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IMPURITIES AND THEIR EFFECTS IN NUCLEAR GRADE BERYLLIA POWDERS

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ABSTRACT

The criteria for sinterability in high purity beryllia powders are discussed. Of common impurities in less pure powders, silicon, aluminium, calcium, magnesium and iron are considered to have the major effects on sinterability. Of these, Si and Al have detrimental effects, and Ca, Mg and Fe beneficial effects. It is suggested that for an impure powder to be sinterable, the combined (Si + Al) content should be no higher than the combined (Ca + Mg + Fe) content, both expressed in p.p.m.

CONTENTS

1. INTRODUCTION

Beryllium oxide in the form of nuclear grade powder is at present an expensive material, costing about £A15-20 per kilogram.

The high price of nuclear grade powders is in part due to the insistence of users on obtaining an almost ideal combination of high purity and high sinterability. A real price reduction might be dependent on a relaxation of user's specifications, particularly those concerning purity. The initiative in this field has been taken recently by Brush Beryllium Company, which announced the introduction of a new grade of BeO, to be of lower purity but cheaper than the hitherto accepted nuclear grade, UOX.

In the present report a review is made of the relationship between purity and other factors, including sinterability, and some general conclusions are drawn which should be helpful when considering lower purity BeO products.

However, two general points should be made. First, any impurity in BeO, with the exception of carbon, will raise the thermal neutron absorption cross section, since Be and O already have the lowest cross sections of any cation or anion respectively, except carbon. Secondly, there is, as yet, no consistent theory which covers the effects of impurities in BeO on its sintering behaviour. Conversely, it is not possible to predict with certainty the effects of impurities in a particular grade of BeO, especially when more than one type of impurity is being considered. Nevertheless, it is possible to make limited predictions, on the basis of a growing body of knowledge. These are discussed in the following Sections and some discussion is included on other factors affecting the sinterability of BeO powders.

2. WHAT IS REQUIRED IN A SINTERABLE BeO POWDER?

The requirements of BeO powder for nuclear use may be summarised as follows :

(i) Neutron absorption cross section must be acceptably low.
(ii) Uniformity of powder must be good.
(iii) Must be sinterable to a high density, high strength, fine grain-size product.
(iv) Required sintering temperatures should preferably not be above 1500°C.
(v) Price must be acceptably low, consistent with satisfactory properties under (i) - (iv).

3. FACTORS AFFECTING SINTERABILITY

Much of the information under this heading is of a negative character, as it is concerned with those factors which are detrimental to achieving satisfactory sintered structures at relatively low temperatures. The following information has been obtained by studying various commercial and semi-commercial BeO powders, with the aim of relating their sintering behaviour and physico-chemical properties.

3.1 Surface Area and Green Density

In a powder of UOX-type purity (see Table 1), surface areas lower than about 10 m^2/g would be expected to lead to sintering temperatures well above 1500°C. An approximate indication of the effect of surface area can be obtained from the equation (Bannister 1965) :

$$10^4/T = 2.8\ (1 + \log_{10} S),$$

where T is the sintering temperature (°K) to achieve 2.90 g/cm^3 after 1 hr in dry N_2, and S is the surface area in m^2/g. The powder is assumed to be pressed to 1.75 g/cm^3; since this is a fairly high figure, and lower pressed densities are unfavourable, use of the above equation tends to predict optimistically low sintering temperatures.

Although in a BeO preparation containing a sintering-enhancing impurity, surface areas lower than 10 m^2/g may still allow sintering below 1500°C, there is another unfavourable effect of low surface areas. Lower surface areas are usually associated with larger crystallite sizes in the powder, and this makes the higher density - fine grain size criterion more difficult to achieve in the sintered product.

For a particular green density and sintered density, for example (1.75 and 2.90 g/cm^3 respectively), sintered grain size G, and initial surface area S may obey the relationship (Bannister 1965) :

$$GS = \text{constant}$$

The more complete equation is :

$$P^{1\cdot25}\, G = 1.33\, P_o^{1\cdot25}/S \quad ,$$

where P is the sintered porosity and P_o is the green porosity.
Although these equations were observed to apply to powders of UOX-type derivation and purity, it is to be generally expected that a powder with larger initial crystallite size will also be coarser-grained when sintered.

For high sinterability and fine sintered grain size, the green density should preferably be about 1.7 g/cm^3 or higher. For every 0.1 g/cm^3 lower than this, the above equation predicts a rise in sintering temperature of 60°C. This tendency would of course be balanced by higher surface areas. However, a practical minimum green density would probably be 1.5 g/cm^3.

Theoretically there is no upper limit on surface area, and experiments are now in progress on powders of surface area 300 m^2/g. However in practice it is difficult to remove sufficient of the anion during calcination (for example OH^- or SO_4^{2-}) and still retain a surface area higher than 20 m^2/g. Also, difficulties are expected in obtaining the required green densities with ultra-fine powders. Higher surface areas will not therefore be considered in the present context.

3.2 Spread of Crystallite Sizes

There are three detrimental effects of a large spread of crystallite sizes in a BeO powder, namely :

(i) Large crystals in a fine-grained powder will remain large even if they do not grow during sintering, and, if larger than the final desired grain size, may be flaws in the final structure.

(ii) Large dense crystallites may, during pressing, "bridge" around a cavity containing little or no fine material. On sintering, this volume will be either of low density or zero density, that is, a void. The composite structure will act as a flaw.

(iii) A high proportion of larger crystallites in an otherwise fine, high surface area powder will dominate the behaviour of the powder; discontinuous grain growth leading to loss of surface area, absorption of fine material and premature pore closure will occur; fine grain size and high density will be difficult to obtain (Bannister 1965). Also, any non-uniformity of packing will lead to density and grain size inhomogeneities.

3.3 Aggregate Structure

The presence of dense, strongly-bound or highly sub-structured aggregates in a BeO powder is detrimental to achieving a dense fine grained high strength structure (Reeve 1963, Bannister 1964a). The general effect of this type of aggregate is the occurrence of internal shrinkage within, and non-bonding between, aggregates, leading to growth of large, stable pores and sometimes cracks. Such aggregates arise during calcination of certain BeO precursor compounds, e.g. $Be(OH)_2$, owing to retention of a pseudomorphic substructure. This substructure may, in some cases, be removed by a ball-milling or similar homogenising treatment as has been shown by Clare (private communication). However, strong aggregates can, in general, be considered undesirable.

3.4 Impurities

3.4.1 Distribution of impurities in BeO

Possible ways in which impurities could exist in BeO powder are :

(i) In stable solid solution.

(ii) In metastable solid solution.

(iii) As a chemically or physically adsorbed layer on crystallite surfaces.

(iv) As inclusions or precipitates within crystallites.

(v) As discrete particles.

(vi) As discrete particles, but "locked" into aggregates of BeO crystallites.

(vii) As a compound with BeO in any of the distributions (iii) - (vi).

Literature on the solid solution behaviour of BeO is almost non-existent. Most phase diagrams show no solubility of other oxides in BeO even at near-eutectic temperatures, although recent more accurate work is causing revision of this simple picture, for example, for PuO_2 - BeO and ThO_2 - BeO (Hough and Marples 1964) and for Al_2O_3 - BeO (Bradhurst, private communication), significant solubility in BeO at eutectic temperatures has been reported. However, it seems likely that, at room temperatures, no other materials are soluble in BeO to the extent of more than a few hundred parts per million at room temperature. Additional evidence on this point has been obtained recently by Sjodahl and Westbrook (1965) who found that in sintered UOX BeO, grain boundaries were significantly harder than the bulk of the material. This effect was absent in ultra high purity BeO and was therefore attributed to segregation at the grain boundaries of the few hundred p.p.m. of impurities in the material.

BeO forms compounds with Al_2O_3, CaO, BaO, SrO, La_2O_3 and SiO_2. However, many of these compounds are difficult to form and the appropriate impurities

will not necessarily exist as such in BeO powders formed by calcination of crystallised or precipitated BeO salts at the commonly-used temperatures of 900-1000°C.

Although there is little real evidence on this point, it seems likely that trace (for example <10 p.p.m.) impurities may be present in BeO powder as either of the forms (i) or (ii) above, but that intermediate and large amounts of impurities will occur as either (iii) or (vi). Whichever mode of distribution applies, impurities are very unlikely to be uniformly distributed. For example, if (i), (ii), (iii), or (iv) is the case, the content of impurity may conceivably vary from one crystallite to another (for example under non-equilibrium conditions of precipitation); if (vi) applies, the impurity content may vary between aggregates. Mode (v) is a special case which is unlikely to apply if care is taken to prevent pick-up of foreign materials during processing.

3.4.2 Unfavourable impurities

$Be(OH)_2$, OH^-, H_2O. There is indirect evidence (Bannister 1964a) that residual hydroxide in a $Be(OH)_2$-derived BeO is unfavourable owing to evolution of H_2O at a critical stage during sintering. If sintering is being carried out in a vacuum, there is a slight or no detrimental effect on sintering, but when sintering in a static or flowing gas atmosphere, the water vapour can apparently remain near the specimen long enough for the competitive evaporation-condensation mechanism, which does not produce densification, to reduce surface area of the compact and slow the sintering rate.

Most hydroxide-derived powders do contain residual $Be(OH)_2$ since removal of all OH^-, at least by air-atmosphere calcination, requires temperatures such that the surface area of the resultant powder is unfavourably low. Special techniques, such as vacuum calcination, may help to overcome this difficulty, but it can be stated in general terms that without special calcination and/or sintering techniques, hydroxide-derived powders are not likely to be highly sinterable.

Residual unbound moisture may also be a problem if heating to sintering temperature is rapid without a large flow rate of purge gas. Aitken (1961) found that vacuum out-gassing to 800°C was necessary to achieve maximum densification rates with BeO powders.

The unfavourable effect of moisture on sintering can apparently be minimised, if not completely overcome, by the addition of 0.25 mole % of MgO as a sintering aid (Aitken 1960). Thus impure powders containing MgO may not be as sensitive to residual hydroxide or unbound moisture.

Si or SiO_2. Two independent observations have been made on the unfavourable effect of Si as an impurity. The first is that of Hey and Livey (1962) who studied the sintering of $Be(OH)_2$-derived powders containing, as major impurities, 1600 p.p.m. of Si, 2000-4000 p.p.m. Na, and ~700 p.p.m. F. Poor sinterability of these powders was attributed to an anomalous low temperature crystallite growth process leading to premature loss of surface area. Si was considered the most likely contributor to this process. Another powder with Si content of 300 p.p.m. sintered less readily than a similar powder containing only 65 p.p.m. of Si.

The second observation is from Bannister (1964b) who added 0.125, 1, and 2.5 mole per cent. of SiO_2, as either colloidal silica or ethyl silicate hydrolysed in situ, to Brush UOX BeO. He noted a marked detrimental effect on sinterability of the BeO at temperatures up to 1600°C in dry atmospheres, but not in moist air; however BeO already sinters poorly in moist air and the slight improvement in this case by addition of silica did not make moist-air sintering attractive. A slight detrimental effect was noted when 100 p.p.m. of Si was added to UOX containing 60 p.p.m. Si. Bannister (1964a) also found that a BeO powder with high Si content (400 p.p.m.) as well as high sodium (300 p.p.m.), but otherwise promising purity, surface area and aggregate structure, was poorly sinterable.

Thus Si as the major impurity appears to be detrimental to achieving high density at temperatures up to 1600°C. These effects may not be so apparent at much higher temperatures or when the Si is present together with other major impurities. However, Na as a major impurity does not appear to over-ride the presumed detrimental effect of Si.

There is no wholly satisfying explanation for the effect of Si on the sintering of BeO. The compound phenacite ($BeO.SiO_2$) is difficult to form, is unstable above 1560°C, and does not seem to play an important part in the sintering of BeO containing SiO_2. The eutectic in the BeO-SiO_2 system is at 1713°C. The apparently special role of Si may be due to its small ionic size (0.41A° for Si^{4+}) and high charge. It was pointed out by Hey and Livey (1962) that because of these properties, Si^{4+} is more likely to enter

the BeO lattice at high temperatures and thus affect sintering rates. A reduction in sintering rates could occur if oxygen vacancy concentration were rate-controlling.

Al_2O_3. Al_2O_3 alone is an unfavourable additive to UOX BeO for sintering at temperatures up to and including 1500°C. Densification is inhibited noticeably by as little as 200 p.p.m. of Al. (Woolfrey, private communication). Al_2O_3 does not inhibit grain growth and in fact seems to have the reverse effect. Above 800 p.p.m. Al, and at 1600-1700°C, Al_2O_3 causes unequiaxed grain growth, accompanied by twinning, in sintered BeO. There is some indication that grain growth becomes equiaxed again above 1800°C, possibly due to a much higher solubility in the BeO lattice.

Al_2O_3 forms three compounds with BeO, namely $BeO.Al_2O_3$ (chrysoberyl), $3 BeO.Al_2O_3$, and $BeO.3Al_2O_3$. Eutectics occur at 1850°C, 1870°C, and 1890°C (Lang and others 1952). There is some indication that chrysoberyl begins to form at 1500-1550°C, and that above these temperatures an enhancement of densification occurs. Thus a simple statement that Al_2O_3 retards or enhances densification of BeO is unjustified since opposite effects would be obtained on powders which normally sinter at say 1450°C and 1700°C respectively.

3.4.3 Favourable impurities

Fe_2O_3 or Fe_3O_4. Beaver and others (1964) found Fe_2O_3 to be the most powerful sintering-enhancing additive, having a very marked beneficial effect when present at 500 p.p.m. Such an effect has also been noted by Bardsley and Ridal (1964) and by Bannister (private communication), who considered Fe_3O_4 to be the most effective form of iron in this respect. This beneficial effect disappears if sintering is carried out in hydrogen and an actual depression of sintering may occur owing to the production of H_2O during the reduction of iron oxide to iron. The mechanism by which iron oxides, but not iron metal, enhance the sinterability of BeO is not known. Beaver and others have pointed out that Fe_2O_3 rapidly diffuses through 90 per cent. dense BeO at 1500°C but no mechanism was postulated for this diffusion. No iron oxide-BeO compounds have been reported, and the eutectic temperature is not known.

MgO. MgO enhances densification and grain growth rates at 500 p.p.m. (Beaver and others 1964) but has not such a large effect as Fe_2O_3 and is therefore usually employed at a level of approximately 0.5-2 wt. per cent. (Aitken 1960, 1961; Chandler and others 1963). Aitken (1960) noted that

0.25 mole per cent. MgO reduced the detrimental effect of water vapour on the sintering of BeO.

MgO forms a eutectic with BeO at 1855°C, and there is some suggestion of a slight solid solubility in BeO at high temperatures. (Williams 1964). The beneficial effect is difficult to explain in terms of an altered oxygen or beryllium vacancy concentration, since these should not be changed when MgO enters the BeO lattice. The possibility exists that MgO is only effective in combination with an unknown but common trace impurity which acts to lower the BeO-MgO eutectic to the sintering temperature range. Sjodahl and Westbrook (1965) have suggested on the other hand that MgO, which they found to segregate at grain boundaries in BeO - 0.5 wt. per cent. MgO, may act in part by restricting BeO grain boundary movement.

CaO. Beaver and others (1964) have noted beneficial effects of CaO on sintering, at levels as low as 500 p.p.m., but it is usually employed at higher levels.

CaO forms a compound 3BeO.2CaO which forms a eutectic with BeO at 1300-1350°C. The effect of CaO in enhancing the sintering and grain growth of BeO is almost certainly associated with the formation of small amounts of liquid phase even if this cannot be seen metallographically. Evidence for this is that the effect seems to be apparent mainly at temperatures higher than 1300°C. Sjodahl and Westbrook (1965) have suggested, however, that grain boundary segregation of CaO may enhance sintering even below 1300°C.

CaO is often used as a sintering aid in BeO, but it tends to enhance grain growth rather more than densification. In an already impure BeO it may help to overcome unfavourable effects of other impurities, for example of Si, on the sintering of BeO.

3.4.4 Other impurities

The cationic impurities discussed above are those likely to be present in major amounts in a commercial or partly purified BeO. Other impurities have not been so extensively studied, but when present in minor amounts, are not likely to control behaviour. From the existing literature however (Aitken 1961, Beaver and others 1964, Pampuch 1960), it appears that Ti, Mn, Co, Zn, and Ni may aid sintering at $\leq$ 1500°C while Cr, Ba, and Zr have no significant effect when present in minor amounts. Na appears to have little effect alone even in major amounts, partly because considerable sodium loss during sintering can be expected. Li should be kept as low as possible on neutron absorption cross section considerations, but appears to have little effect on sintering and, like Na, tends to be lost at high temperatures.

Of common anionic impurities, OH^- has already been mentioned. Residual sulphate in BeO powder appears to be detrimental only when sintering in H_2, and even in this case the effect of 1000 p.p.m. of S is only marginal. Concerning F^-, Aitken (1961) added 0.25 mole per cent. of BeF_2 to BeO and found no effect on the densification of BeO at 1600-1900°C, presumably because of evaporative loss of BeF_2 during sintering. It is not certain however that F^- replacing O^{2-} in the BeO lattice would be lost in this way; F^- entering the BeO lattice, for example during calcination of a Be salt containing "enclosed" BeF_2, would be expected to cause a marked increase in the Be vacancy concentration and decrease the oxygen concentration. Others have suggested such a role for F^- (Rothman 1961) but Hey and Livey (1962) considered that high F (700 p.p.m.) in one of their non-sinterable powders was probably of less importance than the high Si content (1600-1800 p.p.m.).

4. INFORMATION ON COMMERCIAL GRADES OF BeO

Typical analyses and surface areas of the three most readily sinterable nuclear pure commercial grades are given in Table 1. A tighter specification for nuclear pure BeO, based on General Electric Co. experience in the oxyacetate/hydroxide route, is that given in Table 2 (Kirkpatrick and others 1961). This specification however, does not appear to be met by any commercially-available sinterable powder.

The best-known "commercial grade" powder is Brush "LOH" grade, whose specification is shown in Table 3.

Another impure "commercial grade" powder is that marketed by The Beryllium Corporation. This powder contains, as major impurities, Si (1.5%), Mg(1.5%), Na (1.5%), Ca (0.2%), and F(1%). No sintering data are available for this powder.

Data on other impure but non-commercial grades, together with sintering data on these and on Brush LOH, are given in Table 4.

5. DISCUSSION

It has been established that Si and Al, either singly or in combination, are unfavourable impurities in BeO if sintering is to be carried out at 1500°C or below. Na as a major impurity appears to have little effect, and this is probably true if Na is a major impurity together with Al and Si.

Conversely Fe, Ca, and Mg as impurities enhance the sintering of BeO at temperatures as low as 1350°C. The efficacy of these impurities decreases from Fe to Ca to Mg.

It might now be constructive to classify powders according to the total unfavourable, and total favourable, impurity contents. In doing this, impurity contents will be added on a p.p.m. by weight basis. No direct allowance is made for the greater effect of Fe and Ca, other than by use of p.p.m. by weight, which implies a larger atomic effect for these impurities of higher atomic weight. The atomic weights of Mg, Al, and Si fall within a narrow range.

Table 5 classifies the eight powders of Table 4, plus UOX, according to (Al + Si)/(Ca + Mg + Fe) ratio.

The information in Table 5 suggests that the (Al + Si)/(Ca + Mg + Fe) ratio might be used as a tentative criterion of the sinterability of a powder which on other grounds would be expected to be sinterable. Tentative tests for sinterability might therefore be as follows :

1. (Al + Si)/(Ca + Mg + Fe) $\leq$ 1 .... Powder expected to be sinterable.
   {for (Al + Si) in range 115-800 p.p.m.}
2. (Al + Si)/(Ca + Mg + Fe) $\geq$ 4 .... Powder expected to be non-sinterable.
   {for (Al + Si) in range 500-1600 p.p.m.}

It thus seems that a high silica, or silica plus alumina, content can, under some conditions, be "neutralised", as far as sinterability is concerned, by an equally high content of sintering-enhancing impurities. This may not be true however, for very high Si + Al, and Table 5 does not show it to be true for Si + Al higher than 500 p.p.m.

There are several other effects of a high level of impurities in a BeO powder, in addition to the possibility of non-sinterability, which must be considered. These are :

(i) As mentioned above, the thermal neutron absorption cross section of BeO rises with increasing impurity content.

(ii) The thermal conductivity of BeO falls with increasing impurity content.

(iii) In impure BeO powders with high (Al + Si) and (Ca + Mg + Fe) it is almost certain that liquid phases will form during sintering. It may not then be possible to obtain high density products with a fine grain size, owing to enhancement of grain growth by the liquid phase.

(iv) Strength will fall at relatively lower temperatures because of the formation of liquid phases.

One set of data on thermal conductivity vs. total impurity content is given in Table 6. It will be noted that the effect of impurities is most marked at temperatures below 400°C.

Data on high temperature strength and creep resistance vs. impurity content are so incomplete that these aspects will not be discussed.

Table 7 shows the concentrations of each of the five common impurities necessary to raise the thermal neutron absorption cross section of BeO from an assumed 9 mb by 0.2 mb for each impurity, or by 1 mb for the five impurities. If the impurities are present in other proportions, the total effect can, of course, be readily obtained from these figures. The proportions shown in the Table satisfy the sinterability criterion. Other allowable combinations, for a total cross section increment of 1 mb, would be

$$\left.\begin{array}{lr} \text{Si} & 1400 \\ \text{Al} & 900 \\ \text{Ca} & 2580 \end{array}\right\} , \qquad \left.\begin{array}{lr} \text{Si} & 1400 \\ \text{Al} & 900 \\ \text{Ca} & 430 \\ \text{Mg} & 1500 \\ \text{Fe} & 340 \end{array}\right\} \qquad \text{etc.}$$

These considerations, of course, ignore contributions from high cross section atoms such as Li, B, Cd, etc. These impurities will probably be present at a higher level in a generally impure powder than in a highly pure one. To obtain acceptably low cross section powder however, these impurities must be kept to such low levels that they will have little effect on sinterability. The primary consideration determining the degree of purification required in respect of these and other moderate-to-high cross section absorbers is the overall cross section required in the resultant BeO product. In deciding what level is acceptable, analysis and cross section tests should be made both on powder and on sintered specimens, since some high cross section impurities, notably Li, are appreciably volatile and tend to distil out from BeO compacts during sintering.

6. CONCLUSIONS

1. Impurities in a BeO powder may be allowable if they:
   (1) give good sinterability, and
   (ii) do not raise the thermal neutron absorption cross section to unacceptably high levels.

2. The impurities likely to be present in largest amounts are those likely to have the major effect on sintering; the impurities with most effect on cross section should be present in such small amounts that there is not likely to be a serious effect on sintering.

3. If the major cationic impurities are some or all of Na, Si, Al, Mg, Ca, and Fe, the following rules can be of limited use in determining sinterability acceptance:
   (i) Na content is of little importance.
   (ii) Si and Al contents should be as low as possible.
   (iii) (Si + Al), expressed in p.p.m., should be no higher than (Ca + Mg + Fe).

   A total content of these 5 impurities of 0.64 wt.per cent in the right proportions should add no more than 1 mb to the cross section.

4. In addition, for a powder to be sinterable it should preferably satisfy the following:
   (i) Surface area of 10 m^2/g or higher.
   (ii) No residual hydroxide.
   (iii) No dense or highly structured aggregates.
   (iv) Capable of being pressed to ≥ 1.5 g/cm^3 at moderate pressures.
   (v) Small spread of crystallite sizes.

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TABLE 1.

IMPURITIES IN NUCLEAR GRADE BeO POWDERS
(expressed in p.p.m.)

	Brush UOX	Pechiney PY60	NGK-CF (guaranteed values)
Na	30	< 35	50
Mg	45	10	20
Ca	35	< 20	100
Al	70	80	10
Si	45	25	100
Fe	35	25	20
Surface Area (m^2/g)	10	8	20

TABLE 2

GENERAL ELECTRIC SPECIFICATION FOR NUCLEAR PURE BeO

Impurity	Max. p.p.m. (based on BeO)	Condition
F+S+P	80	dried 110°C
Al+Fe+Cr	30	ignited 1000°C
Ca + Mg	20	"
Si	50	"
Co+Li+Ag	3	"
C + Cd	3	"
Others (except C)	< 1 each	"

TABLE 3

BRUSH SPECIFICATION FOR LOH BeO

Impurity	Max. Level (p.p.m.)	Impurity	Max. Level (p.p.m.)
Al	600	Ni	100
Si	600	Cr	300
Mg	5000	B	3
Ca	500	Li	-
Fe	200	Ti	-
Na	5000	F	-
Mn	300	Total Cations ≦ 1.3‰ of BeO	

TABLE 4

DATA ON IMPURE BeO POWDERS
(Impurities in p.p.m.)

Impurity	Powder 1 Hey and Livey (1962)	Powder 2 Bannister (1964a)	Powder 3 Reeve and Bridgford (1964)	Powders 4 and 5 LOH Ward and Funk (1960) Gates(1960) (in powder)	 Freas and others (1960) (Sintered)	Quirk and Others (1957) Powder 6	 Powder 7	 Powder 8
Al	< 10	85	1000	130	400	500	200	< 30
Si	1600	400	500	330	400	300	400	400
Mg	200	25	120	< 500	700	4000	500	150
Ca	100	40	n.d.	< 50	100	2000	50	50
Fe	40	70	120	20	100	75	100	150
Na	3800	300	400	3000	-	2000	400	300
Mn	15	-	-	130	10	400	100	10
Ni	-	-	-	50	200	100	20	< 5
Cr	-	-	-	15	60	200	400	50
B	< 1	-	-	2	3	< 1	15	15
Li	300	-	-	50	-	-	-	-
Ti	-	-	-	-	300	-	-	-
F	700	-	-	-	-	-	-	-
Total cations % of BeO	0.6	0.1	> 0.2	0.2	0.4	1.0	0.25	0.15
Sintered to(g/cm³)	2.44	2.57	2.73	2.95		2.92 2.95	2.95	2.92
Conditions(°C,hr)	1800,6,dry air	1600,1,dry N_2	1600,1,dry N_2	1530,2,H_2		1450,1,N_2 1420,1,H_2	1420,1,H_2	1420,1,H_2
Pressed at (tsi)	10	20	20	9		20 45	45	45

TABLE 5

CLASSIFICATION OF IMPURE BeO POWDERS

Powder No. (Table 4.)	Al + Si. p.p.m.	Ca+Mg+Fe p.p.m.	(Al+Si)/(Ca+Mg+Fe) (approx.)	Sinterable at 1500°C
1	1600	340	5	No
2	480	135	4	No
3	1500	300	5	No
4	460	500	1	Yes
5	800	900	1	Yes
6	800	6000	< 1	Yes
7	600	650	1	Yes
8	400	350	1	Yes
UOX	115	115	1	Yes

TABLE 6

THERMAL CONDUCTIVITY OF DENSE BeO
(COORS PORCELAIN 1964)

T °C	k (cgs. units) 4% Impurities	 2% Impurities	 0.5% Impurities
20	0.36	0.49	0.60
100	0.32	0.37	0.45
400	0.16	0.17	0.20
800	0.06	0.06	0.07

TABLE 7

IMPURITIES IN BeO TO CONTRIBUTE 0.2 mb PER IMPURITY

Impurity	Content (p.p.m.)
Si	1400
Al	900
Ca	730
Mg	3000
Fe	170