UNITED STATES MINERAL RESOURCES

BERYLLIUM

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ABSTRACT OF CONCLUSIONS

Beryllium metal is used in a variety of products in which its low density and other physical properties are particularly valuable. More than half the metal produced is used with copper in strong, fatigue-resistant alloys. Beryllium oxide and beryl are used in many ceramic and other products. The total amount used is small; less than 1,000 tons of beryllium was used in all forms in the year of highest consumption. The annual consumption may increase to as much as 4,000 tons by the year 2000.

About 95 percent of the beryllium ore used in the United States has been imported, three-fourths of it coming from Brazil, the Republic of South Africa, India, Argentina, and Mozambique. Significant domestic production began in 1969 and probably will increase until it accounts for at least half the ore consumed.

The resources of beryllium in known domestic deposits are estimated at 60,000 tons, and these can be increased by further exploration to become sufficient to supply our needs for many decades.

INTRODUCTION

The beryllium industry is both small and young as compared with most base-, ferrous-, and light-metal industries. Beryllium thus is one of many minor commodities, one that has been rather highly publicized because of glamorous actual and potential uses in nuclear energy and manufacture of space vehicles. Nonetheless, many important uses for beryllium have developed during the 40 years since production began. The industry is shifting from complete dependence upon imported beryl concentrates derived from small pegmatitic deposits to the mining of large domestic nonpegmatitic deposits. Deposits containing 60,000 tons of metal—enough to satisfy national needs for several decades—were found in about 10 years. More deposits doubtless can be found if markets develop sufficiently to stimulate prospecting.

PROPERTIES AND USES OF THE METAL

Beryllium, with a specific gravity of 1.85, is one of the lightest metals stable in air. Like aluminum,

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it develops a coherent oxide coating when exposed to air, which protects it from further oxidation and increases its apparent hardness. Unfortunately, oxygen-free beryllium metal is very difficult to prepare. Most metal in commerce contains nearly 2 percent oxygen, which contributes to its brittleness. This brittleness requires production of articles by powder metallurgy and machining—a costly procedure—and limits reshaping by rolling or drawing.

The high thermal conductivity, high melting point, high specific heat, low density, and rigidity of the metal make it useful in heat sinks and in specialized structural elements for aircraft and spacecraft. Its low neutron absorption and its emission of neutrons under appropriate gamma or alpha bombardment lead to uses in nuclear energy. In the early 1970's, nearly 20 percent of the beryllium extracted was used as the metal.

PROPERTIES AND USES OF BERYLLIUM ALLOYS

More than half the beryllium reduced from its ore is used in alloys, principally in beryllium-copper alloys containing about 2 percent beryllium and about 0.2 percent nickel or cobalt. These alloys have the greatest strength and wear resistance of any nonmagnetic material, with a tensile strength about twice that of hard-drawn iron and two-thirds that of mild steel. They also are excellent conductors of electricity and heat and are very resistant to corrosion. Below a temperature of about 300°F, they are much more resistant to fatigue than steel. They are much used in springs, electrical connectors, and many other specialized items. The use of the alloys in computers and other electrical equipment has resulted in greatly increased consumption during the last 20 years.

Beryllium has been used in small amounts with nickel to make hardenable alloys with very high tensile strength that are usable at higher temperatures than copper alloys.

In light alloys with aluminum and magnesium, beryllium can improve the properties or facilitate the production of the metal. Addition of 0.02 percent of beryllium to aluminum-magnesium alloys reduces reaction with green sand molds and improves oxidation resistance. It eliminates the need for elaborate precautions against burning of magnesium, inasmuch as the molten metal containing beryllium can be poured safely at a temperature of 1,400°F. "Lockalloy," containing 62 percent beryllium and 38 percent aluminum, has some of the desirable properties of beryllium, is reasonably workable, and can be used at temperatures as high as 800°F. Various composite materials containing beryllium in nonbrittle matrices are strong and light.

PROPERTIES AND USES OF THE OXIDE

Beryllium oxide is the third major form in which beryllium is used. This oxide, with a high melting point, a high thermal conductivity, and very low electrical conductivity, can be used as an electrical insulator in applications where heat must be transferred or dissipated, as in power transistors. The high thermal conductivity results in high thermal shock resistance, which is important in special ceramics. These, and the nuclear properties, lead to the use of beryllium oxide in reactor fuel elements.

BERYL AS AN INDUSTRIAL MINERAL

In addition to the uses of beryllium that require extraction of the metal from its ore, there are many uses that are met by incorporating undecomposed beryl into an industrial product. These uses account for about one-tenth of the beryl ore used during the last 20 years. Some of these uses are chemical—the addition of beryllium to a ceramic or glass mix; others rely upon one or more physical properties of the mineral beryl itself such as its structure, its thermal conductivity, or its ability to adhere to plastics.

END USES OF BERYLLIUM

The amount of beryllium used in various ways in the United States is summarized in table 15.

TABLE 15.—*End uses of beryllium in the United States, 1968*

[Data from Heindl, 1970, p. 498]

Use	Short tons	Percent of total
Nuclear applications	35	10
Guided missiles and space vehicles	35	10
Instruments	45	13
Switch gear	90	26
Welding equipment	40	11
Electronic computers	40	11
Radio and television equipment	25	6
Other	38	13
Total	348	100

SECONDARY RECOVERY

Much recoverable beryllium scrap is produced in making articles out of beryllium metal. This is an inevitable result of the necessity of making blank or roughly formed pieces of metal by powder metallurgy, then machining the final product from them. Not much metal, however, can be salvaged from the final articles. Components of missiles and rockets are commonly destroyed in use, whereas those of manned capsules and orbiting observatories may be

recoverable. Many beryllium aircraft parts can readily be salvaged; so can beryllium used in nuclear energy establishments, if it is not too strongly contaminated by radioactive substances. Beryllium-copper alloy is used mostly to make very small items and this beryllium generally cannot be salvaged. The same is to a large extent true of the beryllium in ceramic ware, whether high or low in BeO.

TOXICITY OF BERYLLIUM AND ITS COMPOUNDS

Much was written during the 1940's and 1950's about the toxicity of beryllium and its compounds. Subsequent studies have shown that the ores are not hazardous and that industrial products can be handled safely with reasonable precautions. The toxicity has caused few restrictions on its use, the most notable being its elimination from phosphors in fluorescent lamps and its exclusion from the fuel of most rockets.

HISTORY OF PRODUCTION AND CONSUMPTION

The beryllium industry is rather new; commercial production began in the United States in 1932. Consumption increased steadily until 1943, as indicated in figure 11. After the World War II stimulus and the postwar slump, ore consumption increased rather steadily until about 1960, but since then it has not changed greatly. In most years imports of beryl ore have exceeded consumption, and stockpiles have accumulated. The opening of the beryllium mine near Delta, Utah, in 1969, and release of ore from the Federal stockpile are at least partly responsible for the relatively low imports in 1970 and 1971. This proportion of imports probably will continue, with about half of the U.S. needs imported, the other half produced domestically. Thus, increasing amounts of beryllium will be obtained from
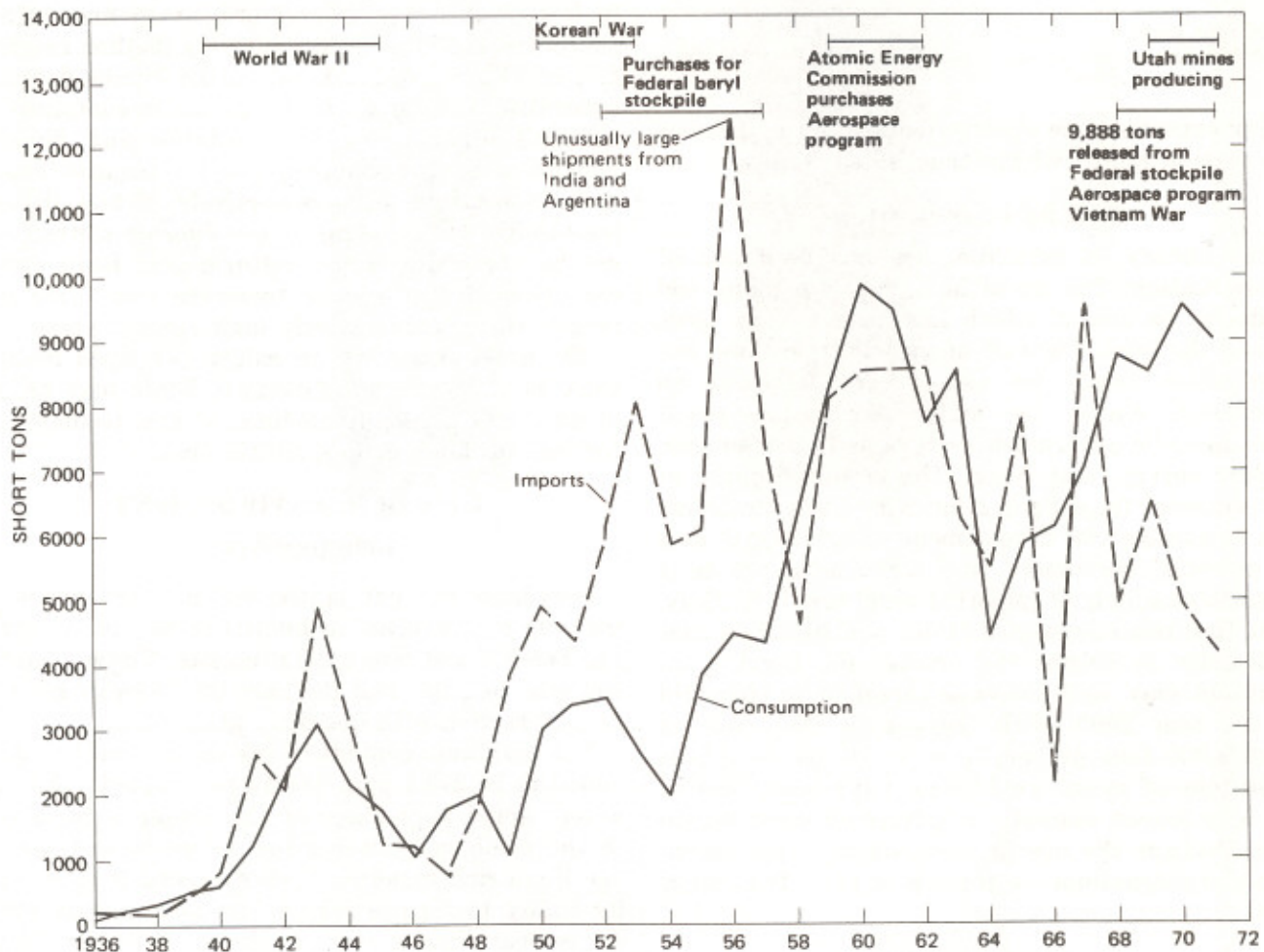

FIGURE 11.—Beryl ore imported and consumed by U.S. industry, 1936–71. Nonberyl ore, recalculated to equivalent amounts of beryl ore, not important before 1969. Data from U.S. Bureau of Mines Minerals Yearbooks.

nonberyl ores. Nonberyl ores were recalculated as equivalent amounts of beryl in preparing figure 11. There has otherwise been little change in the sources (table 16) since 1939, when Brazil first became a

TABLE 16.—*Sources of beryl ore used in the industry of the United States*

[Data from U.S. Bureau of Mines, 1953; 1953–69]

Country	Percent of total		
	1936–51	1952–59	1960–68
Brazil	49	27	32
Republic of South Africa	10	11	5
India	8	11	13
Argentina	12	15	10
Mozambique	2	13	10
United States	10	5	4
Zaïre	-----	5	7
Rhodesia	4	7	3
Kenya and Uganda	-----	<1	8
Australia	4	2	5
Malagasy Republic	-----	2	3
Portugal	-----	2	<1
Other	1	<1	<1
Total tons beryl (rounded)	32,000	98,000	161,000

major exporter. One evident feature is the decreasing portion mined within the United States.

FUTURE CONSUMPTION

The history of beryllium use has been one of diversification. The metal has gone into many end products, no one of which has been a very large part of the total. The rate of growth, therefore, has been rather steady for many years, following an exponential curve; the major fluctuations result from sporadic government programs in armaments, nuclear energy, and space. The assured supply of raw material from Spor Mountain, Utah, doubtless will encourage the development of additional uses by potential consumers who lack confidence in a dependable supply of imported beryl ore. It is likely, even, that this new source of ore will stimulate uses sufficiently to bolster the market for beryl. Consumption may well increase threefold or fourfold by the year 2000, with the use in that year of 3,000–4,000 tons of beryllium in all forms. About 4,500 tons of metal would then have been used of our total known domestic resources of about 60,000 tons. Perhaps the use in light alloys—with aluminum and magnesium—will increase more than other uses.

EXTRACTIVE METHODS

To extract beryllium, beryl ore is heated, with or without fluxes, and then is leached to give an aque-

ous solution of beryllium fluoride or sulfate. In the United States, Kawecki-Berylco Industries sinter finely pulverized beryl with fluorides and sodium carbonate, then leach the sintered material with water to obtain a beryllium-fluoride solution from which beryllium hydroxide is precipitated. Brush-Wellman Co., in an alternate process, fuses lump beryl ore, quenches the melt, and leaches the beryllium with sulfuric acid. Ore can also be mixed with a carbonate flux, fused, then leached with sulfuric acid. The nonberyl ore from Spor Mountain, Utah, yields its beryllium upon leaching with sulfuric acid with no pretreatment. All these procedures can extract more than 90 percent of the beryllium in the ore.

The different extraction methods are not equally applicable to all types of ore, and therefore are of significance in assessing the resource potential of various beryllium-rich materials. The fuse-quench method is well adapted to coarse beryl ore, but not to low-grade ore, nonberyl ore, or to fine-grained concentrates. The fluoride-sintering method requires fine grinding of ore and can readily handle flotation concentrates, even if the beryllium is contained in minerals other than beryl. Apatite and fluorite, which commonly accompany beryl in pegmatitic and hydrothermal deposits, respectively, reduce the extractability of beryllium by the fluoride method but not by carbonate fusion–sulfuric acid leach methods; these methods may therefore come into use despite their comparatively high reagent costs.

The novel extractive procedure developed for use with the ores of Spor Mountain, Utah, may be the precursor of markedly modified or new technologies for use on other nonpegmatitic ores.

GEOLOGIC ENVIRONMENT

GEOCHEMISTRY

Beryllium has one stable isotope, Be^9, which is the only one involved in industrial use and in most geochemical and geological processes. Three unstable isotopes, Be^7, Be^8, and Be^{10}, are produced by cosmic-ray interaction with the upper atmosphere.

The beryllium content of the earth's crust is estimated to be 2–3.5 ppm (parts per million). All but a very small percentage of this metal is contained in the common rock-forming minerals and not in beryllium-rich minerals. This dispersal is caused by its ability to replace silicon—its ionic radius (0.31 A) is near that of the silicon ion (0.41 A). However, because of the difference in charge (+2 instead of +4), the difference in size, and the greater tendency of beryllium to form covalent bonds, the

substitution of beryllium for silicon impairs the stability of a crystal's structure. Hence, beryllium is most concentrated in minerals whose structures are most tolerant of the resulting distortion. Plagioclase feldspar probably contains much of the earth's beryllium, but micas and clays are also important hosts.

During the crystallization of a magma, beryllium becomes progressively more concentrated in the fluid as crystallization proceeds. One result of this is an increasing concentration of beryllium in successively younger rocks in genetically related suites. This enrichment reaches a point where beryllium minerals can form only in the presence of complexing agents, such as F^- or CO_3^{-2}, that keep an unusually large proportion of the beryllium in the residual liquids. In igneous rocks the beryllium content therefore increases along with silica and alkali contents. The average content of beryllium in peridotite is less than 0.25 ppm, that of basalt and gabbro is about 0.5 ppm, and that of rhyolite and granite is about 5 ppm. Detailed study of each of these groups shows the relations to be complex. For example, in silicic rocks the beryllium content passes through a maximum as silica content increases. In addition, the average beryllium content of plutonic rocks is higher than that of volcanic rocks, perhaps reflecting the loss of beryllium in vapors during volcanism.

The very coarse texture of pegmatites has made them difficult to sample for beryllium content, although the coarseness facilitates the determination in the field of the contents of beryl and other economic minerals.

In a series of related pegmatites, the beryllium content can increase in successively intruded rocks to a maximum of about 180 ppm; it then remains rather uniform. This is apparently the maximum concentration that can be reached through magmatic processes in magmas of granitic composition. Much higher beryllium contents may characterize beryl-rich inner zones of pegmatite dikes, but averaging these with the larger beryl-poor outer zones shows that few, if any, bodies contain more than 200 ppm overall, which corresponds to about one-half of 1 percent beryl. This is the maximum grade that can be expected in large bodies of pegmatite. Most pegmatites contain much less and may average a few tons of parts per million of beryllium.

Beryllium is very scarce in most hydrothermal deposits, generally constituting 1 ppm or less. Ores formed by replacement commonly contain about as much beryllium as the rock that was replaced. For example, most tactites in limestone contain less than 1 ppm beryllium, and replacement veins in granite or gneiss commonly contain a few parts per million. Certain hydrothermal deposits are low in base and precious metals but are rich in beryllium. They generally contain fluorite, magnetite or hematite, carbonate minerals, zinc minerals, and if fluoritic, one or more metals that, like beryllium, form water-soluble fluoride complexes, such as tin, tungsten, bismuth, manganese, rare earths, titanium, or niobium. These metals are largely in oxygen compounds; sulfide minerals are rather uncommon.

Beryllium is released from the rock-forming minerals as they weather, and is incorporated in clay minerals. Thereafter, it remains in clayey soil or is carried off in suspension in running water. Most coarse sedimentary materials—pebbles, sand, and derived rocks—have low beryllium contents, corresponding to that of the quartz that is generally the dominant component. Near beryllium deposits, coarse sediments may contain detrital particles of beryllium minerals, many of which are resistant to weathering. Industrial beryl, and gem chrysoberyl, phenakite, and euclase $(AlBeSiO_4(OH))$ have been mined from such extremely local concentrations. Very little migration of beryllium takes place in solution in normal waters because the beryllium released upon weathering is quickly adsorbed by mineral particles. High acid or carbonate- or halide-rich water can cause small-scale migration of beryllium, but not on an economically important scale.

The beryllium contents of rocks change very little with metamorphism. Thus, most micaceous metamorphic rocks contain a few parts per million of beryllium, and quartzite and marble contain very little.

MINERALS

The only beryllium mineral that has had much economic importance is beryl, which has yielded nearly all the beryllium used in industry. Bertrandite, phenakite, helvite, chrysoberyl, and barylite are known to occur in moderately large deposits. The other 39 known beryllium minerals have been found in only small amounts. It is possible that some of them will become important, as bertrandite and barylite have. Twenty years ago bertrandite and barylite were thought to be very rare, but now they are known to form large bodies of present or potential economic value. The common or important minerals are shown in table 17.

TYPES OF BERYLLIUM DEPOSITS

Beryllium deposits can be divided into two broad categories: (1) pegmatitic, and (2) nonpegmatitic

TABLE 17.—*Characteristics of berryllium minerals known to form large deposits*

Mineral	Usual BeO content (percent)	Hardness	Specific gravity	Common colors	Size of grains	Associated minerals	
						Pegmatitic deposits	Nonpegmatitic deposits
Beryl ($Be_3Al_2Si_6O_{18}$) _____	12–13.5	7.5	2.6 –2.9	White, pale blue, or green.	<0.1 inch– 2 feet	Quartz, sodic plagioclase, microcline, muscovite, spodumene.	Quartz, fluorite, carbonates, iron oxide minerals.
Bertrandite ($Be_4Si_2O_7(OH)_2$).	42	6	2.6	White __	<0.001–⅛ inch.	Beryl, quartz, feldspars.	Quartz, beryl, fluorites, carbonates, iron oxide minerals.
Phenakite (Be_2SiO_4) _____	45	7.5	2.9 –3.0	White __	<0.1–2 inches.	Beryl, quartz, feldspars, fluorite, topaz.	Beryl, fluorite, topaz carbonates.
Chrysoberyl (Al_2BeO_4) ___	19.8	8.5	3.5 –3.8	Green, yellow.	<0.1–2 inches.	Microcline, sodic plagioclase, quartz, beryl, mica.	Fluorite, disapore, tourmaline.
Helvite ((Mn,Fe,Zn_4)$Be_3Si_3O_{12}S$).	11–14	5.5–6.5	3.16–3.66	Brown, yellow, gray.	<0.1–3 inches.	Feldspars, quartz, fluorite.	Quartz, fluorite, carbonates, iron oxide minerals.
Barylite ($BaBe_2Si_2O_7$) ____	16	7	4	White, yellow.	<0.1 inch.	--------------	Quartz, albite, carbonates, sodic amphiboles.

or hydrothermal. Each of these must be further subdivided: the pegmatitic into fine-grained unzoned deposits and coarse-grained zoned deposits; the hydrothermal deposits into several categories, in general conforming to Lindgren's classification of hypothermal, mesothermal, and epithermal.

PEGMATITIC DEPOSITS

The pegmatitic deposits that are significant as sources of beryllium minerals are composed of major amounts of quartz, sodic plagioclase, and microcline, with or without spodumene, muscovite, or lepidolite. The association of beryl with spodumene is close, and few spodumene-bearing pegmatites lack beryl. Muscovite is also a common associate of beryl, especially in nonlithian pegmatites. Commonly, however, the muscovite found with beryl will not yield sheet mica, which limits the production of beryl as a byproduct from mica mines.

The fine-grained unzoned pegmatite dikes that have attracted most attention as potential sources of beryl are aggregates of albite, microcline, spodumene, quartz, beryl, and muscovite. These are moderately uniform in composition, differing from place to place mainly in the size and orientation of the mineral particles. Spodumene and microcline crystals range in maximum dimension from a fraction of an inch to a few feet, and lathlike crystals of spodumene may be parallel or random in orientation. Albite, quartz, muscovite, and beryl form a fine-grained matrix that surrounds the spodumene, microcline, and lumps of quartz. Fine-grained beryl,

generally white, constitutes about ½ percent of the pegmatite.

These pegmatites are important sources of spodumene, scrap mica, and feldspar, but the small amount and fine grain size of the beryl have prevented its recovery, even in conjunction with flotation of the other minerals.

Most zoned pegmatites are composed of the same minerals as the unzoned pegmatites. They differ in that the proportions of minerals and the textures of the rocks vary markedly from place to place in a dike, generally changing from the wall to the core of the pegmatite body. This internal structure of pegmatite dikes is uniform throughout the world. Near the walls the rock consists of plagioclase and quartz, with or without muscovite or microcline, and it has a very coarse granitic texture. Toward the center of the dike, this composition gives way to a zone of blocky microcline that may be monomineralic or may contain plagioclase and quartz interstitial to the microcline blocks. The center of the dike is occupied by a core of quartz. The margins of the quartz core are the loci of crystals of beryl; some crystals are very large, 3 feet or more wide and 20 feet long. The beryl is not evenly distributed along the margins of the cores but is in pockets separated by barren rock.

The much less common, but more spectacular, zoned lithian pegmatites usually have spodumene-bearing zones between the microcline-rich zone and the quartz core. Many of these zones are rather similar in composition to the unzoned spodumene-

bearing pegmatites. The crystals of spodumene and beryl may be very large, which permits them to be recovered by hand sorting in rather simple mining operations.

The coarse zoned pegmatites have yielded nearly all the beryl used in industry.

HYDROTHERMAL DEPOSITS

The hydrothermal deposits that are of most interest as actual or potential sources of beryllium ore are mainly hypothermal types formed at high temperature and at least moderate depth, and epithermal types formed at shallow depths. These deposits have provided a very small proportion of the total supply of ore but will become dominant in the near future.

HYPOTHERMAL DEPOSITS

Hypothermal deposits are generally quartz-rich moderately coarse-grained veins and beryl-bearing granite, both associated with greisen. In North America they are most commonly mined for tungsten, but a few have yielded tin minerals, and the ones near Lake George, Colo., were mined for beryl and bertrandite. Other examples of beryllium-bearing hypothermal deposits are those near Lost River, Alaska; in the Bagdad area, Arizona; in the Mineral and Sheeprock Ranges, Utah; and in the Mount Wheeler and Eureka areas, Nevada. Most of these are veins in silicate rocks; a few, as in Nevada, are in carbonate rocks; and in the Sheeprock and Mineral Ranges beryl is dispersed in granite.

Contact-metasomatic deposits are hypothermal replacement bodies in carbonate rocks, most commonly along or near contacts of intrusive rocks. They contain a wide variety of silicate minerals and, rather uncommonly, helvite. Much of the beryllium reported in these deposits is contained in idocrase or other minerals of low-beryllium content. The deposits at Iron Mountain, N. Mex., have been thoroughly studied. Others are at Iron Mountain, N.H., and in the Victorio Mountains, N. Mex.

MESOTHERMAL DEPOSITS

The mesothermal deposits that yield most of our lead, zinc, and copper are notably poor in beryllium. A little helvite has been found in deposits rich in rhodochrosite or rhodonite near Philipsburg, Mont., and Silverton, Colo., but these deposits show no promise as sources of beryllium.

For convenience, the chrysoberyl deposits of the Seward Peninsula, Alaska, are included here, although they might also be grouped with the hypo-

thermal deposits with which they are associated. These replacement bodies in limestone consist largely of very fine grained fluorite, diaspore, and chrysoberyl, and they lack silicate gangue minerals. They contain some of the largest known resources of beryllium and of fluorite and may form the basis for a multiproduct mining operation.

EPITHERMAL DEPOSITS

Concentrations of beryllium minerals in epithermal deposits were overlooked for many years because they are not closely associated with the famous gold- and silver-bearing sulfide deposits of this genetic type. Instead, they are in sulfide-poor altered rocks that contain small amounts of fluorite as the only readily recognizable economic mineral. The largest known beryllium deposits are the epithermal mantos at Spor Mountain, Utah, in which a rhyolite ash bed containing as much as 65 percent of limestone and dolomite in pebbles and cobbles was replaced by montmorillonite, silica, fluorite, adularia, and bertrandite. The ore is too fine grained to be beneficiated, but nearly all the beryllium can be leached from it with acid. A somewhat similar deposit is a few miles north of Iron Mountain, N. Mex.

Large veins of quartz, calcite, adularia, and bertrandite cut monzonite in the Gold Hill district, Utah, and are unusual in that they contain no fluorite and are not in calcareous host rocks.

REGIONAL DISTRIBUTION OF BERYLLIUM DEPOSITS

Pegmatite deposits of Paleozoic age have been found along much of the Appalachian Mountains from Nova Scotia to central Alabama. Beryl is widespread in the northern Appalachians, but is largely restricted in the southern Appalachians to the tin-spodumene belt near Kings Mountain, N.C., the Amelia-Powhatan County area, Virginia, and the Troup County area, Georgia. Pegmatites of Precambrian age yield beryl in the Black Hills, S. Dak., northern Colorado, northern New Mexico, and south-central Wyoming. Beryl-bearing pegmatites are not as productive elsewhere in the west.

Nonpegmatitic deposits have an entirely different distribution. Most are in the block-faulted regions of the West, and a few are in strongly faulted areas in Alaska, the Mississippi Valley, and northern New England. The beryllium deposits are in, and probably are features of, fluorspar metallogenic provinces, especially in the West, where they commonly are associated with igneous rocks of middle or late Tertiary age. Many of the deposits are in limestone or dolomite.

RESOURCES

The only resources that have been reasonably well delineated in pegmatites are those in the fine-grained spodumene-bearing pegmatites that are being mined for lithium. These contain a very large amount of beryl; 800,000 tons has been estimated to be in the pegmatites of North and South Carolina alone. However, because of the low beryl content of the rock (about one-half of 1 percent) and its fine particle size, this beryl will not be economically recoverable. Hence, it is not included in the resource tabulation.

The coarse zoned pegmatites, on the other hand, contain beryl that is readily recoverable, but the known beryl resources are no more than 10,000 tons, because no exploration is done in advance of mining.

The larger nonpegmatitic deposits are persistent enough to be explored thoroughly before mining and to yield fairly reliable resource estimates with minimal exploration. The three largest districts, Spor Mountain, Utah; Seward Peninsula, Alaska; and Gold Hill, Utah, account for most of the resources of beryllium in known nonpegmatitic deposits as given in table 18.

TABLE 18.—*Estimated resources of beryllium, in short tons of metal*

	In known deposits		In undiscovered deposits	
	Peg-matitic	Non-peg-matitic	Peg-matitic	Non-peg-matitic
United States ____	300	60,000	600	250,000
Other countries ___	600	32,000	4,500	400,000

The 60,000 tons of beryllium in nonpegmatitic deposits in the United States are in deposits discovered in a period of about 10 years, after which exploration abruptly ceased. Additional deposits doubtless remain to be discovered. These are assumed to contain about four times as much beryllium as the deposits that are now known. The following characteristics of major districts were used in evaluating potential future discoveries: most beryllium districts (1) are associated with high-angle faults of regional extent, generally block faults; (2) are in fluorite metallogenic provinces; and (3) have calcareous rocks as the most favorable host for mineralization. Figure 12 shows areas that are most promising for additional exploration. It
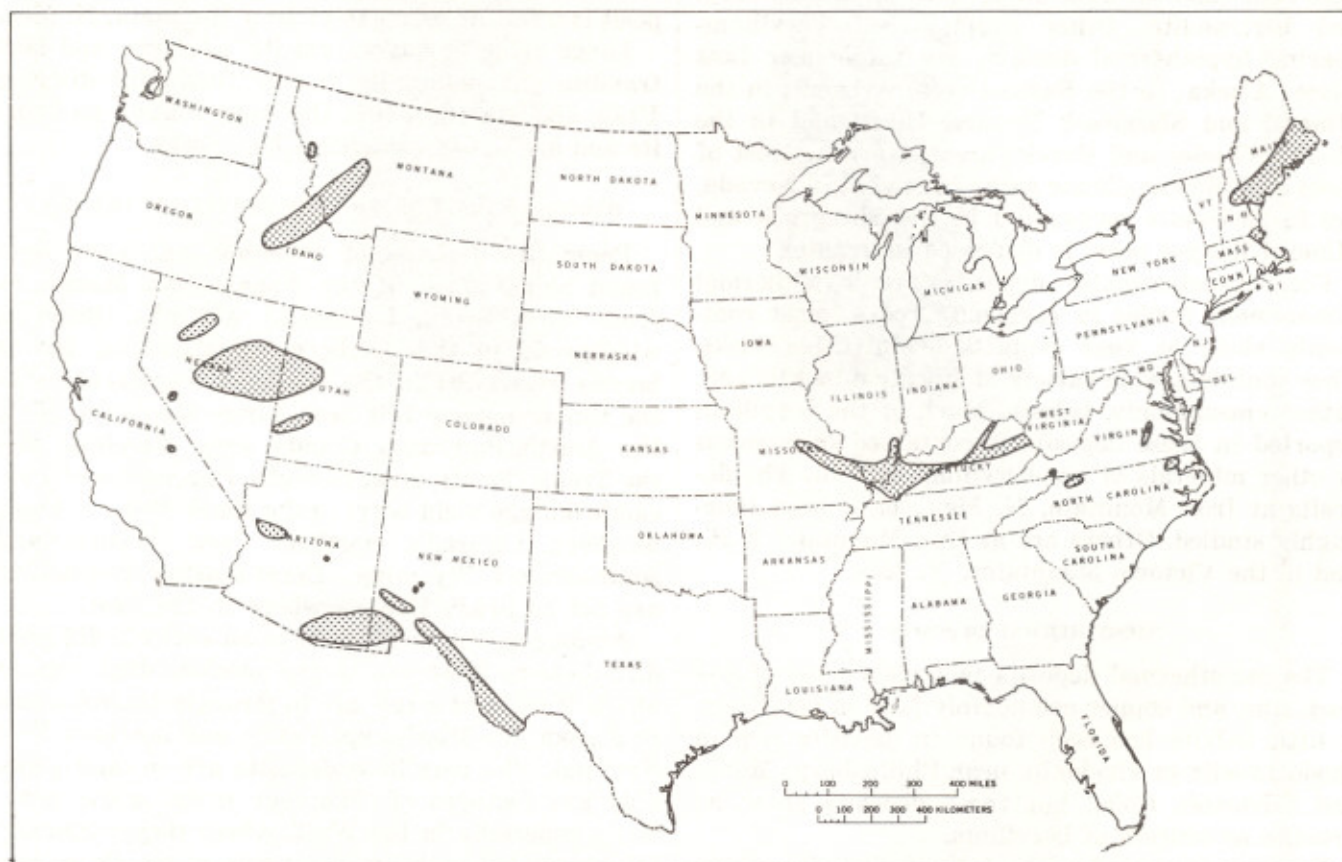

FIGURE 12.—Areas of the conterminous United States in which beryllium deposits are most likely to be found.

should be emphasized that the diagnostic characteristics given above pertain to most, but not all districts. Beryllium districts may well be found that do not conform to these generalizations, but their potential cannot now be estimated.

Beryllium minerals of hydrothermal deposits seldom can be recognized readily in the field, and the deposits themselves are likely to be covered by soil. Hence, they are most likely to be found by a study of regional geology, followed by geochemical surveys of the most promising areas. Resources now known are large, but small-scale search is justified for deposits that might be better economically than those that are now known.

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——— 1953–1969, Minerals yearbooks.

it develops a coherent oxide coating when exposed to air, which protects it from further oxidation and increases its apparent hardness. Unfortunately, oxygen-free beryllium metal is very difficult to prepare. Most metal in commerce contains nearly 2 percent oxygen, which contributes to its brittleness. This brittleness requires production of articles by powder metallurgy and machining—a costly procedure—and limits reshaping by rolling or drawing.

The high thermal conductivity, high melting point, high specific heat, low density, and rigidity of the metal make it useful in heat sinks and in specialized structural elements for aircraft and spacecraft. Its low neutron absorption and its emission of neutrons under appropriate gamma or alpha bombardment lead to uses in nuclear energy. In the early 1970's, nearly 20 percent of the beryllium extracted was used as the metal.

PROPERTIES AND USES OF BERYLLIUM ALLOYS

More than half the beryllium reduced from its ore is used in alloys, principally in beryllium-copper alloys containing about 2 percent beryllium and about 0.2 percent nickel or cobalt. These alloys have the greatest strength and wear resistance of any nonmagnetic material, with a tensile strength about twice that of hard-drawn iron and two-thirds that of mild steel. They also are excellent conductors of electricity and heat and are very resistant to corrosion. Below a temperature of about 300°F, they are much more resistant to fatigue than steel. They are much used in springs, electrical connectors, and many other specialized items. The use of the alloys in computers and other electrical equipment has resulted in greatly increased consumption during the last 20 years.

Beryllium has been used in small amounts with nickel to make hardenable alloys with very high tensile strength that are usable at higher temperatures than copper alloys.

In light alloys with aluminum and magnesium, beryllium can improve the properties or facilitate the production of the metal. Addition of 0.02 percent of beryllium to aluminum-magnesium alloys reduces reaction with green sand molds and improves oxidation resistance. It eliminates the need for elaborate precautions against burning of magnesium, inasmuch as the molten metal containing beryllium can be poured safely at a temperature of 1,400°F. "Lockalloy," containing 62 percent beryllium and 38 percent aluminum, has some of the desirable properties of beryllium, is reasonably workable, and can be used at temperatures as high as 800°F. Various composite materials containing beryllium in nonbrittle matrices are strong and light.

PROPERTIES AND USES OF THE OXIDE

Beryllium oxide is the third major form in which beryllium is used. This oxide, with a high melting point, a high thermal conductivity, and very low electrical conductivity, can be used as an electrical insulator in applications where heat must be transferred or dissipated, as in power transistors. The high thermal conductivity results in high thermal shock resistance, which is important in special ceramics. These, and the nuclear properties, lead to the use of beryllium oxide in reactor fuel elements.

BERYL AS AN INDUSTRIAL MINERAL

In addition to the uses of beryllium that require extraction of the metal from its ore, there are many uses that are met by incorporating undecomposed beryl into an industrial product. These uses account for about one-tenth of the beryl ore used during the last 20 years. Some of these uses are chemical—the addition of beryllium to a ceramic or glass mix; others rely upon one or more physical properties of the mineral beryl itself such as its structure, its thermal conductivity, or its ability to adhere to plastics.

END USES OF BERYLLIUM

The amount of beryllium used in various ways in the United States is summarized in table 15.

TABLE 15.—*End uses of beryllium in the United States, 1968*

[Data from Heindl, 1970, p. 498]

Use	Short tons	Percent of total
Nuclear applications	35	10
Guided missiles and space vehicles	35	10
Instruments	45	13
Switch gear	90	26
Welding equipment	40	11
Electronic computers	40	11
Radio and television equipment	25	6
Other	38	13
Total	348	100

SECONDARY RECOVERY

Much recoverable beryllium scrap is produced in making articles out of beryllium metal. This is an inevitable result of the necessity of making blank or roughly formed pieces of metal by powder metallurgy, then machining the final product from them. Not much metal, however, can be salvaged from the final articles. Components of missiles and rockets are commonly destroyed in use, whereas those of manned capsules and orbiting observatories may be