully annealed sample remained unchanged after ten heating and cooling cycles to 1500°C during two weeks.

J. R. Hensler and E. C. Henry⁽²²⁾ attributed measured differences in specific resistance of sintered alumina during the first and second heating cycles to poor initial contacts between the sample, the platinum coatings on the sample, and the platinum electrodes (Figure 5b). T. L. Gregory⁽²³⁾ noted a change (Figure 5c) in resistance before and after the sample had been annealed. He indicated that the change resulted from the removal of surface contamination after heating for 12 hours at $\sim 1000^\circ\text{C}$.

B. Cutler⁽¹⁴⁾, however, suggested a different explanation for the changes with cycling (Figures 6a and 6b). Cutler found the resistivity of Al_2O_3 to decrease with repeated heating and cooling in air, and attributed this change to oxidation of Fe impurities. K. A. Hansen⁽⁸⁾ reported the same data as Cutler and he indicated that possibly all currents measured may have been conduction through the atmosphere instead of conduction through the sample.

Cutler⁽¹⁴⁾ and Hansen⁽⁸⁾ showed a steady decrease in resistivity with

FIGURE 5. Resistivity Changes Noted During Initial Testing

FIGURE 6. Changes in Resistivity with Repeated Testing in Air
 A) Continuous Decrease in ρ with Time
 B) Increase in ρ Observed when Fired in Reducing Atmosphere

repeated heating (see Figures 6a and 6b). However, their samples were heated in air and were possibly increasing in oxygen content with heating. This theory is supported by Figure 6b, which showed that firing the sample at 1325° in a reducing atmosphere increased the resistivity.

The most comprehensive data for Al_2O_3 are reported by R. F. Havel⁽²⁴⁾. He presented in 24 graphs the $\ln \rho$ vs $1/T$ data for different heating and cooling cycles on high purity and "Alucer" Al_2O_3 in various atmospheres and employing different susceptors (heaters). A representative selection is shown in Figures 7a through 9b. These results point out the dependence of insulator resistivity on the heat treatment history of the sample. In contrast to the results reported by Cutler and Hansen, the results of Havel show the resistivity increasing with repeated heating (Figures 7a through 7d), decreasing (Figures 8a and 8b), and both increasing and decreasing (Figures 9a and 9b). The most convincing results, however, are those in Figures 7b and 7d which show a significant increase in resistivity with time at temperature. Consideration of the atmospheres indicates that the presence of at least 1000 ppm H_2 causes the resistivity to increase with time at temperature.

The effects of time at temperature on electrical resistivity can be illustrated with data published by Hartmann⁽³⁾. His data show the effect of annealing at 450°C in various atmospheres for extended time intervals. When first heated to 450°C in vacuum, the resistivity was greater than $10^{11} \Omega\text{-cm}$, too large to measure with his apparatus. After heating for ten hours at this temperature, however, the resistivity was low enough to measure. The results obtained by Hartmann are shown in Figure 10a for after the sample was heated for 80 hours in vacuum at 450°C [curve (a)], after the sample was heated for 120 hours in vacuum [curve (b)], after the sample was heated an additional 15 hours at 400°C in an oxygen atmosphere of 3 Torr [curve (c)] and after firing at 375°C in a reducing atmosphere of 5 Torr of H_2 [curve (d)]. These results also support an increase in resistivity with time at temperature, and a significant dependence on the oxidizing or reducing nature of the atmosphere.

Hensler and Henry⁽²²⁾ published some interesting results on the effect

FIGURE 7. Increases in Resistivity with Repeated Testing in Inert and Reducing Atmospheres

FIGURE 8. Decreases in Resistivity with Repeated Testing in Reducing Atmosphere

FIGURE 9. Inconsistent Changes in Resistivity with Repeated Testing

FIGURE 10. Effect of Annealing (Time at Temperature) on Resistivity

- A) Sample processed in the following order:
 a - Heated for 80 hrs in vacuum at 450°C
 b - Heated for 120 hrs in vacuum at 450°C
 c - Heated for 15 hrs in oxygen atmosphere of 3 Torr at 400°C
 d - Fired at 375°C in reducing atmosphere of 5 Torr
- B) Samples processed in the following manner:
 a - Sintered at 1800°C for 1/2 hr
 b - Sintered at 1650°C for 1 hr
 c and d - Sintered at 1000°C for 10 hrs, raised to 1500°C (tested), held there for 10 hrs, then cooled (curve c)

of time at sintering temperature on the resistivity of sintered Al_2O_3 . These results are given in Figure 10b. Unfortunately, valid conclusions are difficult to make since all increases in time at temperature correspond with decreases in the sintering temperatures. In general, the samples fired at higher temperatures resulted in lower porosities and higher resistances. Curves c and d are for one sample. The sample was sintered (annealed) at 1000°C for ten hours followed by an increase to 1500°C , (curve d). The sample was then maintained at this temperature (1500°C) for 10 hours and cooled, (curve c). As indicated by the line connecting the curves, the resistance increased during the time of annealing at 1500°C .

K. Heldt and G. Haase⁽¹¹⁾ gave a good demonstration of the effect of annealing on resistance. A sample sintered at 1800°C and then exposed to air possessed a resistance of $10^9 \Omega$ at room temperature in air and 10^{12} in vacuum. When subsequently heated to 1500°C in vacuum, held there for 10 minutes and then cooled back to room temperature, the resistance was $10^{14} \Omega$. A sample which was not sintered had a resistance of $1.3 \times 10^9 \Omega$ in vacuum at 700°C , which rose to $2.5 \times 10^9 \Omega$ after 90 minutes at 700°C . When heated to 1500°C and then rapidly cooled to 700°C , the resistance was $1.2 \times 10^{11} \Omega$.

Although Cutler⁽¹⁴⁾ and Hansen⁽⁸⁾ associated their decrease in resistivity upon repeated heating with oxidation of Fe impurities, some consideration should be given to crystal size in polycrystalline samples. Cutler noted that during sintering the sample shrinks as the grain sizes increase. This change appears to be associated with a reduction in the number of grain boundaries which could account for the decrease in resistivity. This, however, contrasts with the results of Hensler and Henry who noted that a decrease in porosity and larger grain size with sintering resulted in an increase in resistivity.

Among the first to study the effect of grain size on resistivity was K. Heine⁽²⁵⁾ who examined corundum. The results depicted in Figure 11a illustrate that the resistivity decreased strongly with increasing grain size. Heine explained this effect by assuming that the "transition resistances present between individual crystals are high in comparison with

FIGURE 11. Effects of Grain Size on Resistivity
 A) Decrease in ρ with Increasing Grain Size
 B) and C) Increase in ρ with Increasing Grain Size

the resistance of the material itself". This result is in agreement with the common assumption that a powder material is a better resistor than a polycrystalline or single crystal material. J. R. Floyd⁽²⁶⁾ made similar measurements but with different results. He also noted that the crystal size of the specimens increased with additional heat treatment. However, as Figures 11b and 11c show, the volume resistivity increased as the crystal size of the bodies increased.

Before concluding the section on the effects of annealing, some mention should be made regarding dislocations. J. B. Wachtman⁽²⁷⁾ used plastic deformation as a tool to investigate annealing of sapphire, indicating that plastic deformation increases the electrical resistivity at constant temperature. Wachtman suggested that work hardening associated with plastic deformation (creep) causes an increase in electrical resistivity. Annealing at high temperatures for extended periods removes some of the work hardening, and the resistivity decreases accordingly. The resistivity of the undeformed rod was greater than that of the deformed rod (see Figure 12a, curves a and d) because the undeformed rod was work hardened as a result of stresses occurring during growth.

P. J. Harrop⁽²⁸⁾ noted that straining a sample decreased the electrical resistivity. These results are shown in Figure 12b. Heat treatment of the strained sample returned the resistivity values to that of the unstrained annealed sample.

These few references do not completely review the reported data on the effect of grain size, dislocations, and straining on resistivity. The results presented are inconclusive and a more thorough compilation will be made in the future.

EFFECTS OF ATMOSPHERE

Results reported by Hartmann⁽³⁾, Have11⁽²⁴⁾, Cutler⁽¹⁴⁾, and Hansen⁽⁸⁾ point out a marked dependence of the electrical resistivity on the atmosphere, and especially on oxygen partial pressure. This probably results from the dependence of stoichiometry of oxides, such as Al_2O_3 , on the oxygen partial pressure of the atmosphere. Heldt and Haase⁽¹¹⁾ noted a

FIGURE 12. Effects of Deformation and Strain on Resistivity

five order of magnitude difference in resistance of a sample annealed in vacuum and in air at room temperature.

J. Pappis⁽¹⁶⁾ gave a demonstration of the direct dependence of resistivity on oxygen partial pressure for single crystal sapphire (Figure 13a) and polycrystalline Al_2O_3 (Figure 13b). Pappis attributed the decrease in resistivity at high and low oxygen partial pressures to result from p-type and n-type semiconduction, respectively. Pappis also showed $\log \rho$ vs $1/T$ curves to be affected by oxygen partial pressure, (Figures 14a and 14b). The curves of Figure 14a show a maximum for resistivity to occur for an oxygen partial pressure $\approx 10^{-5}$ Torr.

D. Dasgupta⁽¹⁹⁾ published similar results on $\log \rho$ vs $1/T$ in various atmospheres. As shown in Figures 15a and 15b Dasgupta obtained different results for crystals from Linde and Semi Elements in various pressures of air. However, relations between the applied voltage, current in the sample, and probe voltage make any qualitative conclusions impractical.

J. A. Champion⁽²¹⁾ indicated a dependence of the conductivity of Al_2O_3 at low temperatures on the moisture content in the ambient gas. Figure 16b shows the resistivity to vary with water content in atmospheres of air with room humidity, argon dried over a molecular sieve, and nitrogen dried in a liquid nitrogen trap. Champion noted current pulses in a humid atmosphere that were absent when the specimen was kept in dry nitrogen. His conclusion was that the peaks in conductivity near and above 100°C were due to the evaporation of moisture.

The most careful analysis concerning the effect of environment on the electrical resistivity of Al_2O_3 was reported by L. F. Feinstein⁽⁶⁾. Measurements were conducted on ruby and on sapphire in air, on sapphire in helium, and without a sample both in air and helium (Figure 17a). The resistivity in air appears to be equal to or less than the resistivity of the sample. Helium has a higher ionization potential than nitrogen or oxygen, which is consistent with the higher gas resistivity measured when the chamber was flushed with helium. These two curves (for He) indicate that the intrinsic resistivity of Al_2O_3 lies above the resistivity shown for helium. This suggests that the problem of atmospheric conduction may be significant in all

FIGURE 13. Dependence of Resistivity on Oxygen Partial Pressure

FIGURE 14. Changes in Resistivity vs Temperature Curves with Oxygen Partial Pressure

FIGURE 15. Resistivity vs Temperatures Curves in Varying Atmospheres

FIGURE 16. Effect of Humidity on Resistivity

- a) In air with room humidity
- b) In argon
- c) In dried nitrogen

FIGURE 17. Resistivity Curves in Various Environments

non-vacuum, high temperature, high resistivity measurements with Al_2O_3 since the effective parallel resistance of the atmospheres is less than the resistance of the Al_2O_3 . A similar experiment conducted in vacuum resulted in an increase in the shunting current over the previous air experiments. Since the current saturated with increasing voltage at constant temperatures, and decreased with increasing pressure, the shunt current was thought to be due to **thermionic** emission of electrons from the metal wires and electrodes in the system.

Results by D. Shakhtin⁽³¹⁾ showed a shunting resistance for his system in nitrogen and argon to be higher than the apparent resistivities of Al_2O_3 in the respective atmospheres (Figure 17b). Again, the shunting resistance decreased significantly in vacuum.

SUMMARY

The summarized ~~information~~ indicates a reason for lack of understanding of conduction mechanisms in high temperature insulators. In general, **re-**sistivity decreases with ~~increasing~~ temperature. The atmosphere and mechanical and thermal history of the sample have a marked effect on the sample resistivity; however, a complete specification of parameters is required before any valid conclusions can be drawn. In addition to quality control and adequate specification of sample parameters, experimental techniques must be carefully analyzed. All high temperature data are suspected because of polarization and atmospheric conduction. Obviously, before any conclusions can be drawn about the details of conduction mechanisms and processes in insulators at elevated temperatures, more reliable data must be obtained.

REFERENCES

1. J. Cohen. "Electrical Conductivity of Alumina", Am. Cer. Soc. Bull. 38, 441-6 (1959).
2. R. A. Verneti and R. L. Cook. "Effect of Metal Oxide Additions on the High Temperature Electrical Conductivity of Alumina", J. Am. Cer. Soc. 49, 194-99 (1966).
3. W. Hartmann. "Electrical Investigation of Oxide Semiconductors", Zeitschrift fur Physik 102, 709-33 (1936).
4. E. G. Rochow. "Electrical Conduction in Quartz, Periclase, and Corundum at Low Field Strength", J. Appl. Phys. 9, 664-669 (1938).
5. T. Matsumura. "The Electrical Properties of Alumina at High Temperatures", Canadian Journal of Physics 44, 1685-98 (1966).
6. L. Feinstein, et al. "Research on Dielectrics for Microwave Electron Devices", AS 629942 (1966).
7. M. O. Davies. "Transport Phenomena in Aluminum Oxide", NASA TN D-2765 (1965).
8. K. W. Hansen. "Electrical Conductivity of $\text{Fe}_x\text{O}-\text{MgO}$ Solid Solutions and Al_2O_3 ", Ph.D. Thesis: Univ. of Utah, (1962).
9. G. M. Stulova and Yu. K. Shalabutov. "Investigation of the Electrical and Optical Properties of Synthetic Sapphires at High Temperatures", Fizika i Tekhnika Poluprovodnikov 1, 996-998 (1968).
10. W. B. Haidler. "A Study of the Electrical Conductivity of Alumina at High Temperatures and in a Radiation Field", Ph.D. Thesis, Univ. of Arizona, Tucson (1964).
11. K. Heldt and G. Haase. "Electrical Resistance of Pure, Vacuum-Sintered Aluminum Oxide", Zeitschrift fur angewandte Physik 6, 157-60 (1954).
12. A. N. Lyulichev, et al. "Determination of the Electrical Conductivity of Refractory Materials in a Vacuum at 2200°", Zavodskaya Laboratoriya 23, 931-4 (1957).
13. J. V. Florio. "Dielectric Properties of Alumina at High Temperatures:", J. Am. Cer. Soc. 43, 262-267 (1960).

14. L. B. Cutler and P. Gibbs. "Recrystallization and Sintering of Oxides", TID-13592 (1961).
15. J. A. Champion. "The Electrical Conductivity of Single-Crystal Alumina", Brit. J. Appl. Phys. 15, 633-38 (1964).
16. J. Pappis and W. D. Kingery. "Electrical Properties of Single-Crystal and Polycrystalline Alumina at High Temperatures", J. Am. Cer. Soc. 44, 459-64 (1961).
17. L. Hays, et al. "Electrical Heater for Liquid Metals at Elevated Temperatures", JPL - Technical Report 32-1146 (1967) or pp. 242-243 in BNL 50096 (PR-30), Propulsion Systems and Energy Conversion - TID-4500 (1967).
18. R. W. Wallace and E. Ruh. "Electrical Resistivity of Refractories", J. Am. Cer. Soc. 50, 358-64 (1967).
19. S. Dasgupta. "D. C. Conductivity of Alumina Single Crystals", Brit. J. Appl. Phys. 17, 267-70 (1966).
20. T. Arizumi and S. Tani. "On the Electrical Conductivity of Alumina", J. Phys. Soc. Japan 5, 442-7 (1950).
21. J. A. Champion. "The Electrical Conductivity of Sapphire and Ruby Crystals", Proc. Brit. Cer. Soc. 10, 51-61 (1968).
22. J. R. Hensler and E. C. Henry. "Electrical Resistance of Some Refractory Oxides and Their Mixtures in the Temperature Range 600° to 1500°C", J. Am. Cer. Soc. 36, 76-83 (1953).
23. T. L. Gregory. "Irradiation of High Purity Alumina", N68-13368, NASA CR-72334, GEST-2101 (1967).
24. R. F. Havell, et al. "High Temperature Electrical Properties of Insulators and Their Compatibility with Refractory Metals", NASA-CR-54125, N65-18933 (1965).
25. K. Heine. "Investigations on the Electric Conductivity of Some Basic Materials, Binders and Their Mixtures, for the Production of Insulating Material for Electric Heating Units", Elektrowarme 10, 261-66 (1938).
26. J. R. Floyd. "Effects of Firing on the Properties of Dense High-Alumina Bodies", Trans. Brit. Cer. Soc. 64, 251-65 (1965).
27. J. B. Wachtman, Jr. and L. H. Maxwell. "Plastic Deformation of Ceramic-Oxide Single Crystals, 11", J. Am. Cer. Soc. 40, 377-385 (1957).

28. P. J. Harrop and R. H. Creamer. "The High-Temperature Electrical Conductivity of Single-Crystal Alumina", Brit. J. Appl. Phys. 14, 335-9 (1963).
29. D. B. Binns, et al. "Factors Affecting the Surface Resistivity of Alumina Ceramics", Proc. Brit. Cer. Soc. 10, 31-39 (1968).
30. D. W. Peters, et al. "On the High-Temperature Electrical Conductivity of Alumina", J. of Chem. Phys. 42, 2345-6 (1965).
31. D. M. Shakhtin, et al. "Electrical Conductivity of Refractory Oxides at High Temperatures", Ogneupory Refractories 30, 37-41 (1965).

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