



Physics and chemistry of beryllium

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The combination of properties of beryllium which results in this very low Z element being a candidate for use in fusion reactors is reviewed. The occurrence, availability, and processing of beryllium from both bertrandite (domestic) and beryl (imported) ores are described. The available beryllium grades are characterized. The purity level of these grades, which are all unalloyed in the usual sense, is presented in detail. The crystallographic factors which establish the physical and mechanical characteristics are reviewed. Powder metallurgy techniques are used almost exclusively to provide beryllium with modest ductility at room temperature (e.g., 3% tensile elongation) and excellent strain capacity at elevated temperature (> 40% tensile elongation at 400°C). The metallurgical behavior of the powder metallurgy product is summarized. The physical properties of this low density metal (1.85 g/cm³) are reviewed with emphasis on the favorable thermal properties. Mechanical properties at room and elevated temperature are presented. The solubility and reactivity of hydrogen with beryllium are both nil while it is an extremely good “getter” for small amounts of oxygen. The combination of beryllium characteristics which has led to the proposed use of beryllium in tokamak reactors as limiter surfaces and in fusion breeders as a neutron multiplying shield are reviewed.

I. INTRODUCTION

Beryllium, atomic number 4, is a silver gray metal of low density (1.85 g/cm³), moderately high melting point (1287°C), and quite good stability in the atmosphere. Favorable mechanical properties, particularly specific stiffness (Young’s modulus/density), have resulted in a number of aerospace applications including major components on the Space Shuttle. The nuclear properties of beryllium are favorable resulting in the use of the metal in test reactors as a neutron reflector and the generation of the present interest in beryllium for fusion reactors.

It is the intention of this discussion to review the production of beryllium as commercially practiced, the physical and mechanical properties of the metal, and the characteristics particularly affecting its usage in fusion reactors.

deposits being mined primarily for feldspar, spodumene, or mica content. The beryl crystals are usually selectively recovered by hand sorting on the basis of shape and color. Ore processing facilities have required a minimum of 10% BeO (14% is theoretical BeO in beryl) for economical processing yields. World production of beryl in 1973 and 1974 was approximately 3600 metric tons with the Soviet Union and Brazil being the principal suppliers.² Substantial production has also been recorded from China, Zambia, Argentina, Angola, and Rwanda.³

Beryl ore was essentially the only source of beryllium until 1969 when Materion Natural Resources began commercial extraction from bertrandite. Materion maintains a beryl extraction plant at its Delta, Utah facility and processes beryl to provide a portion of the requirements for beryllium.

II. EXTRACTION AND METAL PRODUCTION

A. Occurrence and minerals

The beryllium content of the earth’s surface has been estimated at 4–6 ppm.¹ Beryllium is placed between uranium and thorium in order of abundance. Some 45 beryllium-containing minerals have been identified. Of these, the commercially important or potentially important beryllium minerals are: Beryl 3 BeO · Al₂O₃ · 6SiO₂; Phenakite 2 BeO · SiO₂; Bertrandite 4 BeO · 2SiO₂ · H₂O; Chrysoberyl BeO · Al₂O₃.

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I. Beryl

Beryl has been known since ancient times as the gemstones emerald (green), aquamarine (light blue), and beryl (yellow). The ancient name beryl, in fact, supplied the name for the element after its discovery. Beryl is widely distributed over the world in pegmatite dikes. It is found in pockets of the last-to-solidify portion of low melting point fractions. With the possible exception of the Soviet Union and China, beryl mining for its own sake has not occurred, the pegmatite

2. Bertrandite

A large deposit of beryllium occurs at Spor Mountain, Utah in water-laid tuff. This mineralization is believed to have occurred through the ascent of fluorine-rich hydrothermal solutions. Much of the beryllium is present as bertrandite. The presence of beryllium was originally discovered using a beryllometer, an instrument utilizing the $Be^9 (n, 2n) Be^8$ reaction to detect beryllium as there is no visual indicator for the presence of beryllium in the fine-grained tuff. Materion Natural Resources began commercial mining of this deposit in 1969 by open-pit mining techniques. The ore averages only about 0.6% BeO as mined and has not as yet been successfully beneficiated. Nevertheless, the size of the deposit and the fact that the beryllium content is acid leachable make this an economically viable operation supplying the major portion of western world requirements for beryllium since 1970. At 1984 consumption rates, the proven reserves in this deposit are adequate to supply these needs well into the next century.

3. Other minerals

Deposits of other beryllium-containing minerals are known and being studied for possible commercialization. Most notable among these are phenakite at Yellowknife, Northeast Territory, Canada, and the chrysoberyl deposits of the Seward Peninsula, Alaska.

B. Extraction processes

I. Bertrandite process

The ore is transported by truck from the Spor Mountain deposit to Materion's extraction facility near Delta, Utah, a distance of about 47 miles. A flow sheet for the extraction process is shown as Fig. 1. The ore is wet milled to provide a slurry of -20 mesh particles which is leached with sulfuric acid at temperatures near the boiling point. An aqueous solution containing dissolved beryllium sulfate is separated from the solids by countercurrent decantation thickener operations. The resulting solution contains 0.4-

0.7 g/l Be, 4-7 g/l Al, 3-5 g/l Mg, and 1.5 g/l Fe, plus assorted other minor impurities.

A beryllium concentrate is produced from the leach solution by a countercurrent solvent extraction process using di-2-ethylhexyl-phosphoric acid in kerosene as the organic extraction. This process has been described in detail by Maddox and Foos.⁴ The raffinate from this operation contains most of the aluminum and all of the magnesium present in the original leach solution. The loaded organic phase is stripped of its beryllium content with aqueous ammonium carbonate. The strip solution is heated to 70°C precipitating the coextracted iron and aluminum which are removed by filtration. Heating the solution to 95°C causes nearly quantitative precipitation of beryllium basic carbonate $2 BeCO_3 \cdot Be(OH)_2$. After filtration and repulping in deionized water, further heating to 165°C yields a beryllium hydroxide product. This hydroxide is the common input to either beryllium-copper alloy, beryllium oxide ceramics, or pure beryllium metal manufacture.

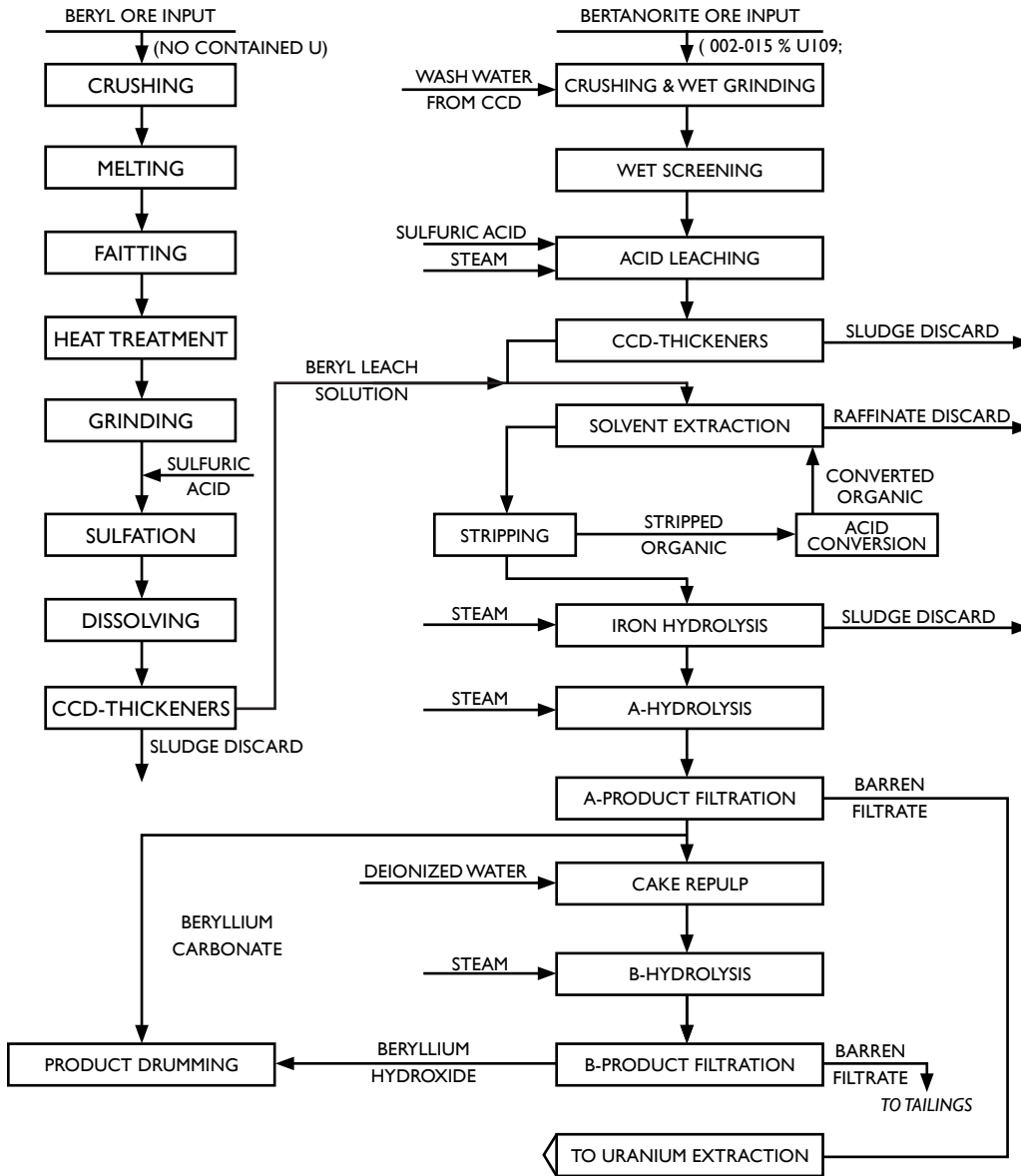
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FIG. 1. Beryllium extraction processes at Materion Natural Resources, Delta, Utah Plant.



2. Beryl process

Unlike bertrandite, the silicate structure of beryl is not acid soluble. The Kjellgren sulfate process⁵ used at the Delta, Utah mill of Materion first melts the ore at 1650°C followed by quenching in water to destroy the original silicate structure. The fritted beryl is then given a further heat treatment at 900–1000°C in a rotary kiln to increase the reactivity with sulfuric acid. A slurry of the powdered beryl frit with sulfuric acid is heated to 250–300°C converting the beryllium and aluminum contents to water soluble sulfates. The silica is present in the water insoluble, dehydrated form and is discarded.

The original Kjellgren process proceeded to separate aluminum and other impurities from beryllium by a series of crystallization and precipitation steps. Materion's practice today is to introduce the aluminum-beryllium sulfate solution into the solvent extraction plant operating with bertrandite feed combining the two streams when beryl is being processed. Thus the product of beryl extraction is again beryllium hydroxide [Be (OH)₂].



C. Production of primary beryllium

I. Magnesium reduction of beryllium fluoride

The primary beryllium produced in the United States since World War II has nearly all been manufactured by the magnesium reduction of anhydrous beryllium fluoride.^{3,6} The fluoride cannot be directly prepared by an aqueous route. The crude beryllium hydroxide from the extraction plant is dissolved in ammonium bifluoride solution, purified by precipitation treatments for a variety of impurities and ammonium fluoroberyllate $[(\text{NH}_4)_2\text{BeF}_4]$ is crystallized from the purified aqueous solution. This salt is thermally decomposed to beryllium fluoride at about 900–1000°C producing NH_4F gas and molten BeF_2 which is cast into small pigs.

The reaction between beryllium fluoride and magnesium producing beryllium and magnesium fluoride is carried out in large graphite crucibles which are incrementally charged with the fluoride and magnesium to control the exotherm from the reaction which initiates at about 900°C. In order to obtain good separation of molten beryllium from the molten magnesium fluoride, excess beryllium fluoride is provided in the charges (i.e., magnesium is supplied to reduce about 75% of the BeF_2 present) decreasing the slag viscosity. After

reaction, the charge temperature is taken above the melting point of beryllium, the metal collecting in a biscuit which floats on the slag. As this biscuit contains substantial quantities of entrapped slag, the molten charge is poured into a cold receiver breaking up the beryllium biscuit into pea-to-marble-sized pebbles which are relatively slag-free. After cooling, the charge is water-leached in a ball mill readily separating the magnesium fluoride and beryllium pebble and dissolving the excess beryllium fluoride for recycle.

2. Electrowinning of beryllium

The electrowinning of beryllium has been the objective of many research efforts but has not been used to produce substantial quantities of the metal. Early work in Germany resulted in the use of fused salt electrolysis of beryllium chloride-sodium chloride during World War II.⁷ This procedure was used in the U. S. for a short time by Clifton Products, Inc., and in France by Pechiney, but is not known to be in commercial use today.

Electrorefining of beryllium using a KCl-LiCl-BeCl_2 bath has also been operated in the U. S. by Materion Beryllium & Composites and Kawecki Berylco Industries, but again is not being practiced today. This remains a preferred route to beryllium of exception-ally high purity.

3. Vacuum casting

The final processing step for beryllium pebbles is vacuum casting to remove any remaining reduction slag and magnesium metal. The processing of electrolytic material has incorporated the same step to remove any entrapped salt from the electrolysis bath. This operation also provides a recycle point for beryllium machining chip or other high quality forms of beryllium scrap. The pebble and scrap are comelted in a MgO crucible and poured into a graphite mold resulting in a 400 lb ingot in present production practice.

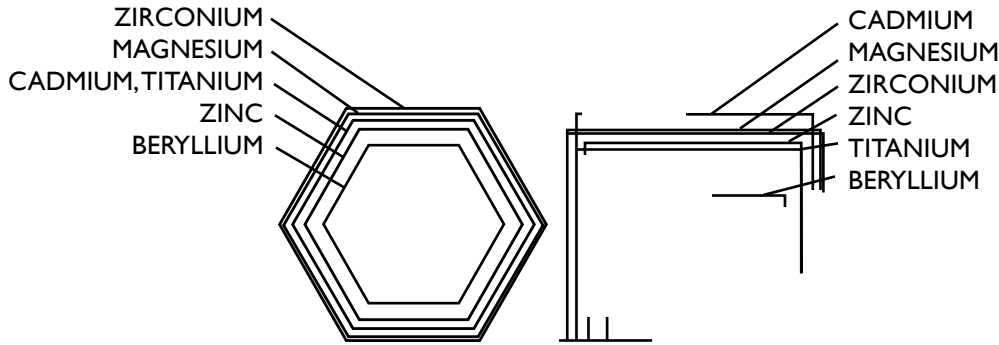
III. BERYLLIUM METALLURGY

A. Beryllium crystal

The crystal structure of beryllium is closed-packed hexagonal. The c/a ratio is only 1.567 as compared to an ideal structure with a ratio of 1.633. This unit cell is the smallest of the close-packed hexagonal metals as shown by the relative plot in Fig. 2. The crystal planes of importance are diagrammed in Fig. 3. Slip is possible on the basal plane (0001



FIG. 2. Relative sizes of common hexagonal unit cells (Ref. 8).



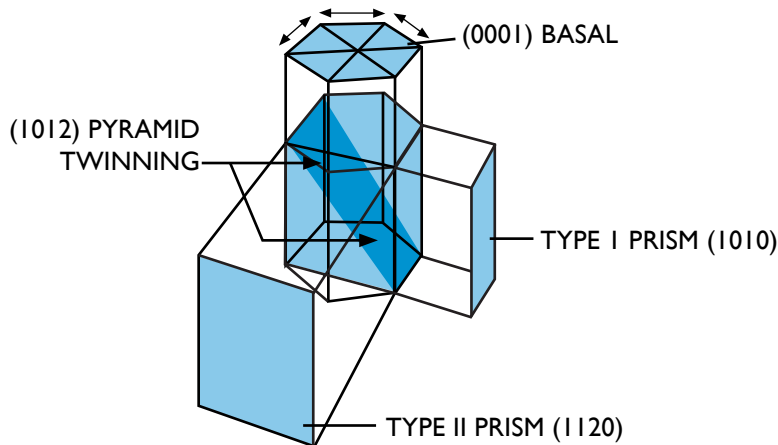
or 0002) and the type I prism plane (1010). In each case, however, this slip is possible only in a direction that lies in the basal plane. This limitation of the slip direction limits the “ductility” of the metal at room temperature and is a principal feature of the behavior of beryllium.

Extensive attempts have been made to achieve a truly ductile beryllium with no success to date. Very high purity beryllium has been prepared (~ 10 ppm total impurities) with no change in the fundamental crystal behavior. This lack of success is possibly due to lack of solubility of gases such as hydrogen, oxygen, and nitrogen which cause interstitial embrittlement in other metals.

While still controversial, it has been postulated that the lack of room temperature ductility is caused by a substantial amount of covalent bonding in the c-direction of the crystal and is, therefore, inherent with beryllium. Potentially, alloying could be used to alter the crystal structure, but the quantity of an alloying metal needed has been estimated as quite large resulting in the loss of the favorable characteristics of beryllium; density, modulus, and apparent low atomic number.

Above 200–250°C, beryllium behaves as a ductile metal and can be worked by rolling, extrusion, and forging. Beryllium undergoes a hcp–bcc phase transformation at 1254°C which is quite close to the melting point of 1287°C.

FIG. 3. Deformation modes in the beryllium crystal (Ref. 9). Stress values shown represent critical applied stresses.





B. Polycrystalline beryllium

Beryllium is virtually always utilized as a powder metallurgy product at a density of 99% of theoretical or higher. Beryllium can be cast successfully by most of the standard techniques, but the achievable grain size has been no finer than about 100 μm even with alloying additions or extensive working and recrystallization operations. The powder metallurgy products have grain sizes ranging from about 15 to 5 μm . The strength, ductility, and machining characteristics are all adversely affected by the large grain size of castings.

1. Powder manufacturing

No acceptable chemical procedure for the direct production of beryllium has as yet been produced. Mechanical methods are used, therefore, exclusively. The vacuum cast ingots from primary metal production are first reduced to machine chips on lathes with multiple cutters and then fed to either attrition mills, impact grinding units, or a ball mill. The attrition mill is similar to the old flour mill in that the beryllium chips are fed between a stationary and a rotating beryllium plate. Size reduction proceeds primarily by basal plane cleavage resulting in a tendency for such powder to have a shape factor approaching platelets. This grinding procedure is being replaced with impact grinding which involves the pneumatic blasting of beryllium chip against a beryllium target. Additional fracture mechanisms are involved yielding a powder which is much more equiaxed than attritioned powder. For very fine powders, ball milling is the preferred manufacturing technique. Most beryllium powder is prepared as - 325 mesh powder with the subsieve particle size distribution controlled with Coulter Counter measuring techniques. J. Vac. Sci. Technol. A, Vol. 4, No. 3, May/June 1986

2. Powder consolidation

Vacuum hot pressing in the temperature range of 1025–1125°C is the primary procedure for consolidating beryllium powder into 99 + % of theoretical density beryllium billets. Pressures on the order of 1200 psi are applied to the powder column contained in graphite or IN-100 dies at the sintering temperature. Capacity exists to make pressings up to 72 in. in diameter, though the majority of the pressings made fall between 9 and 20 in. in diameter with L/D ratios of 7.4 to 3.1, respectively. Hot pressings are usually made in the shape of right cylinders with skillful use of layout and machining techniques to maximize yield of metal in finished components.

Alternate powder metallurgy techniques such as cold press sinter coin are used where sufficient production volume is attained to warrant the necessary engineering and tooling such as was the case with aircraft brake components for the F-14 and S3A aircraft. Currently, hot isostatic pressing (HIP), both containerless HIP and direct HIP of powder are receiving major development efforts so as to allow near-net-shape consolidation of beryllium powder. Materion has just brought a 30 in. diam by 65 in. hot isostatic press into operation in its production facility at Elmore, Ohio.

3. Factors affecting mechanical properties

The strength of beryllium is related to the grain size by the Hall–Petch relationship (strength inversely proportional to the square root of the grain size). A typical plot of this relationship is shown in Fig. 4. The grain size is established in the powder metallurgy product primarily by the particle size distribution of the starting powder and secondarily by consolidation conditions, increasing grain growth being encountered as the hot pressing/sintering temperature is raised. HIP is particularly attractive for high strength as the high consolidation pressure available allows the use of relatively low temperatures.

Ductility is affected by texture, grain size, and certain impurities. One of the major goals of beryllium powder metallurgy processing is to attain as nearly a random orientation of the beryllium grains as possible. As a result of the limited slip behavior of the beryllium crystal, preferred orientation of basal planes limits strain capacity to the planes of this orientation. Attritioned powder, because its platelike particles are produced by basal plane cleavage, tends to align in the pressing dies so that a preferred slip direction is transverse to the pressing direction. Thus, tensile elongations in a hot-pressed billet may be substantially higher in the transverse direction as compared to the direction parallel to the pressing direction or longitudinal direction. Guaranteed minimum tensile elongation in any direction in a hot pressing produced from attritioned powder is thus limited to 1%. Impact ground powder, on the other hand, with control of other factors allows the minimum guaranteed tensile elongation in any direction to be increased to 3% (S-65 grade).



FIG. 4. Strength vs grain size relations in intermediate purity vacuum hotpressed beryllium (Ref. 11).

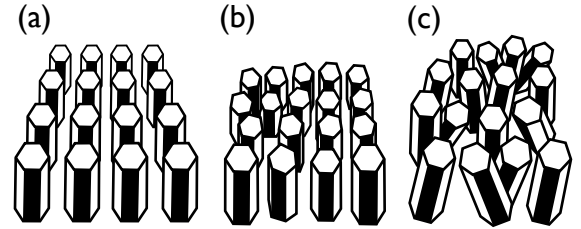
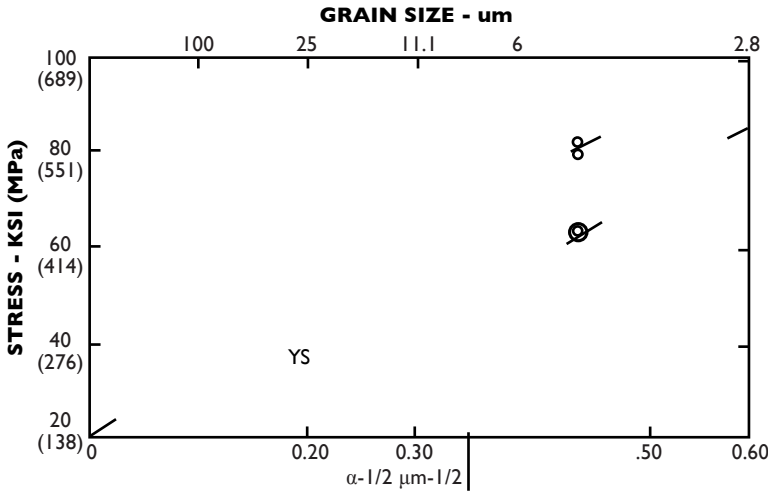


FIG. 5. Schematic of textures in worked beryllium (Ref. 9). (a) Basal plane layer texture with prism planes in preferred positions. (b) Basal plane layer texture with prism planes at random in two dimensions. (c) Imperfect basal plane texture.

The effect of preferred orientation is particularly dramatic in worked beryllium. When rolled, extruded or forged, the basal planes align in the direction of working. Some of the various types of textures which can be developed are illustrated in Fig. 5. Preferred orientations as high as 24 X random are not unusual in such products. The effect of these textures is illustrated by rolled beryllium sheet where a tensile elongation of 10% is a guaranteed minimum in the plane of the sheet and values of 20% are quite typical. The tensile elongation in the thickness direction of such material would, however, be essentially zero.

Grain size also affects ductility in that a large-grained body is in effect textured within the single grains. Finer grain size thus effectively can lead to a more random texture and a better overall ductility.

The role of oxygen is limited in its effect upon ductility in that the solubility of oxygen in beryllium is extremely limited. The oxide is found primarily in the grain boundary, and the overall concentration increases as the grain size decreases due to the increasing surface area of the starting powder. The oxide would appear to act as void or inclusion leading to early failure during plastic deformation. In practice, little effect of the oxide content upon ductility has been found at levels up to about 1.2%. At higher concentrations, room temperature, and elevated temperature, ductility drops off with increasing BeO concentration.

FIG. 5. Schematic of textures in worked beryllium (Ref. 9). (a) Basal plane layer texture with prism planes in preferred positions. (b) Basal plane layer texture with prism planes at random in two dimensions. (c) Imperfect basal plane texture.

Iron and aluminum impurities can also affect the ductility of beryllium adversely, iron being a solid solution element and aluminum an insoluble grain boundary constituent. The morphology and phase relationship of these two elements with beryllium is sufficiently complex that an adequate discussion cannot be carried out within the scope of this paper, but Stonehouse12 and Gelles13 have prepared detailed discussions. These elements are well controlled in today's commercial beryllium.

C. Commercially available grades

The available grades of beryllium are summarized in Table I showing the guaranteed purities, minimum room temperature tensile properties in any direction, and the type of beryllium powder used to manufacture each grade. These are specification values, the actual purities and tensile properties will typically be improved over the values listed in Table I.



The three grades with the S- designation are considered structural grades with S-65B being the grade exhibiting the most ductility and the grade of most interest to the fusion reactor community. The I- designation indicates usage primarily in instrumentation such as inertial guidance components. Microyield strength (the stress to produce the first microinch of permanent strain) is an important parameter for these materials. I-70A is a grade with low BeO tailored for use in space-borne optical components.

Plate, sheet, and foil are also available as standard materials in thicknesses ranging from 0.6 to 0.0005 in.

IV. PROPERTIES

A. Physical properties

Selected physical properties of beryllium are given in Table II and Figs. 6 and 7. More detailed presentations and discussion of these values have been made by Pinto,¹⁴ Darwin and Buddery,¹⁵ and Stonehouse et al.,¹⁶ and will not be elaborated upon further.

B. Mechanical properties

The mechanical properties of various grades of beryllium metal have been published in a number of reviews.^{14,17,18} The discussion in this instance will be limited to S-65B, the material being considered for use in fusion reactors. This grade with a guaranteed minimum tensile elongation of 3% in any direction at room temperature is considered the most ductile of the available commercial grades. It is in service on the

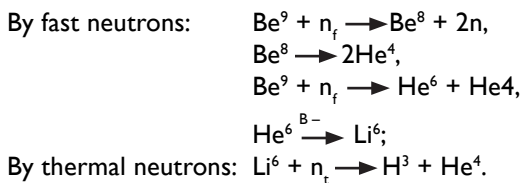
ksi (in)^{1/2} at room temperature. Poisson's ratio is 0.08. Smith et al.¹⁹ have carried out thermal fatigue tests on S-65B with the conclusion that the thermomechanical properties were acceptable for use on high heat flux surfaces in ISX-B, Joint European Torus (JET), and probably most other near-term fusion devices. This was confirmed by a successful test of a beryllium limiter in ISX-13.²⁰

C. Nuclear properties

Natural beryllium contains 100% of the Be⁹ isotope. The principal isotopes of beryllium which have been identified and their half-lives are¹⁵: Be⁶, 0.4 s; Be⁷, 53 days; Be⁸, 10⁻¹⁶ s; Be⁹, stable; Be¹⁰, 2.5 X 10⁶ yr.

The absorption cross section for thermal neutrons is 0.009 b while the scattering cross section is 6 b, making the metal an excellent reflector for thermal neutrons. The scattering cross section for fast neutrons is about 1 b.²¹

When beryllium is irradiated, gas-producing nuclear reactions occur as follows²²:



space shuttle as the umbilical doors, window frames, and the navigation base. Unfortunately, the data base for elevated temperature properties of this material is somewhat limited. The ductility exhibited at room temperature is, however, carried into elevated temperatures with elongation values that are quite respectable, approaching 50% at 400°C as shown in Tables III and IV. Young's modulus remains at 44 X 10⁶ psi and the fracture toughness KIC value is 9-9.5

These nuclear reactions are calculated to produce about 2.2-2.6 cm³ of gas per cm³ of beryllium after a fluence 1 X 10²¹ N/cm². Beryllium irradiated and tested at temperatures below 100°C exhibits an increased yield strength and nil ductility. Beryllium irradiated and tested at temperatures above 350°C generally exhibits a small increase in yield strength and small decrease in ductility. At lower temperatures the helium atoms remain in the matrix; at higher temperatures

**TABLE I. Commercially available grades of vacuum hot-pressed beryllium.**

	S-65B	S-200E	S-200F	I-70A	I-220B	I-400A
Chemical composition						
Be, min %	99.0	98.0	98.5	99.0	98.0	94.0
BeO, max %	1.0	2.0	1.5	0.7	2.2	4.25 ^a
Al, max ppm	600	1600	1000	700	1000	1600
C, max ppm	1000	1500	1500	700	1500	2500
Fe, max ppm	800	1800	1300	1000	1500	2500
Mg, max ppm	600	800	800	700	800	800
Si, max ppm	600	800	600	700	800	800
Other, each max ppm	400	400	400	400	400	1000
Tensile properties at room temperatures						
Ultimate strength (ksi)	42.0	40.0	47.0	35.0	55.0	50.0
0.2% offset yield (ksi)	30.0	30.0	35.0	25.0	40.0	...
Elongation, % min	3.0	1.0	2.0	2.0	2.0	...
Microyield strength (ksi)	...				5.0	9.0
Attritioned powder						
	S-200E					
Impact ground powder						
	S-65B, S-200F, I-70A, I-220B					
Ball milled powder						
	I-400A					

^a% BeO is minimum in this case

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TABLE II. Physical properties of beryllium.

Atomic number	4
Atomic weight	9.0122
Crystal structure:	
Hexagonal close-packed:	$a = 2.854, c = 3.5829, c/a = 1.5677$
Body-centered cubic (above 1254 °C):	$a = 2.550$
Density:	1.8477 g/cm ³
Melting point:	1287 °C
Boiling point:	2472 °C
Vapor pressure:	$\log P(\text{atm}) = 6.186 + 1.454 \times 10^{-4} T - 16.734 T^{-1}$
Heat of fusion:	2.8 kcal/mol
Heat of sublimation:	76.56 kcal/mol
Heat of evaporation:	53.55 kcal/mol
Specific heat:	$C_p = 4.54 + 2.12 \times 10^{-3} T - 0.82 \times 10^{-5} T^2$ cal/K/mol
Thermal conductivity:	See Fig. 6
Thermal expansion:	$11.5 \times 10^{-6}/^\circ\text{C}$ (0-50°C) See Fig. 7
Entropy 25°C:	2.28 cal/°C/mol
Enthalpy 25°C:	465 cal/mol
Electrical resistivity:	4.31 μΩ cm
Magnetic susceptibility (293 K):	-1.00×10^{-9} m ³ /kg
Velocity of sound	12 600 m/s
Volume contraction on solidification:	3%

they diffuse and agglomerate causing swelling. As the fluence increases, the temperature required to produce complete annealing appears to increase and the temperature to produce 1% swelling decreases.²³

The (n, 2n) reaction with a high reaction cross section enables beryllium to function as a neutron multiplier. The combination of high neutron multiplication, low absorption, and high scattering characteristics provide excellent neutron thermalization. Beryllium would, therefore, provide a high performance breeding blanket for fusion systems.²³

V. BERYLLIUM AS THE FIRST WALL IN MAGNETIC FUSION SYSTEMS

Beryllium has recently received attention for its potential as a limiter material in tokamaks, particularly the JET. Rebut and Dietz.²⁴ have provided a review of this potential as have Smith and Mullendore.²⁵ A successful test of beryllium as a limiter has been conducted in the ISX.²⁰

The performance of a tokamak like JET will depend on the minimum level of impurities which can be achieved inside the plasma. The acceptable percentage of these impurities depends strongly on their atomic numbers. Heavy impurities which cannot be fully stripped could prevent ignition at a level of 0.1%. Low Z elements could be tolerated at the level of several percent even for an ignited plasma. Thus, the requirements for the material facing the plasma are: low Z number, good thermal conductivity, good resistance against thermal shock, and low erosion through sputtering or chemical effects. Beryllium



FIG. 6. Thermal conductivity of beryllium (Ref. 14).

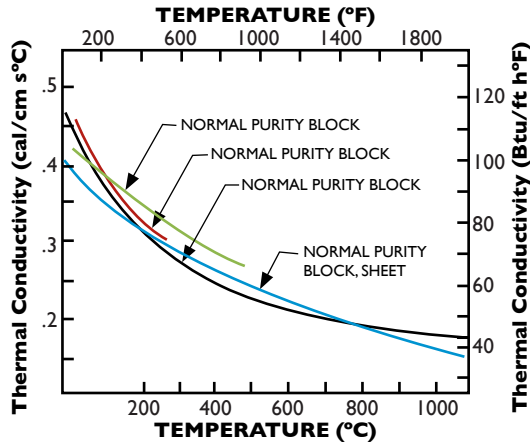
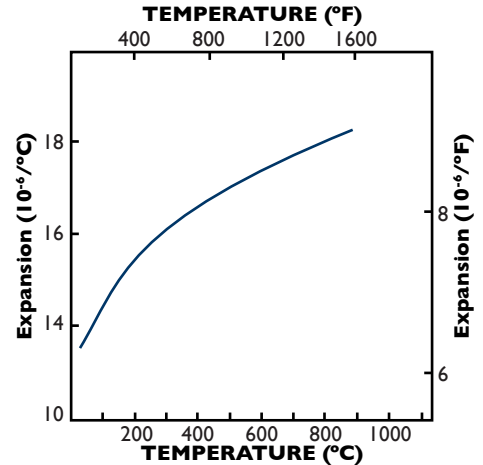


FIG. 7. Thermal expansion of beryllium (Ref. 14).



or graphite appeared to be the only material choices for the JET limiters.²⁴

The main advantages of beryllium are: very low Z value, high thermal conductivity, high resistance against thermal shock, no chemical reactions with hydrogen, and sputtering yields for energies below 50 eV, one order of magnitude smaller than for graphite at ambient temperature. Compared with graphite, the thermal shock resistance is nearly identical, but the thermal conductivity is a factor of 4 higher, decreasing the surface temperature in claddings of equal thickness. Hydrogen retention and chemical erosion are not expected to present problems as with graphite, and bonding techniques to the copper cooling structure are available. On the negative side, the permissible surface temperature will be lower for beryllium, hydrogen blistering may occur, and additional health and safety precautions will be required with beryllium. The bottom line is that beryllium shows a distinct advantage compared with graphite.²⁴

VI. HEALTH ASPECTS OF BERYLLIUM

There is no record of any ill effects resulting from ingestion or dermal contact with beryllium or beryllium oxide. The only potential problem associated with handling of beryllium is the inhalation of excessive amounts of respirable beryllium; dust particles with a size below about 10 μ. Physiological reaction to beryllium exposures appear to be a matter of individual susceptibility. The majority of people, perhaps as much as 99%, apparently do not seem to react adversely to exposures at any level. A small percentage of people do develop an immunological response. There is no way of predetermining those who might be hypersensitive. As with many other industrial toxicants, beryllium can be

TABLE III. Tensile properties of S-65B beryllium fabricated by cold pressing-sinter-hot isostatic pressing.

Test temperature	Ultimate tensile strength (ksi)	Yield strength 0.2% offset (ksi)	% Elongation	% Reduction in area
Room	49.6	30.6	5.2	...
370°C	33.0	19.3	49.4	66.9
650°C	17.8	11.7	38.5	29.5

^a Average of four or more tests. Tests made under contract to JET, Abingdon, England. All tests transverse to cold pressing direction.

**TABLE IV. Tensile test results for vacuum hot-pressed S-65B beryllium. ^a**

Temperature (°C)		Ultimate strength		Yield strength		Elongation %
		(MPa)	(ksi)	(MPa)	(ksi)	
20	<i>L</i> ^b	421	61.1	270	39.1	3.0
20	<i>T</i> ^c	454	65.8	273	39.6	5.4
200	<i>L</i>	382	55.4	232	33.6	10.2
200	<i>T</i>	389	56.4	234	34.0	23.4
400	<i>L</i>	270	39.2	179	25.9	50.0
400	<i>T</i>	268	38.8	177	25.6	49.5
600	<i>L</i>	160	23.2	119	17.2	25.2
600	<i>T</i>	167	24.2	122	17.7	31.9

^aReference 19.^bLongitudinal direction (parallel to molding pressure).^cTransverse direction (perpendicular to molding pressure).

safely handled with a minimum of controls, but it can present a serious health hazard if these controls are not observed.

There has never been an illness caused by beryllium where exposures were kept at or below the current threshold values. Two in-plant limits have been established by the Occupational Safety and Health Administration (OSHA) to cover the chronic and the acute reactions to beryllium. These are (1) 2 µg per m³ is the maximal atmospheric concentration for 8 h exposure, and (2) a short exposure tolerance of 25 µg per m³ of air for less than 30 min exposures. The U. S. Environmental Protection Agency (EPA) has set a nonoccupational limit at a monthly average concentration of 0.01 µg per m³ of air for the maximal atmospheric concentration outside of the plant. In order to maintain that maximal concentration, EPA limits the emission of beryllium into the ambient air surrounding a beryllium facility to 10 g in any 24 h period.

Special precautions are required in the processing of or the handling of beryllium when dust, fumes, or mists might be created.

At Materion, the world's primary producer of beryllium products, tons of beryllium compounds are handled every month. Most of these are in the particulate form, the form potentially most hazardous. Beryllium is not a new material. It has been produced commercially for over 50 yr. For 30 odd years, its toxicity has been known and successfully controlled.

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Note: Handling Aluminum-Beryllium Alloys in solid form poses no special health risk. Like many industrial materials, beryllium-containing materials may pose a health risk if recommended safe handling practices are not followed. Inhalation of airborne beryllium may cause a serious lung disorder in susceptible individuals. The Occupational Safety and Health Administration (OSHA) has set mandatory limits on occupational respiratory exposures. Read and follow the guidance in the Material Safety Data Sheet (MSDS) before working with this material. For additional information on safe handling practices or technical data on Aluminum Beryllium Alloys, contact Materion.

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