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High Temperature Use Fractal Insulation Materials Utilizing Nano Particles

Brian Kandell

MHI Inc. 750 Redna Terrace, Cincinnati, OH 45215, U.S.A.
brian.kandell@mhi-inc.com

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ABSTRACT

Refractories are used in a variety of processing industries including the ceramic, steel, aluminum, metal casting and heat treatment industries. Refractories provide thermal insulation, and do so by providing stagnant or "dead" gas space, namely, they contain a large volume fraction of voids. The prime criterion for material selection is refractoriness (i.e. use temperature) and the dimensional stability. One key property required for insulating refractory qualification is the service temperature limit (STL), which is related to composition, sinterability at use temperature, sintering temperature, and void volume. During the past ten years nano-pore and nano-scale fractal refractories have become available which are possibly significantly less toxic when compared to fibrous refractories. The materials used in fractal refractories are discussed in this article. Apart from use as high temperature thermal insulators the new class of materials are also finding use in a variety of products and applications of structural components such as nano-pore high performance coatings, sensors, filters and membranes used in the electronics, aeronautics, space, energy, and biomedical engineering fields.

Review of Refractories

The typical refractories commonly employed in the high temperature processing industry normally contain stable oxides and refractory metal compounds such as Al_2O_3, SiO_2, ZrO_2, CaO, MgO, $FeCr_2O_4$, SiC, graphite and their combinations [1, 2, 3].

Classification of Insulations/Refractories. The two major types of refractories in use prior to the onset of fractal refractory materials were the *Cellular and/or Fiber* containing porous materials discussed below.

Cellular Ceramics or Porous Ceramics. Porous ceramics can be grouped in general categories of reticulate or foam structure ceramic. A reticulated ceramics are materials consisting of interconnected voids surrounded by a web of ceramic. A foam ceramic has closed voids within a continuous ceramic matrix. These porous structure materials have relative low mass, low density, and low thermal conductivity. Reticulate and foam ceramics differ in the property of permeability. Permeability is high in reticulate ceramics and low in foam ceramics. The difference is due to the open versus close cell structure. With a larger void volume fraction, the solid will begin to assume the micro-structural characteristic of foam. The word *cellular* will be used to describe these full range materials.

Cellular refractories have existed in the insulating line of products well prior to the introduction of modern fiber refractory. IFBs (Insulating Fire Bricks) can be traced back in to the 19th century. Cellular refractories are made either by expanded aggregate or expanded matrix or a combination of the two [4, 5]. Rotary equipment is used to sinter the porous grains without collapsing the porosity.

These, approximately monosize, grains will give rise to a fairly open packing [6, 7]. Inexpensive cellulose particles, such as sawdust with a controlled particle size, can be used to create permanent voids in the material by introducing them into the matrix and then later burning them out. This method is used as a technique in creating an expanded matrix and is described as the 'burnout' method. Brick making takes advantage of this technique.

Foaming is the other technique and is accomplished with foam stabilizers or gelling agents or both [8]. Foaming is accomplished by frothing or chemical gas forming techniques. Frothing involves the whipping of air into a mix by whisk or beater methods similar to that used in common baking situations. Chemical Gas forming techniques involve an acidified mix, or 'blowing' agent, such as aluminum powder. The acidified mix releases H_2 [9] and other components (both organic and inorganic) that react to generate CO_2. This process is akin to that found in the baking processes which involve rising dough (i.e. bread making) [8, 9].

The expanding of aggregate and the expanding of refractory matrix differ primarily in the manufacturing stage that it is carried out. Commercial cellular refractories can have a void fraction as high as 85%. This solid structure is a series of thin walls or ligaments that have been inundated by perforations created from internal gas pressurization and subsequent shrinking due to thermal firing. This produces a material that is thermally shock resistant and rigid, but is fairly weak and easy to crumble. The thermal shock resistance is high due to empty space causing crack isolation while retaining the compliance (flexibility) of many of the thin ligaments [10]. The result of increasing void fraction (medium to high) is a material that exhibits flaws and failure in a transition from fracture (brittle) to local tears (isolated cracks) respectively.

Although cellular type refractories are very useful, some critical problems exist which have not been overcome as noted from the data found in the literature or from company brochures. Mostly use is limited to use temperatures to below 1200°C because such refractories tend to sinter at very high temperatures. Densification increases their thermal conductivity. During densification they also shrink and harden leading to machinability problems and low thermal shock resistance during further use. To overcome these drawbacks fiber refractories (discussed below) have been developed.

Porous ceramics suffer from relatively low strength, particularly when they are made by the polymeric-sponge process. In this case, after the organic sponge is burned out, very thin webs of ceramic structure may be left which will not withstand handling or loading. Adequate and reliable strength is important for the filtering application, where reticulate ceramic must be able to withstand thermal shock and resist the high temperature corrosive environment of hot metal or gases.

Porous ceramics are commonly made by either polymeric sponge method or reactant method. Reticulated structure ceramic is usually made by burning out of a polymeric sponge, impregnated with ceramic slurry. The polymer burns out leaving a porous structure. A foam structure ceramic is usually made by producing foam from evolved gas by reactions. This foaming method can also produce reticulate structure ceramics. Several other methods are also used to fabricate porous ceramics, including chemical leaching, solid state sintering, sol-gel processing, CVD methods, pyrolysis of polymer precursor, and combustion synthesis.

Application of Porous Ceramics. Porous ceramics have found use in many applications. Its continuous expansion in recent years is due to its inherent chemical properties, physical properties, mechanical properties, microbiological stability and improved fabrication techniques. Porous materials have many applications, depending upon pore size and property of materials. Depending on the pore sizes, porous ceramic can be used in conventional filtration, micro-filtration, ultra-filtration and reverse osmosis. The most common applications for the porous ceramics are used as filters, membranes, and sensors.

Filters

Advantage:

- inertness
- non-wettability by molten metals
- thermal stability
- uniform pore structure
- strength

Applications:

- molten metal filters
- particulate filters for diesel emissions
- filter for high temperature gas clean up
- catalyst support
- casting molds

Membranes

Advantage:

- difficult to thicken the cake on the ceramic membrane under external pressure
- lower reduction in volume flux through the membrane,
- abrasion resistant
- high temperature chemical attack

Applications:

- separation of various substances
- molecular sieves for chemical process
- filter for high temperature gas clean up
- catalyst and catalyst support.

Sensors

Advantage:

- abrasion resistant
- high temperature chemical attack

Applications:

- catalyst and catalyst support.
- Electrode for fuel cells

Fibrous Refractory Types. In the production of fibrous refractories, molten silicates are blown (or spun) into long fibers while in a vitreous state. The fibers are then under-cooled while still a viscous liquid to ensure the state is maintained. This method can be seen in the production of fiberglass, which is a standard fibrous refractory. The materials that are becoming fibers in this way started as standard clays, then kaolins, then higher alumina mineral mixes, and finally selected mixtures of synthetics and minerals. In addition to glassy fibers, a few crystalline fibers are also made. Alumina [11, 12] and Zirconia [13, 14] (cubic stabilized) are examples of such fibers. In this way, one can impregnate a porous polymer filament with aqueous aluminum or zirconium hydroxycloride. The polymer matrix is then dried and heated, thus burning off the polymer and concurrently crystallizing the oxide left behind. This method can create very fine ceramic fibers [approximately 3 to 6 microns diameter with crystal sizes of tenths of a micron].

Typical fibers that are currently in use include the above mentioned crystalline oxides which are relatively expensive [11 – 14], as well as combinations of crystalline and vitreous fibers [15]. Also included are compositions of alumina-silica with alumina content not exceeding 70%. The alumina-silica compositions, when fiberized, will be come a loose or tangled mass of interpenetrating filaments. This tangled mass is then compacted lightly and produces a ‘wool’ type material. This is commonly recognized as fiberglass (un-bonded). The material is then further compressed and compacted, sprayed with inorganic binders and resin [16] and becomes a felt-like material which can be easily handled as it maintains its flexibility and elasticity. The process of densifying is finished by rolling thick layers of the above wool, spraying with binder and pressed under vacuum to make a rigid bonded board. This then can be used as tile or brick depending on thickness and cut to convenient sizes for use.

Service Temperature Limit (STL). STL, or service temperature limit, is a designation used when grading refractories. Linear shrinkage for a material will become permanent at a certain temperature. This shrinkage will continue to increase as the temperature increases above this limit. Materials such as insulating products have a large empty volume that thus causes the shrinkage to be more pronounced. Porous materials that are formed are quite under-sintered – however if the material is re-heated beyond this limit the densification will continue. Glassy fibers can undergo thermal re-crystallization or continued crystal growth when continually re-heated above this limit [17]. For uniformity, manufacturers in the United States have set an agreeable limit for the re-heat shrinkages. Standards in ASTM classification No. C155 [18] for porous firebricks and classification No. C401 [18] for porous insulating castable alumina-silica materials, spell out the allowable limits.

At a recommended STL, one can expect a linear shrinkage in the range of 2-5% while the material is in service. This shrinkage should be accounted for in design mechanism. The STL range for fibrous refractories will exceed the STL of porous refractories, starting low and finishing as high as 1850°C. Silica containing materials are often used in bonding in fibrous refractories. These silica materials reduce the STL to approximately 1800°C. To summarize, fibrous refracories have a higher STL (up to 1800°C) and have a low bulk density (approximately 0.7 g/cc). The bulk density is even lower for fibrous refractories rated lower than 1600°C [12 – 17].

Some Problem with Fiber Refractories. There are serious carcinogenic concern from the manufacture, use and disposal of short fibers. Synthetic mineral fibers (SMFs) pose the following hazards [18,19]:

- Carcinogenic risk, occurrence of airway dysfunction
- Presence of interstitial disease and pleural effects
- Skin irritant
- Free silica content (cancer risk)
- Disposal of the Synthetic mineral fibers
- In the year 2000 there were about 225,000 workers in the United States exposed to synthetic mineral fibers in manufacturing and downstream use in a wide range of workplaces

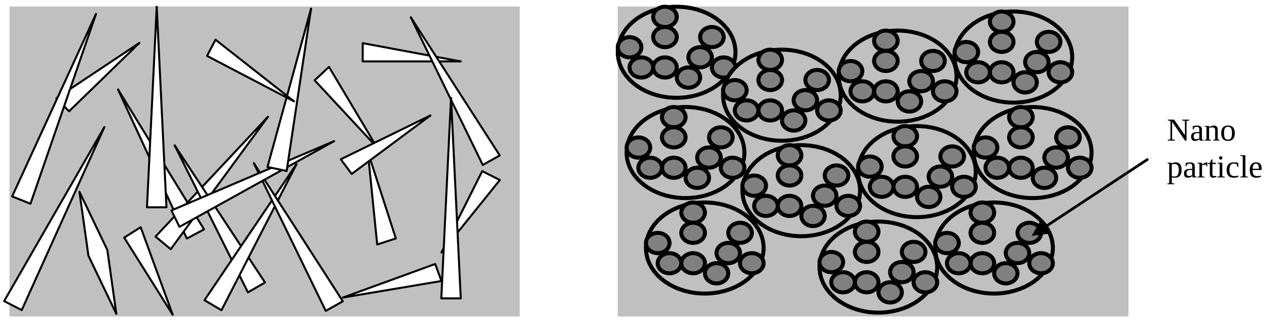
Fiber refractories were the best insulating materials available around the turn of the century (in terms of STL), but as noted above there are several problems associated with the fibers such as the inhalation health hazard of most refractory fibers. The hazard pertains to manufacture, handling and disposal of fiber products. Fibers are always toxic and are dangerous when airborne. Fibrous insulation materials release air-borne fibers during manufacture, use and disposal. About 1 fiber/cc per 8 hour exposure is a level which is commonly thought to be dangerous. Fibers are inherently irritating. Manufacturers of refractory fibers and refractories/insulation containing fibers often take great pains to educate users on the dangers of fibers. The use of face and body masks is highly recommended. Fiber refractories have been classified as class 2B (high carcinogenic possibility) by the International Agency for Research on Cancer. One of the only differences between fibers used for high temperature insulation and asbestos, apart from a small difference in diameter, relates to the fiber fracture mode during mechanical deformation.

The cost of using high temperature fiber refractory often called RCF's is also high because of (1) the high cost of the materials (primarily because of the use of fibers which are expensive especially zirconia) (2) the high cost of fabrication, machining and handling and (3) the high cost of the liability risk associated with selling short fibers containing materials. Products that use fibrous insulation are therefore very expensive. As an example a simple laboratory 12"X12"X12" ceramic furnace operating at 1800°C costs upward of $20,000 mostly from the refractory cost. In addition, during use of high temperature kilns and furnaces, there is the real danger of airborne fiber from the refractory when opening doors or placing samples (charge) in the furnace.

Based on animal toxicology and on some human epidemiological studies, the International Agency for Research on Cancer classified these materials as "possibly carcinogenic to humans". Of particular concern among industry health and safety professionals is the animal toxicology studies of refractory ceramic fibers, which have indicated the development of lung cancers and mesothelioma, a rare cancer of the pleura. For this reason, the GRC permissible exposure limit for RCF has been set to a lower level than either fiberglass or mineral wool. Refractory ceramic fiber that has been exposed to temperatures above 1800 °F may form crystalline silica, a suspected human carcinogen. Synthetic inorganic fiber materials are available in various forms, including loose fill bulk insulation, blanket insulation, paper type wrap insulation, and compressed products such as gaskets. The binding agent used for blown ceramic fiber insulation consists of aluminum phosphate and phosphoric acid. Phosphoric acid is a corrosive material that is a known irritant of the respiratory tract, eyes, and skin. Some workers cannot tolerate exposures exceeding 100 mg/m^3, and exposures between 3.6 mg/m^3 and 11.3 mg/m^3 produce cough. Because of the unusually high-level exposure found in this incident, with apparent decreased ability of the binding preparation to adequately bind the ceramic fibers to the pre-heater, the possibility exists that a malfunction during mixing of the binding agent occurred. This may have resulted in an increase or decrease in the concentration of phosphoric acid present in the binding material [19].

Refractory ceramic fibers (RCF) have been shown to cause cancer in experimental animals, OSHA continued. In a recent study, 42 percent of hamsters exposed by nose-only inhalation for two years developed mesothelioma, the cancer of the lung lining almost exclusively associated with asbestos exposure. Furthermore, another study showed that chest pain and decreased lung function were linked to RCF exposure. The International Agency for Research on Cancer has classified glasswool, rockwool, slagwool, and refractory ceramic fibers as "possibly carcinogenic to humans" (Group 2B). The National Toxicology Program, in the Seventh Annual Report on Carcinogens, has identified glasswool (respirable size) and ceramic fibers (respirable size) as "substances ... which may reasonably be anticipated to be carcinogens". The American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values (TLVs) for both mineral wool fiber (total dust) and fibrous glass dust are 10mg/m^3; these TLVs were recommended in 1986 [19].

Fractal balls and Fractal Refractory. Fractal balls and fractal refractory consist of balls (~5mm) which contain fractally stacked particles starting from nano-sized constituents. As shown in the caption of Figure 1, the stacking sequence starts with nano-sized balls and continues with fractal particle stacking. Then a critical size envelope seems to stabilize at a ball size in the order of millimeters. These balls are then stacked to form a refractory board or any shaped refractory. Mullite and Alumina have been made into porous balls and boards and are now commercially available through the site *www.buyrefractory.com* (products also shown in the Figure 2). Typical properties of the fractal balls formed porous mullite material is shown in Table 2 and compared with high temperature fiber board materials. The generic manufacture steps for making Fractalballs and shaped boards/bricks are shown in the Figure 3.



Fibrous Refractory

Ball Refractory

Figure 1. Comparison of the Fibrous and Ball Refractory Ceramic. Note the fractal like arrangement of the small-nucleated balls which form larger clusters that are further stacked to give much larger clusters. Thus the porosity decreases with volume inside a ball cluster (fractal like packing). When the larger size envelopes are stacked the density of the material becomes constant and dependent on the stacking sequence of the large ball clusters thus give rise to consistent engineering products.

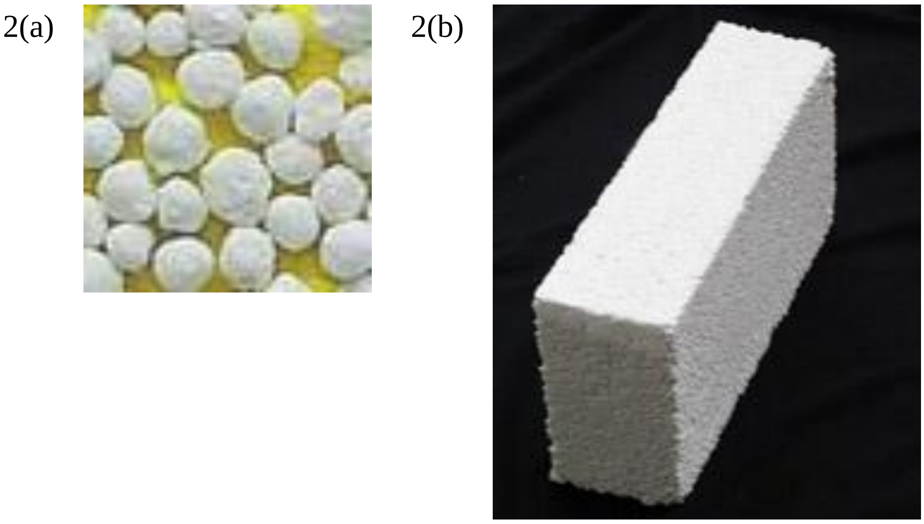


Figure 2. Mullite and alumina porous balls Figure 2(a) and boards Figure 2 (b) are made from fractal technology (now commercially available through the e-commerce web site www.buyrefractory.com).

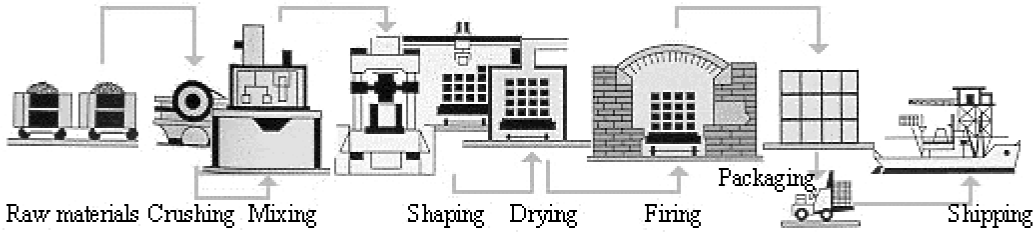


Figure 3. The generic manufacturing steps for making Fractalballs and shaped boards. The crushing and mixing steps is where the Fractalball™ formation takes place.

Microstructure of Fractal Products. A porous fractal-like microstructure is noted in the balls used to form the refractory board as shown in the following Figures 4 and 5. A measurement of porosity confirms that the porosity in the balls evolved according to Equation 1 (discussed further below). The pore size ranges from 50 nm to 2 µm as shown in Figure 5.

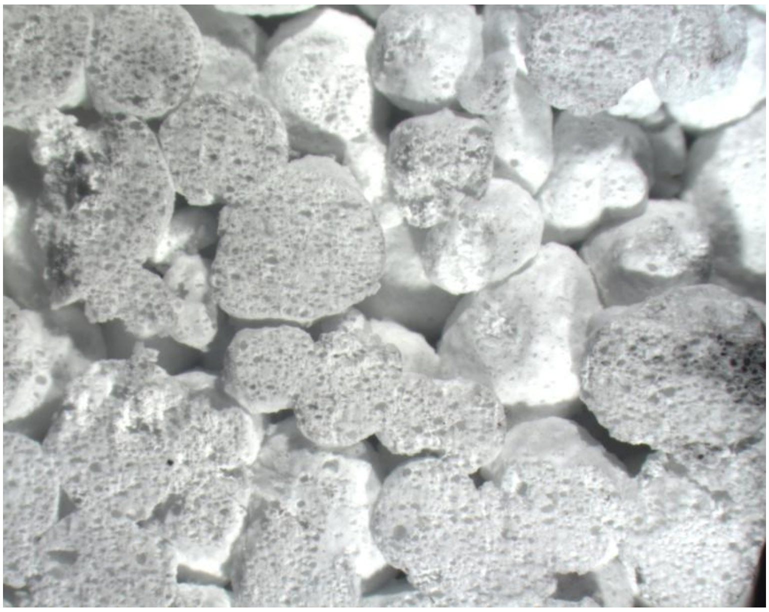


Figure 4: A photo micrograph of the porous fractal material in alumina. Note fractal porosity distribution from center to edge. Overall porosity is greater than 80%. Each ball is approximately 3mm. This structure remained unchanged after heating to 1800°C. Each ball size is about 3 mm.

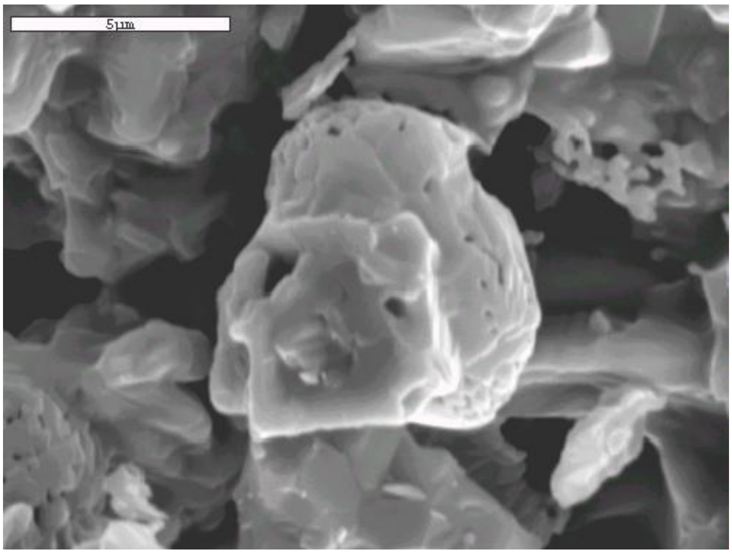


Figure 5. A high magnification image of the Fractalball™.

The fractal ball material (Figure 2 (a)) provides for a material without toxic fibers that can meet many of the thermal and mechanical property requirements and exceed the performance of the cellular or fibrous high temperature ceramic refractories. The ball is formed by the nucleation and clustering of the nano-sizes nuclei creating the "dead" gas space as shown in the Figure 1. The ball ceramic concepts may create better strength since the ball ceramic is stacked by numerous balls. Because of the numerous crack deflection sites (Figure 6) a better fracture toughness is also expected when compared with standard porous materials. The ball ceramic may also create better “dead” gas space since the air is trapped inside and outside of the numerous balls. The commercial advantages of the stacking ball concept refractory in manufacturing are:

(1) The process and material is low cost for the ball material (raw material is powder) whereas fiber making is costly especially for fibers made out of high temperature materials such as mullite and alumina.
(2) The stacking ball offer better strength properties. Typical data is given in Figures 7 and 8.
(3) The “trapped dead gas space” may be manipulated with different size balls and composite materials, a design feature not possible in cellular fibrous insulators.
(4) Easy processing to shapes without any specialized requirements or equipment.

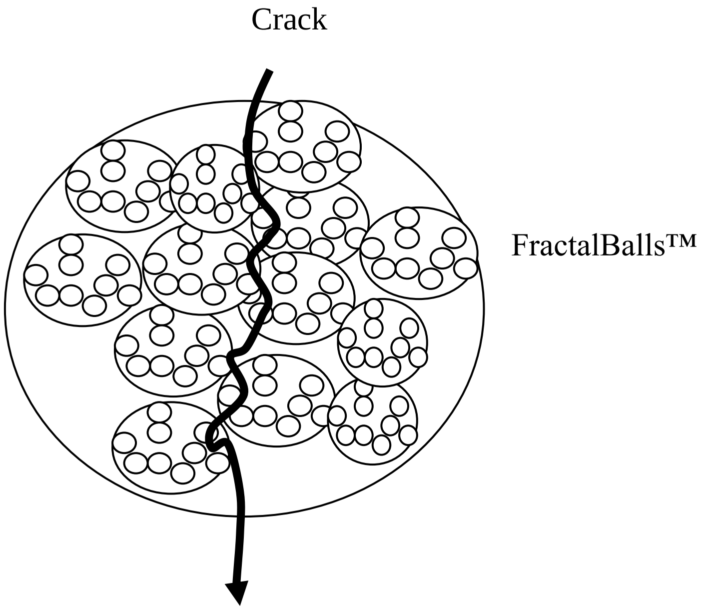


Figure 6. Illustration of the crack deflection mechanisms available in fractal insulation materials.

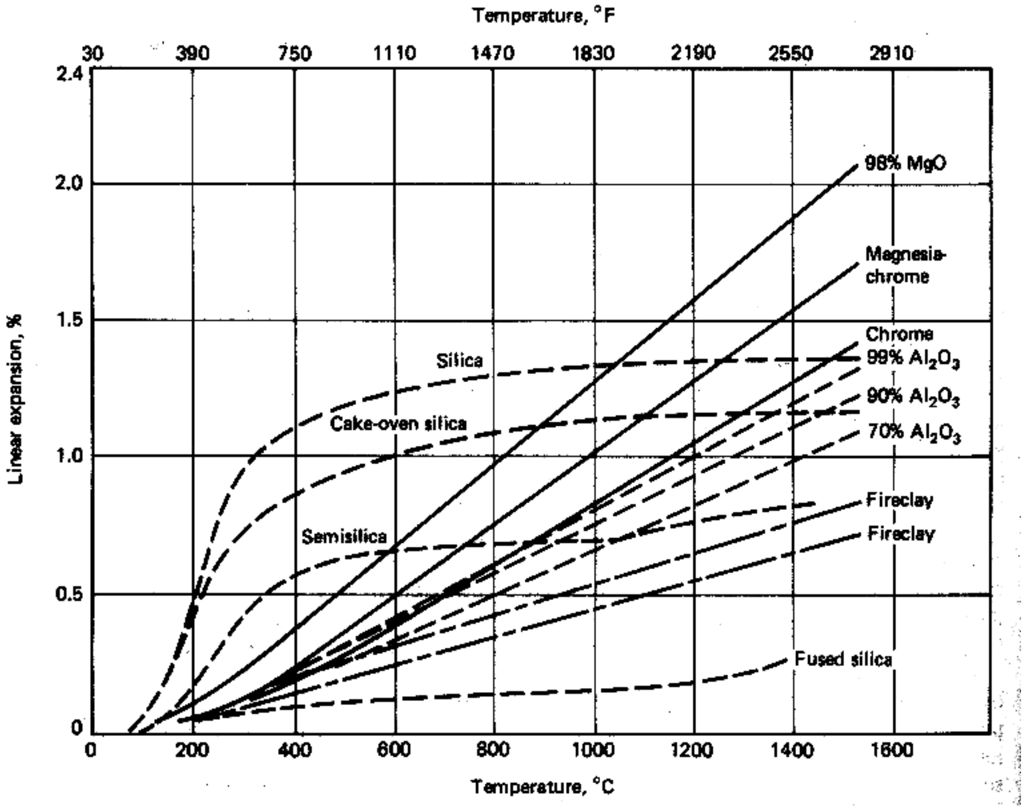


Figure 7. Thermal expansion coefficient of various commercial refractory bricks.

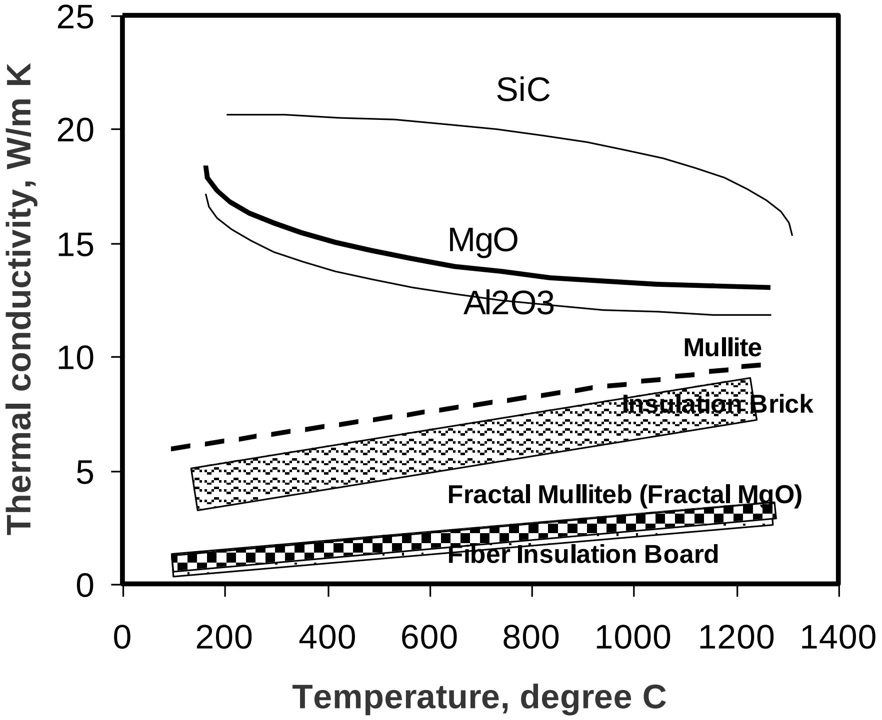


Figure 8 . Thermal conductivity of various refractory bricks. Some data for the fractal materials is also shown.

Estimated Energy Calculations and Benefits: Good refractories perform exceptionally well in cyclic service[3-4]. Other major uses include seals for charging doors and expansion joints as well as gaskets and caulking compounds. The general class of porous materials under which refractories fall, are also used as membranes in the chemical and food industry. There are two reasons for interpolating an insulating layer between a hot working chamber and the "outside". These are (a) to cool the back face to a low temperature Ti, mainly to preserve the mechanical integrity of an enclosing metal shell for reasons of safety outside a wall or roof; and (b) to reduce the heat flux *J* through the lining and hence improve process fuel economy. In a simple case of a plane wall at steady state, where the hot face temperature T_h is fixed by a given operation, the heat loss flux *J* may be easily calculated at steady state as:

$$J = k_w(T_h-T_i)/Z_w = k_i(T_i-T_b)/Z_i= k_s(T_b-T_o)/Z_s=J_0 \qquad (1)$$

where the mean thermal conductivity is k_w and mean thickness is Z_w of the working lining of an insulating lining "i" of (low) mean thermal conductivity k_i and thickness Z_i. T_i is the temperature of the interface between linings "w" and "i", T_b is the refractory back face temperature or that of the interface between lining "i" and shell "s"; and T_o is temperature outside of the shell. J_o is the heat flux to the "outside", existing by virtue of water-cooling or forced or convective air-cooling of the shell. The equation is solvable, given all *k*'s, once T_o or J_o is fixed. An empirical equation for convective cooling of vertical exterior surfaces by ambient air at about 25°C, is approximated by:

$$J_o = 0.19\ T_o^2 + 27.3\ T_o - 800 \qquad (2)$$

This rough guide applies to a refractory cold face to up to some 300°C. Good refractories save process energy and manufacturing cost per part. In addition, good refractories improve lot variability and product performance as they aid uniformity of temperature in a furnace. Assume that the hot zone of a tunnel kiln, for melting aluminum averages 1000°C at the hot face. Assume that the working refractory sidewalls and roof are 22.86 cm thick, exposed to the air outside, constructed of super duty firebrick whose mean thermal conductivity is (9.5 Btu.in./ft^2 hr. °F) or 490 kJ cm/m^{2}hr °C. Then,

$$J = 485\ (1000 - T_o)/22.9 \text{ and } J_o = 0.19\ T_o^2 + 27.3\ T_o - 800 \qquad (3)$$

with T_o = 236°C the heat loss *J*=16,380 kJ/m^2 hr. By adding about 5 cm of lightweight insulation to the outside of a mean thermal conductivity of about 30 kJ.cm/m^{2}hr°C

$$J = 485\ (1000 - T_i) / 22.9 = 30\ (T_i - T_o) / 5 \qquad (4)$$

Now simultaneously solving with the above air cooling equation for J_o, one obtains T_i~ 804°C, T_o ~ 105°C and the heat loss *J* ~ 4,190 kJ/m^2 hr. The saving in lost heat at steady state is (16,380 - 4,190)/16,380 or very close to 75%. If the kiln hot zone dimensions are 80ft. by 10 ft. wide by 12 ft. high (24.4 x 3 x 3.7 meters), the total heat loss area is about 250 m^2 and the saving in lost heat is about 3 million kJ/hour or 73 million kJ per day, or 69 million Btu per day. That is worth about $120,000 in energy savings alone for one year just for one kiln! In general, interpolating an insulating refractory layer or increasing its effectiveness by decreasing the thermal conductivity (a) increases T_i and decreases J at a fixed value of T_o; or (b) increases T_i and decreases Z_w and T_o at a fixed value of *J*. These effects on T_i, (which is the cold face temperature of the working lining) make that lining increasingly vulnerable to corrosion (oxidation). Of the two effects on T_i, the first is much more pronounced. The refractories used today belong to the class of insulating refractories (low density refractories) described and classified in the section after the example below. The temperature of 1000°C is chosen because this represents a fairly low temperature where the savings are the least. With an increase in temperature, the savings increase dramatically. For a 1700°C furnace good low thermal conductivity refractories save more than 150 million kJ per day per typical kiln. In cyclic situations, the numbers are more dramatic. Consider a periodic shuttle kiln, at 1000°C. Each charge of ware plus kiln furniture (or melt charge in a casting situation) consumes 20 million kJ in firing, and an additional 20 million kJ goes up the stack if it is not recovered. The entire cycle occupies 22 hours, leaving two hours per day for charging and discharging. The cycle consists of 12 hours heat-up plus 4 hours steady-state at 1000°C, plus 6 hours of slow cooling. Assume 9" thick free standing refractory walls and roof, using super duty firebrick, as a basic of comparison. For an insulating refractory in place of the former, take a 9" thickness backed by sufficiently heavy gauge sheet steel as to permit hanging the lightweight lining from it. The sheet steel (outer jacket) will be ignored in order to simplify the heat flow calculations. The required property data for each of these refractories are tabulated below. The wall thickness Z in each case is 0.23m.

	Thermal Conductivity k,kJ m/m^{2}hr°C	**Bulk Density** Pb,kg/m^3	**Specific Heat** c,kJ/kg°C
Firebrick	4.90	2,300	0.70
Insulating Refractory	0.30	130	0.70

The overall estimated heat consumption in a complete cycle in this kiln is:

Total Heat, 10^6kJ	9" Dense Firebrick	9" Insulating Refractory
Heating/sintering the ware:	20.0	20.0
Lost in the stack (no recycle.):	20.0	20.0
Lost in heating the refractory:	27.6	1.32
Lost through walls in heat-up:	8.5	0.48
Lost through walls at steady state:	8.5	0.65
Total heat consumed/cycle:	84.6	42.5
Process energy efficiency:	23.5%	47.0%

In the above examples we have used data for one of the group of low mass of *fiber* refractories which have drastically changed clean vessel lining practices over the past several decades.

Estimated Density/Porosity for Fractalballs. The porosity/density of this ball ceramic board can be estimated by the fractal nature of balls. The density (ρ) of this fractal ball material can be estimated as follows (from fractal dimension theory) Where M and V are material mass and volume, C is a constant, r is the radius of spherical volume and d is the fractal volume. Assume an alumina ball ceramic board consists of numerous balls and the balls form numerous clusters as shown in the Figure 1. If alumina ball (inside the cluster) dimension is 0.1 mm and the ball density is 80% of alumina (3.98 g/cm^3) and cluster dimension is 2 mm and the fractal dimension is 2.50. Then the board density can be calculated as following:

Cluster density:

$$C = \rho r^{3-2.5}$$
$$= (3.18\ \text{g/cm}^3)\ (0.01\ \text{cm})^{0.5}$$
$$= 0.318\ \text{g/cm}^{2.5}$$
$$(\rho) = C\, r^{2.5-3}$$
$$= (0.318\ \text{g/cm}^{2.5})\ (0.2\ \text{cm})^{-0.5}$$
$$= 0.71\ \text{g/cm}^3$$

If the alumina board is comprised of numerous clusters with 90% of packing density after sintering then the board density is 0.64 g/cm^3 (0.71g/cm^3 x 0.9), which has 84 % of porosity. This porosity content is also very similar to the fiber board ceramic as indicated in the Table 1. The properties of the commercial Al_2O_3 and ZrO_2 fiber boards are listed in the Table 1.

	Al_2O_3 Fiber board	*ZrO_2 Fiber board*	*Fractal Ceramic [20]*
Physical Properties			
Density (g/cm^3):	0.5-0.8	0.5-1.0	~0.6-1.0
Porosity (volume percent):	85%.	80-90%	~75-85%
Maximum Service Temperature:	1780°C	2200°C(3992°F)	~1820°C
Melting point	1870°C	2590°C(4700°F)	~1870°C
Mechanical Properties			
Flexural Strength, (MPa.):	2.0	0.28	~6.0
Thermal Properties			
Linear Thermal Expansion (x 10-6/°C)	6.0	10.7	~6.0
Thermal Conductivity (W/m.°K)	0.40	0.20	~ 0.2 to 0.4
Price (12”x12”x1.0”) board	~$450*	~$850*	~$200**

- *Source: Largest Discount Price List From Leading Refractory Supplier
- ** Estimate

Table 1. Properties of Commercially Available High Temperature Ceramic Fiber Insulation Boards and measured Fractalball™ Board.

	Fibrous Materials	Fractal Material
Environmental Hazard	Possibly hazardous	Environment friendly
Free Silica content	5-30%	0 %
Thermal shock resistance	Good to Poor	Excellent
Corrosion resistance	Generally Poor	Excellent
Porosity	7-90%	70-95%
Mechanical Properties	Poor	Good
Cost	High	Low

Table 2. A general comparison of fibrous and Fractal refractories

Summary

The introduction of Fractal class of materials is poised to show large impact in a variety of economic and environmental sectors. The Fractal ball structure (Figure 1) allows for high porosity (can be as high as 95%) while making improvements in physical properties such as improved flexural strength of a board material. Corrosion resistance and thermal shock resistance generally are much improved by the Fractal material structure thus making boards made of Fractal material excellent candidates for Furnace or Kiln linings. The estimated energy savings of a well insulated kiln are significant and the manufacturing cost of the Fractal material makes it an ideal component in thermal intensive processes.

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