

# Magnesium oxide as a high-temperature insulant

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*Indexing terms: Dielectrics, Insulators and insulation*

**Abstract:** Magnesium oxide is widely used as a high-temperature insulant in the form of compacted powder. The reasons for its selection, and the nature of electrical conduction in refractory oxides at high temperatures, are discussed. The literature dealing with conduction in single crystals is reviewed, and results of resistivity measurements on compressed powders are reported. These show the effects on powder resistivity of impurities, specific surface, and of adsorbed or bound water. At 1000°C the resistivity of commercially available fused magnesia powders approaches that of high-purity single crystals.

## 1 Introduction

The use of compacted mineral powders for electrical insulation in such varied fields as wiring cables for domestic and industrial use, heating cables and tubular heating elements, and thermocouple cables of a variety of types is now well known. In these applications, the properties unique to this type of insulation such as its thermal stability, incombustibility, tolerance of high levels of irradiation, which cannot be matched by organic polymers, and high electrical resistivity at temperatures of the order of 1000°C are exploited.

Although several inorganic powders have been used as mineral insulation, magnesium oxide is much the most important. This paper will review the published literature (which deals largely with work on single crystals) on high-temperature conduction in refractory oxides, particularly magnesium oxide, and will report resistivity measurements on compressed powders in order to compare crystal and powder behaviour and relate the results to practical conditions.

Although the paper is primarily concerned with the electrical properties of the mineral dielectric itself an outline of the cable manufacturing process is appropriate, since, to some extent, this determines the physical properties required of the powder.

The process commences with a start-tube, which ultimately becomes the cable sheath, into which are introduced the conductors and the insulant, either as powder or as preformed blocks.

The cable is reduced to its final size, which may be as small as 0.5 mm diameter or less, by a sequence of drawing and annealing stages. During the drawing process, the powder undergoes considerable comminution, and reaches a final packing density of 70–80% of the true crystal density. Despite this degree of powder compaction, the cables are still quite flexible after annealing.

The magnesium oxide powders used are of two types:

(a) *Calcined magnesias*, prepared by thermal decomposition of mined magnesite ( $MgCO_3$ ), or of magnesium hydroxide precipitated from sea water or brine deposits. They vary in specific surface, depending on calcining conditions and temperature; 'dead-burnt' (high-temperature-calcined) powders, with lower specific surface, approach the characteristics of the second type.

(b) *Fused magnesias*, produced from selected calcined magnesias by fusion in an electric arc furnace at about 2800°C. The fused mass is crushed to powder, given further heat treatment, and magnetic separation is used to remove iron contamination from the powdered material.

In general calcined magnesias are used in copper-sheathed wiring cables whereas fused magnesia is preferred for applications with operating temperatures up to 1100°C, such as

thermocouples, certain types of heating cables and tubular heating elements.

For both types of powder, the particle size distribution is carefully controlled to match the cable filling process.

## 2 High-temperature insulation

### 2.1 Materials

The requirements for low conductivity at high temperature may be summarised as:

(a) high lattice energy, to minimise thermal formation of defects either of the Schottky type (lattice vacancies) or Frenkel type (interstitial ions), or of nonstoichiometry giving rise to *n*- or *p*- type electronic or hole conduction,

(b) a stable valency state in the cation, with a wide band gap to minimise electronic conduction.

The refractory oxides of Groups II and III, notably BeO, MgO and  $Al_2O_3$ , with melting points of over 2000°C, fulfil these requirements.

In the alkaline earth oxides of Group II, it is found that, with increasing cation size in the sequence Be, Mg, Ca, Sr, Ba, lattice energy decreases, and high-temperature conductivity increases, with an increasing electronic component.

The three outstanding oxides BeO, MgO and  $Al_2O_3$  have been the subject of many studies on conduction mechanisms. BeO has been shown to be a purely ionic conductor up to very high temperatures [1] but the behaviour of MgO and  $Al_2O_3$  is more complex. Since MgO is far more widely used, the review of work on conduction mechanisms in the next Section will be restricted to this compound, but similar studies have also been made on  $Al_2O_3$  crystals [2–4].

### 2.2 Conduction processes in crystals and powders

The nature of the conductivity in MgO crystals was for long a subject of controversy and in 1964 Budnikov [4] listed seven different mechanisms put forward in twelve papers. Gradually, however, the conditions under which electronic or ionic conduction prevails have been clarified by studies of the EMF of electrochemical cells using MgO as solid electrolyte [5–6], by measurement of mass transport [7], and by investigation of the effect of oxygen partial pressure on conductivity [8].

These measurements have been made on single crystals, or on polycrystalline compacts (sintered or hot-pressed) with essentially zero porosity. Most of the work was done in the temperature range above 1000°C although measurements in the range of greater practical interest below 1000°C are reported in a few papers only 8–10.

The results show that ionic conduction prevails up to at least 1000°C. At higher temperatures an electronic component is indicated by the dependence of conductivity on oxygen partial pressure, but in all the work reported the conduction is almost certainly extrinsic, i.e. determined by impurities.

Calculation shows that, in a refractory oxide such as MgO, where the formation energy for lattice defects is of the order

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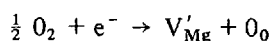
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of 5–6 eV [11], the number of vacancies produced by the presence of a few parts per million of aliovalent cations (with higher or lower charge than  $Mg^{++}$ ) will exceed those produced thermally at all temperatures up to 2000°C.

Schottky defects (lattice vacancies) are generally considered to be the type found in MgO crystals, which have the NaCl structure, although Frenkel defects (interstitials) have also been postulated [7, 12].

The mobile charge carrier in conduction has been identified as the magnesium cation vacancy. The activation energy for high-temperature conduction, of about 3 eV, corresponds to that observed for diffusion of  $Mg^{++}$  ions. Predictions have been made of the conductivity/temperature characteristics of the possible conduction mechanisms [13], and comparison with experimental results eliminates all processes except for the motion of  $Mg^{++}$  vacancies.

It has been pointed out [8] that DC conduction by cation vacancies is not necessarily blocked at inert electrodes, since vacancies can be formed at the cathode by the reaction:



in which oxygen anions, with corresponding magnesium vacancies, are incorporated in the lattice; with the reverse at the anode.

**Table 1: Effects of impurity elements on resistivity of MgO crystals and polycrystals**

Impurity added		Effect on resistivity	Reference
	%		
CaO	1.4	None, up to 1000°C	14
Al <sub>2</sub> O <sub>3</sub>	1.4	Reduced up to 1000°C	14
	4	None up to 1800°C	15
	0.05	Slight reduction up to 1500°C	12
Li <sup>+</sup>	0.02	Increased in range 1000–1300°C (Li <sup>+</sup> in lattice)	5
LiF	0.05	Reduced for polycrystalline specimen	9
LiF	0.08	Reduced for polycrystalline specimen	16
Li <sup>+</sup>	0.05	Large reduction above 1000°C	12
NaCl, KCl	0.4	Reduced up to 1000°C	14
Ni <sup>++</sup>	0.1	None above 1000°C; reduced below 1000°C in porous samples	4
Zn <sup>++</sup>	0.1	Similar to Ni	4
MnO	0.3	Decreased up to 1000°C	14
Cr <sup>3+</sup>	1.9	Decreased in range 1000–1500°C	17
ZrO <sub>2</sub>	1.0	Decreased in range 1000–2000°C	15
	0.3	None 1000–2000°C	15
Zr <sup>4+</sup>	0.5	None 900–1600°C	4
Ti <sup>4+</sup>	0.2	None 900–1600°C	4
TiO <sub>2</sub>	0.5	Decreased up to 1000°C	14
SiO <sub>2</sub>	0.5	None up to 1000°C	14

Since the resistivity of MgO crystals is essentially determined by the concentration of impurity-controlled defects, the effects produced by doping with foreign elements have attracted much attention. The published results are, however, by no means consistent, as may be seen from Table 1 which summarises some of the conclusions.

It is apparent that the distribution of the impurity ions, in polycrystalline specimens, can be more important than the overall concentration given by analysis. Thus, in the case of nickel where, because of the similar cation charge and size up to 0.4% can be dissolved in the MgO lattice without affecting the defect structure [18], the effects on resistivity below

1000°C were related to specimen porosity and were attributed to surface conduction [4].

Similarly, the presence of Li<sup>+</sup> in MgO single crystals can actually increase resistivity at 1300°C [15] (by decreasing the number of cation vacancies) whereas LiF, added as a sintering aid in hot-pressed compacts where it concentrates at grain boundaries, greatly decreases resistivity [16]. The reduction in resistivity and activation energy for conduction, in polycrystalline specimens [9] compared with single crystals, may also be attributed to the presence of LiF (0.05%) at grain boundaries.

Iron is the impurity which has attracted most attention; because of its almost universal occurrence, even in nominally pure crystals, and also as a variable-valency cation, with the Fe<sup>2+</sup>/Fe<sup>3+</sup> ratio depending on the sample's history. Earlier workers proposed electronic conductivity mechanisms involving iron impurity. At high Fe concentrations (> 1% Fe), conduction is greatly enhanced by a low-activation energy, hopping charge-transfer between Fe<sup>2+</sup> and Fe<sup>3+</sup> sites [19]. This mechanism is, however, improbable in purer magnesias with iron concentrations of 0.1% or less, and in the temperature range up to 1000°C where ionic conduction prevails. Under these conditions, the main role of the iron impurity is in controlling the cation vacancy concentration.

The Fe/MgO system is complex [20–3]. Fe<sup>2+</sup> remains in solid solution at all temperatures over a wide concentration range, whereas Fe<sup>3+</sup> has only a limited solubility below 1000°C (0.3% at 900°C), and tends to precipitate as a separate phase (magnesioferrite) on cooling, but can be retained in solution on quenching. On the other hand, Fe<sup>2+</sup> is only stable at high temperatures or in reducing atmospheres, and slowly changes to Fe<sup>3+</sup> below 600°C, but can be retained by rapid cooling. The transition between Fe<sup>2+</sup>/Fe<sup>3+</sup> is reversible, by heating in oxidising or reducing atmospheres.

Based on these valency changes, a conduction mechanism has been proposed [10, 13] to explain the observation that MgO single crystals, containing 0.01–0.07% of iron, showed an activation energy of conduction of 2.9 eV from 1000°C to lower than 500°C if cooled rapidly, whereas samples cooled through 600°C over several hours showed enhanced conductivity below 600°C, with an activation energy in this region of 1.4 eV.

This was attributed to the slow transition of Fe<sup>2+</sup> to Fe<sup>3+</sup>, with formation of unassociated cation vacancies enhancing conduction. A single activation energy of about 2.8 eV for single crystals containing from 0.001–0.02% over the range 1000°C–400°C, has, however, been reported in other work [8, 9]. On the other hand, breaks in the conductivity/temperature curves for iron-doped MgO have been observed at temperatures above 1000°C, which have also been attributed to phase and valency changes involving iron impurities [4, 12]. It has also been observed [24–5] that electrolytic reduction of Fe<sup>3+</sup>, with a corresponding increase in resistivity, can occur with prolonged passage of current at 1000°C.

One may conclude that, although conduction in MgO is determined by impurity-controlled defects, caution is required in singling out any one particular mechanism as being responsible, since interaction between different impurities, with compensation or association of defects can occur at the levels of purity studied.

In addition to the bulk conduction process in single crystals through vacancies whose concentration is controlled by impurities dissolved in the MgO lattice, polycrystalline compacts of zero porosity exhibit enhanced conductivity associated with grain boundaries, which may, in themselves, offer decreased activation energy paths for conduction or, as noted earlier, be sites of high impurity concentration.

The presence of a limited amount of closed porosity in

sintered compacts of this type usually decreases conductivity, as expected from simple models.

Mineral insulation in the form of compacted powders, however, has a rather more complex structure and is typically an assembly of approximately equiaxed crystallites, with the porosity as a highly-dispersed continuous phase. The grain-boundary phenomena are now associated with this crystallite surface area which increases with decreasing crystallite size, and also with increasing porosity (up to 50% pore fraction) as may be shown from consideration of model structures based on assemblages of cubes or spheres.

As with grain-boundaries, the surface of MgO crystallites may be associated with enhanced conductivity owing to either increased vacancy concentration or decreased activation energy for motion. The presence of surfaces may also affect conductivity by interaction with atmospheric gases or adsorption of water during processing.

The experimental work reported in this paper was designed to investigate the effect of variables such as density, specific surface, impurity content and heat-treatment on conduction in compressed MgO powder.

### 3 Measuring techniques

Whereas the extensive literature reviewed in the previous Section was concerned with measurements on crystalline specimens, mineral insulation in practical applications is, as just discussed, in the form of compressed powder. In order to study the properties of magnesium oxide and similar mineral insulants in a realistic form, while avoiding the complexities of the cable manufacturing process, the technique introduced by Fetterley [26] for measuring powder resistivity was adopted. High-temperature resistivity measurements, using cells of this type, were made in these laboratories, as were measurements of specific surface, thermo-gravimetric analyses of weight loss on heating, and determinations of impurities by atomic absorption spectroscopy, emission spectrography or chemical analysis.

In the Fetterley cell (Fig. 1), the powder is compacted, in four consecutive increments in a cylindrical coaxial electrode cell, thus simulating the cable configuration. The compressed powder is sufficiently cohesive to maintain separation between inner and outer electrodes on removal of the base plate after packing. The cell is then suspended in a vertical tube furnace by the leads attached to each electrode, together with a thermocouple for temperature measurement. Powder compaction pressures of 300–500 MN/m<sup>2</sup> were used, giving powder densities similar to those in mineral-insulated cables.

The electrodes may be made of mild steel or of the various stainless-steel alloys used in thermocouple sheaths. In the present series of measurements, made during heating and cooling cycles between 20°C and 1000°C in an atmosphere of nitrogen, the cells were mild steel. Fresh cells were used in each experiment.

Resistance measurements were made at 500 V DC with a Pye multi-megohmmeter. Volume resistivity, calculated from the cell dimensions, is shown on the graphs as Ω cm (or S/cm conductivity) in order to avoid confusion with the unit commonly used in specifications to express cable insulation resistance, Ω m (i.e. insulation resistance × length of cable in metres). There is usually good agreement between volume resistivity calculated from Fetterley cell measurements and that calculated from the insulation resistance of cables filled with the same powder.

For thermocouple applications, the DC resistivity is of primary interest. The results quoted were measured after one minute at 500 V. At temperatures above 700°C, DC resistivity is quite close to 50 Hz measurements. Below 400°C the 50 Hz impedance is predominantly capacitive. In the inter-

mediate region, the transition temperature, at which the resistive and capacitive components are equal, can be regarded as an indication of powder quality [27] since the higher the DC resistivity, the higher the transition temperature.

## 4 Powder resistivity

### 4.1 Comparison between crystals and powders

The conductivity/temperature relationship (log conductivity against 1/T plot) typical of insulation-grade fused magnesia powder measured in the Fetterley cell, is compared in Fig. 2 with published results [1, 8, 9, 10, 11] for single crystals of MgO and other oxides. Results for two other powders, measured in the Fetterley cell, are also shown. These are a fused alumina (99.5% Al<sub>2</sub>O<sub>3</sub>), and a quartz sand (Loch Aline sand, 0.012% Fe); neither approaches the values for fused magnesia.

Single crystal MgO shows a characteristic activation energy for conduction of about 2.9 eV, although a lower activation of 1.4 eV has been reported [10] for lower temperatures, as already discussed. Activation energies similar to the latter have also been observed in polycrystalline specimens [9, 10].

The conductivity of fused MgO powders approaches that for crystals at temperatures of 900°C and above. At lower temperatures of, the activation energies are lower and variable, falling to 1.5 eV or less at temperatures below 500°C.

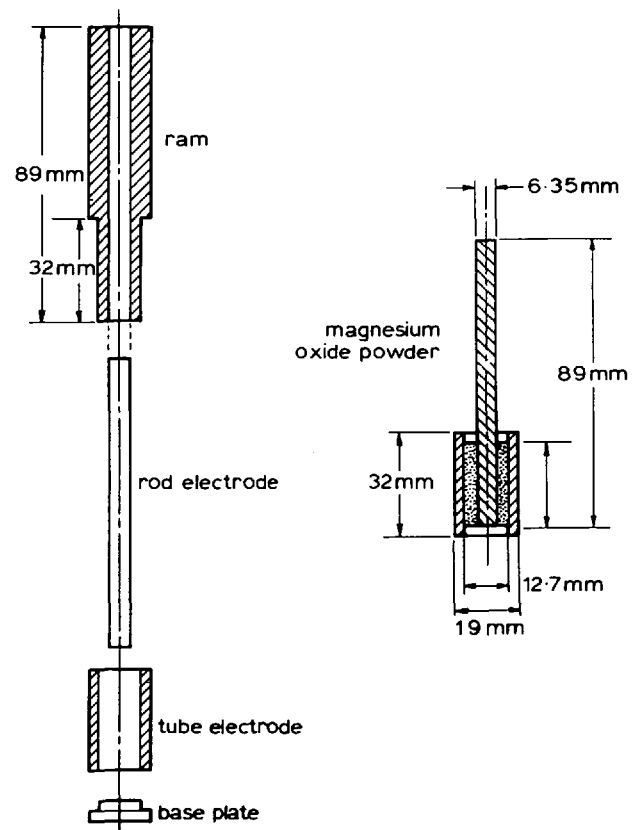


Fig. 1 Fetterley cell for powder resistivity measurements

### 4.2 Effect of packing density and specific surface

By altering the pressure used to compact the powder in the Fetterley cell, the packing density can be varied over a limited range.

No significant effect on resistivity was found over the range 0.7–0.8 solid fraction, corresponding to typical values for mineral cable insulation.

Magnesia powders of widely differing specific surface can give compacts in this packing density range. Fused magnesias and 'dead-burnt' calcined magnesias have specific surfaces in the range 0.01–0.1 m<sup>2</sup>/g. The surface area can be calculated

from the particle size distribution, since the individual particles are essentially nonporous. It must be remembered that compaction, particularly in the cable-drawing process, causes comminution of such particles, with consequent increase in surface within this range. Calcined powders, however, particularly those produced at lower calcination temperatures, can have a high internal surface of  $1 \text{ m}^2/\text{g}$  upwards, as shown by adsorption measurements.

The compression process in the Fetterley cell has a relatively small effect on powder specific surface, typically causing an increase from  $0.03$  to  $0.05 \text{ m}^2/\text{g}$  in fused MgO.

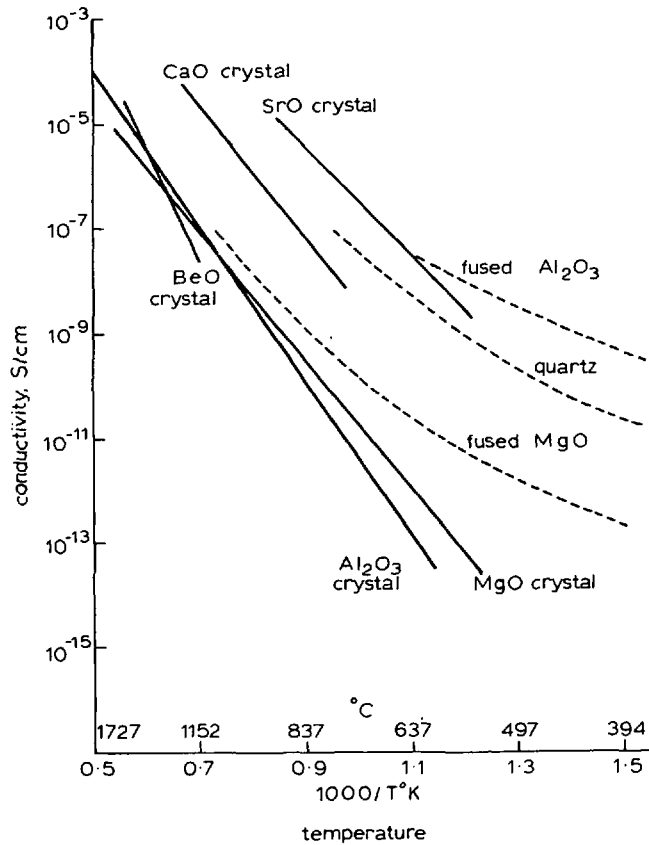


Fig. 2 Electrical conductivity of refractory oxides

— single crystal (Reference 11 etc.)  
 - - - powder (present work)

In Fig. 3 the resistivity (at three temperatures) of a number of magnesia powders, both fused and calcined, is plotted as a function of specific surface.

It will be seen that resistivity decreases with increasing surface area, the effect becoming more marked at lower temperatures. At  $1000^\circ\text{C}$  the effect is small, and powder resistivities approach more closely to single crystal values where surface conduction is excluded.

#### 4.3 Impurities

The systematic study of impurity effects by preparing MgO crystals with known levels of dopants has often been

Table 2: Analyses of Fused Magnesias (Fig. 4) (% by weight)

Powder No.	Fe	Total Alkali metals (Li, Na, K)	SiO <sub>2</sub>	CaO	Al <sub>2</sub> O <sub>3</sub>
	%	%	%	%	%
1	0.013	.0019	—	—	—
2	0.020	.0013	<.01	0.05	0.005
3	0.060	.0034	1.7	0.7	<.01
4	0.080	.0025	1.8	0.8	<.01
5	0.10	—	3.5	1.25	—
6	0.18	.0056	0.05	0.3	0.01
7	0.26	—	1.8	0.7	—

attempted, but as discussed in Section 2, interpretation of the results is rendered difficult by interaction between the various impurities present, deliberately added or otherwise.

With commercial powders, the situation is even more complex. In the present investigation, resistivity measurements have been made on fused MgO powders covering a wide range of purities, and are plotted in Fig. 4 in terms of iron content. Further analyses of the powders are given in Table 2. It will be seen that, whereas the surface effects demonstrated in Fig. 3 have been eliminated by using fused magnesias of similar particle size, the concentration of impurities other than iron also varies from sample to sample.

Nevertheless, the results indicate that iron contents above  $0.15\%$  Fe are associated with a reduction in high-temperature resistivity. There is no evidence, however, that the purer magnesias, with  $0.02\%$  Fe or less, show any improvement over standard insulating grades with up to  $0.10\%$  of iron.

Similarly, the presence of other refractory oxides such as SiO<sub>2</sub>, CaO and Al<sub>2</sub>O<sub>3</sub> in amounts up to  $1-2\%$  does not have a deleterious effect, compared with samples containing less than  $0.05\%$  of these impurities. Although compounds such as forsterite, Mg<sub>2</sub>SiO<sub>4</sub>, are known [28] to have a lower resistivity,

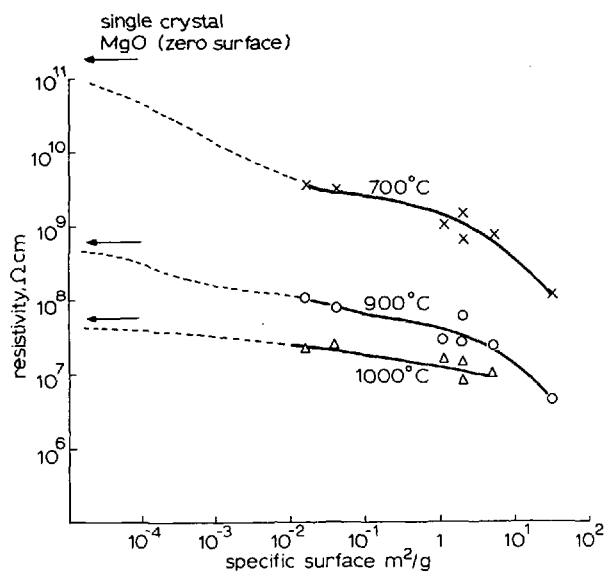


Fig. 3 Resistivity of MgO powders (70% packing) as a function of specific surface

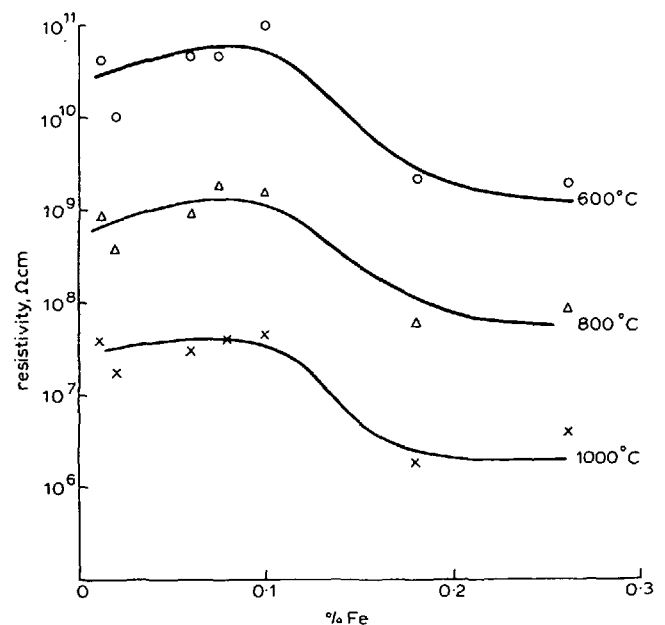


Fig. 4 Resistivity of fused magnesias as a function of iron content

tivity than MgO, it is probable that they segregate from the fused MgO on cooling, and thus have little effect on the resistivity of powdered MgO at these concentrations.

Contamination by chlorides can lower the high-temperature resistivity of magnesias but is not usually a problem in fused MgO.

Resistivity measurements were also made, in the Fetterley cell, on high-purity powders prepared as spectrographic standards. These materials are fine powders, with a higher specific surface than fused MgO powders. Johnson-Matthey Grade 2, (total metal impurity content < 0.01%) gave lower resistivities than those of insulating-grade fused magnesias (e.g. Nos. 3 and 4, Table 2). Specpure MgO and Al<sub>2</sub>O<sub>3</sub> powders (0.0001 and 0.0005% Fe, respectively and total cation impurities < 0.001%) gave resistivity/temperature characteristics similar to those of fused magnesias containing 0.02–0.08% Fe (Fig. 2).

In addition to their effect on resistivity, impurities may be undesirable in powder insulants for other reasons. The boron and sulphur contents of fused MgO are required to be less than 0.0025% for some thermocouple applications, in order to minimise neutron capture by boron atoms or to avoid interaction between nickel alloys and sulphur.

#### 4.4 Effect of heat treatment

Fused MgO powders are normally given a heat treatment at up to 1300°C, subsequent to the fusion and crushing processes. The patent literature contains various claims as to the relative merits of neutral or oxidising atmospheres for this heat treatment. Since mineral-insulated cables undergo a sequence of annealing processes in inert or reducing atmospheres, the effect of further heat-treatment of powders was investigated. Samples were heated at 1100°C in vacuum, in air, in 75% N<sub>2</sub>/25% H<sub>2</sub>, and in N<sub>2</sub>/H<sub>2</sub> followed by reoxidation in air. Resistivity/temperature characteristics were then measured in the Fetterley cell under nitrogen while the powder was cooled from 1000°C. No consistent differences were observed between samples preheated in different atmospheres.

The only significant effect observed was the improvement in resistivity of MgO powders when first heated to temperatures in the region of 1000°C. This is illustrated in Fig. 5 which shows resistivity measurements on a fused magnesia powder, initially equilibrated with the ambient atmosphere, during a cycle in which the sample is heated to 1000°C and then allowed to cool to room temperature again.

Its resistivity rises with temperatures up to about 350°C, and then falls as the temperature is raised further to 1000°C over five hours. On cooling from 1000°C the resistivity rises continuously and is always higher than that at the corresponding temperature in the heating stage. Measurements made on cooling from 1000°C are regarded as indicating the true powder characteristics. If the heating/cooling cycle is repeated within 24 hours only the initial rise in resistivity up to 350°C is observed, the heating and cooling curves from 400–1000°C being identical. If, however, the sample is allowed to reequilibrate with the atmosphere (e.g. in a polyethylene bottle, permeable to water vapour) for 1–3 months, the behaviour illustrated in Fig. 5 is again observed.

Thermogravimetric analysis of a number of fused magnesia powders showed the weight losses given in Table 3.

Table 3: Thermogravimetric analysis of fused magnesias

Temperature range	Weight loss %
20–300°C	0.06–0.16
300–550°C	0.09–0.18
600–1200°C	0.01–0.06
Total 20–1200°C	0.16–0.33

The following mechanisms for these phenomena, based on published work [29–33] on the interaction of water vapour with MgO are proposed:

(a) removal of physically adsorbed water (with an activation energy for desorption of 0.9 eV), at temperatures up to 360°C (the effect of physisorbed moisture on resistivity has also been observed on polycrystalline specimens [4, 10])

(b) persistence of chemisorbed hydroxyl ions, particularly at more active MgO crystal sites [32] with activation energies for desorption of 2.6 eV or higher, at temperatures up to 900°C (well beyond the typical decomposition temperature of 395°C for Mg(OH)<sub>2</sub>)

(c) slow recovery of bound water, after high-temperature desorption, by resorption on cooling followed by reaction to form hydroxyl ions, with accompanying cation vacancies; this reaction has been suggested [30] to account for the effect of water vapour on conductivity in MgO powders at high temperatures, and also for its well known effect in accelerating the sintering of active magnesias [31] by facilitating surface diffusion.

A different mechanism has also been proposed [10] for the adverse effects of the presence of hydrated MgO surface, based on observations of hydrogen evolution from hydrated MgO [34–6]. This, it was suggested [10] could lead to oxidation of Fe<sup>2+</sup> to Fe<sup>3+</sup>, thus increasing the cation vacancy concentration. However, measurements of the amount of hydrogen evolved, and the results on powders of different iron content (Section 4.3), suggests that this mechanism is not of major importance in MgO powders.

## 5 Conclusions

The choice of magnesium oxide as the favoured high temperature insulating material in powder form is easily understood from the results shown in Fig. 1. A few other powders have found limited application. Aluminium oxide is used in certain nuclear reactor applications because of its nonreactivity with water, although its mechanical and electrical properties are unfavourable. Crystalline silica (quartz) has a lower dielectric constant than MgO, but the hazard presented by particles in the respirable size range must not be overlooked. Similarly beryllium oxide, which is used in ceramic form, is too toxic to

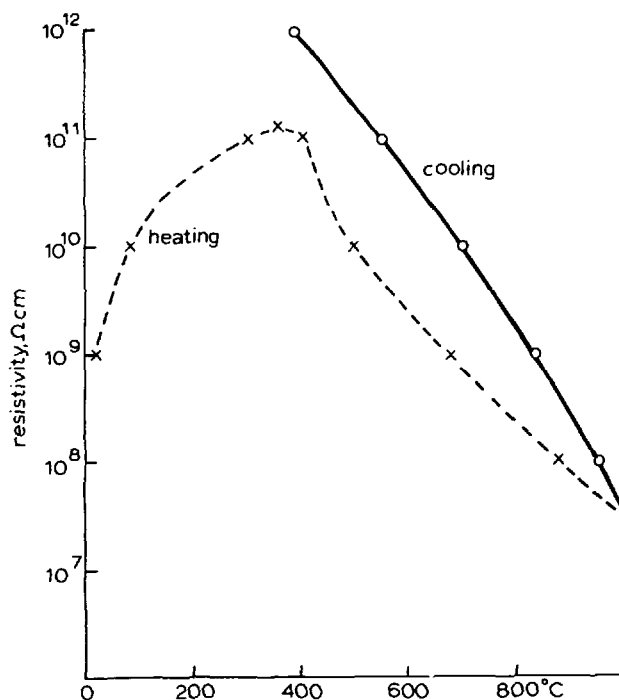


Fig. 5 Heating/cooling cycle in Fetterley cell

consider as a powder insulant, despite its excellent resistivity. The only nonoxide material with comparable high-temperature resistivity is boron nitride, which has been investigated for special applications [37]; it is, however, oxidised in air above 800°C.

In the temperature range up to 1100°C conduction in magnesium oxide is essentially ionic, by magnesium cation vacancies whose concentration is extrinsically controlled by impurities. In single crystals, these impurities are the aliovalent cations dissolved in the lattice, of which iron is a typical example. With mineral insulation in the form of compacted powder, however, a lower activation energy conduction process is observed at temperatures below 1000°C, which, it is suggested, is associated with the crystallite surfaces. Interaction of the MgO surface with adsorbed water is proposed as an additional source of vacancies, enhancing conduction.

At 1000°C, where the higher activation energy bulk conduction process begins to predominate, commercial fused MgO powders can give volume resistivities of  $10^7$ – $10^8$   $\Omega$  cm, approaching the values reported for high-purity single crystals.

These values, which are unsurpassed by any other insulating materials, are attained by powders containing up to 0.1% iron, and 1–2% of refractory oxides such as those of calcium and silicon, provided that careful control is maintained during cable manufacture to avoid surface contamination and to ensure adequate heat-treatment. Purer magnesia powders, in which the metal impurity content is reduced to 0.01% or less, show no improvement in resistivity.

The requirements for the highest possible resistivity values at temperatures of 600°C and above have some primarily from thermocouple and signal cable applications, particularly in the nuclear power industry. Research has, therefore, concentrated on DC resistivity measurements in this range, but the powder requirements will be similar for other applications, such as heating and wiring cables, operating at mains frequencies and voltages.

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