FINAL

Report on Carcinogens Background Document for

Beryllium and Beryllium Compounds

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Prepared for the:
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Criteria for Listing Agents, Substances or Mixtures in the Report on Carcinogens

U.S. Department of Health and Human Services
National Toxicology Program

Known to be Human Carcinogens:

There is sufficient evidence of carcinogenicity from studies in humans which indicates a causal relationship between exposure to the agent, substance or mixture and human cancer.

Reasonably Anticipated to be Human Carcinogens:

There is limited evidence of carcinogenicity from studies in humans which indicates that causal interpretation is credible but that alternative explanations such as chance, bias or confounding factors could not adequately be excluded; or

There is sufficient evidence of carcinogenicity from studies in experimental animals which indicates there is an increased incidence of malignant and/or a combination of malignant and benign tumors: (1) in multiple species, or at multiple tissue sites, or (2) by multiple routes of exposure, or (3) to an unusual degree with regard to incidence, site or type of tumor or age at onset; or

There is less than sufficient evidence of carcinogenicity in humans or laboratory animals, however; the agent, substance or mixture belongs to a well defined, structurally-related class of substances whose members are listed in a previous Report on Carcinogens as either a *known to be human carcinogen, or reasonably anticipated to be human carcinogen* or there is convincing relevant information that the agent acts through mechanisms indicating it would likely cause cancer in humans.

Conclusions regarding carcinogenicity in humans or experimental animals are based on scientific judgment, with consideration given to all relevant information. Relevant information includes, but is not limited to dose response, route of exposure, chemical structure, metabolism, pharmacokinetics, sensitive sub populations, genetic effects, or other data relating to mechanism of action or factors that may be unique to a given substance. For example, there may be substances for which there is evidence of carcinogenicity in laboratory animals but there are compelling data indicating that the agent acts through mechanisms which do not operate in humans and would therefore not reasonably be anticipated to cause cancer in humans.

Summary Statement

Beryllium and Beryllium Compounds

Beryllium and beryllium compounds were first listed in the Second Report on Carcinogens as *reasonably anticipated to be human carcinogens*

Carcinogenicity

Beryllium and beryllium compounds are *known to be human carcinogens*, based on findings of increased risk of lung cancer in occupational groups exposed to beryllium or beryllium compounds (Steenland and Ward 1991; Ward *et al.* 1992) and supporting animal data (IARC 1993; Finch *et al.* 1996). The epidemiologic evidence supports a conclusion that beryllium and beryllium compounds are carcinogenic to humans. An association with lung cancer has been consistently observed in several populations, with an excess risk of 1.2 to 1.6. Higher risks are found in groups with greater exposure or longer time since first exposure, which are dose-response patterns that support a causal relationship. Acute beryllium pneumonitis, a marker for high exposure to beryllium, is associated with elevated lung cancer rates, with an excess risk of 2.3 (Steenland and Ward 1991). Although smoking is a potential confounder, no evidence was found in any of the published epidemiology studies to indicate that the prevalence of smoking in any of the exposed cohorts was substantially greater than in the referent populations.

Animal experiments have shown consistent increases in lung cancers in rats, mice and rabbits chronically exposed to beryllium and beryllium compounds by inhalation or intratracheal instillation. Osteosarcomas have been produced in mice and rabbits exposed to various beryllium salts by intravenous injection or implantation into the bone.

Other Relevant Information

Beryllium compounds were not mutagenic in a variety of *Salmonella* tester strains. However, beryllium compounds induced genetic transformations in a variety of mammalian cells, *in vitro*. The genetic transformation effects of beryllium may be mediated by binding of ionic beryllium to nucleic acids that can produce infidelity in DNA replication.

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1 Introduction

Beryllium and certain beryllium compounds were first listed in the National Toxicology Program's (NTP) Second Annual Report on Carcinogens in 1981 as *reasonably anticipated to be human carcinogens* based on sufficient evidence of carcinogenicity in experimental animals and limited evidence in humans. Beryllium and beryllium compounds were nominated for possible upgrading to *known to be human carcinogens* based on the publication of an International Agency for Research on Cancer (IARC) monograph (1993) which stated that beryllium and beryllium compounds are carcinogenic to humans (Group 1) based on sufficient evidence of carcinogenicity in humans and experimental animals.

1.1 Chemical identification

Elemental beryllium (mol wt 9.01218, CASRN 7440-41-7) is a hard, grayish metal. It is also known as beryllium metal, beryllium-9, beryllium metallic, glucinium, or glucinum. It is one of the lightest of all metals and has one of the highest melting points of the lightest metals. Beryllium occurs naturally as a chemical component of certain kinds of rock, such as bertrandite, beryl, beryl ore, chrysoberyl, and phenakite. It also is found as a component of coal, soil, and volcanic dust. Some of the beryllium compounds discussed in the present review include the following:

beryllium-aluminum alloy
beryllium-copper alloy
beryllium-nickel alloy
beryl ore
bertrandite
chrysoberyl
beryllium acetate
beryllium carbonate
beryllium chloride
beryllium fluoride
beryllium hydroxide
beryllium nitrate
beryllium silicate
beryllium sulfate
beryllium oxide
beryllium phosphate
beryllium zinc silicate.

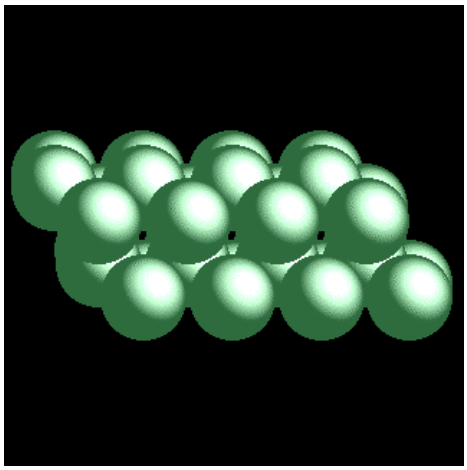
The U.S. Environmental Protection Agency (EPA) codes are K061 for beryllium and P015 for beryllium compounds. Shipping codes are UN1567 for beryllium and 1566 Poison B for beryllium compounds.

1.2 Physical-chemical properties

The structure of Beryllium is hexagonal close-packed, as illustrated in Figure 1-1. Beryllium has a very high specific heat, heat of fusion, sound conductance, and strength-to-weight ratio. Beryllium is lighter than aluminum but is > 40% more rigid than steel. Beryllium's modulus of elasticity is about one third greater than that of steel. It has excellent thermal conductivity and is non-magnetic. At ordinary temperatures, beryllium resists oxidation in air; however, its ability to scratch glass is probably due to the formation of a thin layer of the oxide.

Alloys are substances composed of two or more metals, or sometimes a metal and a non metal, which have been mixed intimately by fusion, electrolytic deposition, or other

means. Beryllium in alloys contributes hardness, strength, and high electrical and thermal conductivity; it confers enhanced resistance to corrosion, wear, and fatigue. Beryllium alloyed with copper, aluminum, and other metals is used in the electronics, automotive, defense, and aerospace industries. Beryllium alloys also are used in dental applications and sporting goods (U.S. DOE 1999).



Source: WebElements2000 (1999)

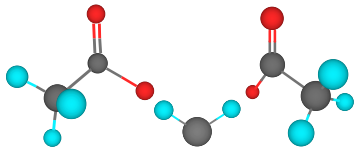
Figure 1-1. Structure of beryllium

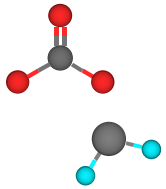
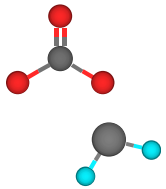
The physical and chemical properties of elemental beryllium and its compounds are listed in Table 1-1 and Table 1-2, respectively.

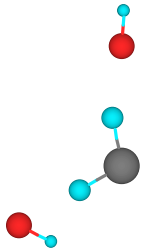
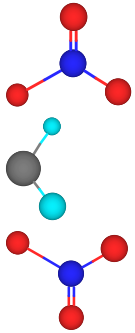
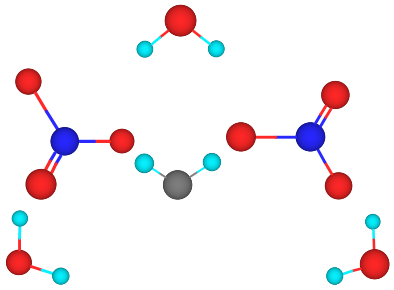
Table 1-1. Physical and chemical properties of elemental beryllium

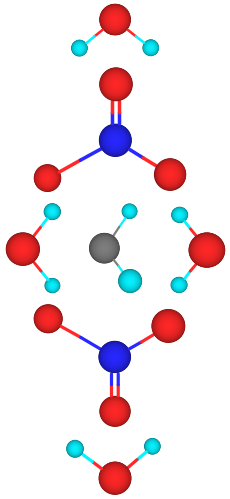
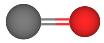
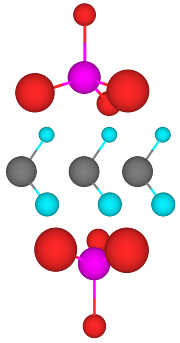
Property	Information	Reference
Molecular weight	9.01218	Budavari *et al.* (1996); CRC (1998)
Color	silvery, resembles aluminum powder	Budavari *et al.* (1996); CRC (1998)
Odor	odorless	CRC (1998)
Physical state	solid	Budavari *et al.* (1996); CRC (1998)
Melting point (°C)	1287	Budavari *et al.* (1996); CRC (1998)
Boiling point (°C)	2970	Budavari *et al.* (1996); CRC (1998)
Density (g/cc at 20 °C)	1.844	Budavari *et al.* (1996); CRC (1998)
Crystal system	hexagonal close-packed	Yang and Coppens (1978)
Young's modulus (psi)	44 x 106	Rossman *et al.* (1991)
Solubility in: Water at 20°C Acids (dilute) Alkalies (dilute)	 insoluble soluble soluble	Budavari *et al.* (1996); CRC (1998); HSDB (1998)

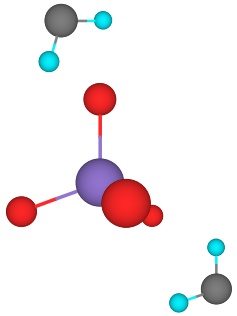
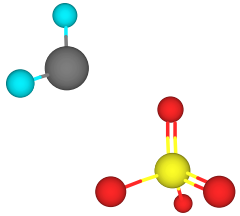
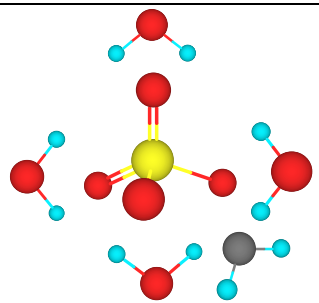
Table 1-2. Physical and chemical properties of beryllium compounds[a]

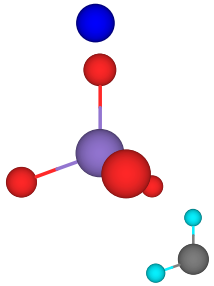
Compound	CASRN	Structure	mol wt	Physical state	Melting point (°C)	Boiling point (°C)	Density (g/cm^3)	Solubility	Decomposition products upon heating
Beryllium-aluminum alloy 62% Be, 38% Al	12770-50-2	NR	NR	NR	NR	NR	NR	NR	toxic fumes of BeO
Beryllium-copper alloy 0.3 - 2.0% Be, 96.9 - 98.3% Cu; 0.2% min. Ni and Co, 0.65 max. Ni, Fe, and Co	11133-98-5	NR	NR	NR	870-980	NR	NR	NR	toxic fumes of BeO
Beryllium-nickel alloy 2-3% Be; up to 4% other additives; rest Ni	37227-61-5	NR	NR	NR	NR	NR	NR	NR	NR
Beryl ore $[Be_3(AlSi_3O_9)_2]$ 2.03% Be, 10.04% Al, 31.35% Si, 53.58% O	1302-52-9	NR	537.502	blue-green, yellow, or white, transparent hexagonal crystal	1650	NR	2.80[b]	insoluble in acid.	NR
Chrysoberyl $[BeAl_2O_4]$ 7.10% Be, 42.5% Al, 50.4% O		NR	126.973	green, yellow, or brown orthorhombic crystal	NR	NR	3.75[b]	NR	NR
Beryllium acetate $C_4H_6BeO_4$	543-81-7		127.10	colorless plates	300 (decomposes)	NR	NR	insoluble in cold water, ethanol, and other common organic solvents slow hydrolysis in boiling water	NR

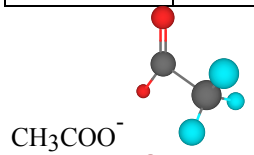
Compound	CASRN	Structure	mol wt	Physical state	Melting point (°C)	Boiling point (°C)	Density (g/cm^3)	Solubility	Decomposition products upon heating
Beryllium carbonate $BeCO_3$	66104-24-3		69.021	NR	NR	NR	NR	soluble in acids and alkali, insoluble in cold water, decomposes in hot water.	NR
Beryllium carbonate; Carbonic acid, beryllium salt (1:1) $BeCO_3 \cdot Be(OH)_2$	13106-47-3		112.05	white powder	NR	NR	NR	soluble in acids and alkali, insoluble in cold water, decomposes in hot water.	NR
Beryllium chloride $BeCl_2$	7787-47-5		79.918	white to colorless deliquescent needles	405[c]	520[c]	1.899[c] (25°C)	soluble in water, alcohol, benzene, ether, and pyridine slightly soluble in chloroform and benzene. insoluble in acetone. insoluble in ammonia.	toxic fumes of BeO, HCl and other chlorinated compounds.
Beryllium fluoride BeF_2	7787-49-7		47.009	colorless amorphous mass	545[c] (800 sublimes)	1,160[c]	1.986[c] (25°C)	readily soluble in water. slightly soluble in sulfuric acid and alcohol.	toxic fumes of BeO, HF and other fluorinated compounds

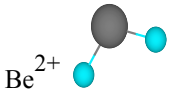
Compound	CASRN	Structure	mol wt	Physical state	Melting point (°C)	Boiling point (°C)	Density (g/cm^3)	Solubility	Decomposition products upon heating
Beryllium hydroxide $Be(OH)_2$	13327-32-7		43.027	three crystal or powder forms metastable tetragonal crystalline solid stable orthorhombic crystalline solid in slightly basic pH appears as a slimy, gelatinous substance	138[c] decomposes to BeO	NR	1.92[c]	slightly soluble in water[g]. soluble in hot concentrated acids and alkalies.	toxic fumes of BeO
Beryllium nitrate $Be(NO_3)_2$	13597-99-4		133.022	deliquescent crystalline mass	60	NR	NR	very soluble in water and alcohol.	NR
Beryllium nitrate trihydrate $Be(NO_3)_2{\cdot}3H_2O$	7787-55-5		187.068	white yellow deliquescent crystalline mass	60.5[e]	142[e]	1.,557[e]	very soluble in water and ethanol.	NR

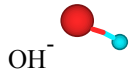
Compound	CASRN	Structure	mol wt	Physical state	Melting point (°C)	Boiling point (°C)	Density (g/cm^3)	Solubility	Decomposition products upon heating
Beryllium nitrate tetrahydrate $Be(NO_2)_3{\cdot}4H_2O$	13510-48-0		205.083	NR	NR	NR	NR	NR	NR
Beryllium oxide BeO	1304-56-9		25.0116	white amorphous powder or gel	2530	3787	3.016	0.2 mg/L (30°C) in water. soluble in acids, alkalies, and ammonium carbonate.	toxic fumes of BeO
Beryllium phosphate $Be_3P_2O_8$	13598-15-7		216.979	NR	NR	NR	NR	slightly soluble in water.	NR

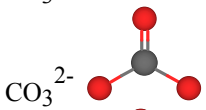
Compound	CASRN	Structure	mol wt	Physical state	Melting point (°C)	Boiling point (°C)	Density (g/cm^3)	Solubility	Decomposition products upon heating
Beryllium silicate Be_2SiO_4	13598-00-0		110.11	triclinic colorless crystals	1560[e]	NR	3.0	NR	NR
Beryllium sulfate $BeSO_4$	13510-49-1		105.07	colorless tetragonal crystals	decomposes 550 - 600[d]	Not applicable	2.443[d]	insoluble in cold water and alcohol, converts to tetrahydrate in hot water.	toxic fumes of BeO and sulfur oxides SO_x
Beryllium sulfate tetrahydrate $BeSO_4.4H_2O$	7787-56-6		177.13	colorless tetragonal crystals	100 (loses $2H_2O$)[d] anhydrous 270[e]	400 (loses $4H_2O$)[d] decom-poses 580[e]	1.713	insoluble in ethanol slightly soluble in concentrated sulfuric acid	toxic fumes of BeO and sulfur oxides SO_x

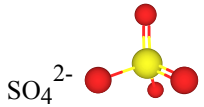
Compound	CASRN	Structure	mol wt	Physical state	Melting point (°C)	Boiling point (°C)	Density (g/cm^3)	Solubility	Decomposition products upon heating
Zinc beryllium silicate BeO_4SiZn	39413-47-3		166.49	crystalline solid	NR	NR	NR	NR	NR

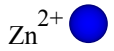


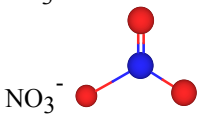


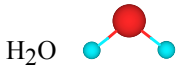


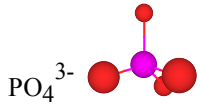


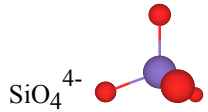












[a] All information obtained from Chemfinder (1998) except where noted.
NR: not reported.
[b] Emsley (1998).
[c] WHO (1990).
[d] Sax and Lewis (1987).
[e] Dean (1992).

1.3 Identification of metabolites

Beryllium metabolites *per se* have not been identified or studied. Snow (1992), however, reviewed effects of beryllium and beryllium compounds on cellular immunity and nucleic acid metabolism. This analysis compared beryllium with the carcinogenic metals, nickel and chromium. It was suggested that insoluble beryllium, engulfed by activated phagocytes, can be ionized by myeloperoxidases. Reactive oxygen intermediates formed in this inflammatory reaction to beryllium can bind to nucleic acids and interfere with the fidelity of DNA synthesis (Lansdown 1995, Leonard and Lauwerys 1987) (see section 6).

2 Human Exposure

2.1 Use

Beryllium is an extremely light metal with a very high melting point. Because of its unique properties, beryllium has many practical uses in industry. When used in alloys, it confers its unique properties, increasing thermal and electrical conductivity and strength (WHO 1990). Addition of only 2% of beryllium to copper forms alloys that are six times stronger than copper alone (LLNL 1997). Beryllium alloys find limited use in industry because of the low solubility of most other metals in solid beryllium, making alloys difficult to make or very brittle (WHO 1990).

Table 2-1 summarizes the uses for beryllium and beryllium compounds.

Table 2-1. Industrial uses for beryllium

Compound	Uses
Pure beryllium metal	Aircraft disc brakes, X-ray transmission windows, space vehicle optics and instruments, aircraft/satellite structures, missile parts, nuclear reactor neutron reflectors, nuclear weapons, fuel containers, precision instruments, rocket propellants, navigational systems, heat shields, mirrors
Beryllium oxide	High-technology ceramics, electronic heat sinks, electrical insulators, microwave oven components, gyroscopes, military vehicle armor, rocket nozzles, crucibles, thermocouple tubing, laser structural components
Beryllium alloys	Electrical connectors and relays, springs, precision instruments, aircraft engine parts, non-sparking tools, submarine cable housings and pivots, wheels, pinions, automotive electronics, molds for injection molded plastics for automotive, industrial and consumer applications

Source: LLNL (1997), WHO (1990), and ATSDR (1993).

2.1.1 Beryllium

Beryllium's earliest application was as a window for X-ray tubes. Because beryllium is relatively transparent to X-rays, these tubes were of the highest standard. Beryllium was then used in aircraft brake manufacturing because of its high specific heat (four times that of steel). Beryllium has a low density yet is very stiff, which results in dimensional stability. Because of these unique properties, it is used in missile, aircraft, and spacecraft guidance systems. Beryllium also is used in test reactors, tokamak reactors, and fusion reactors because it has a combination of high neutron multiplication, low absorption, and high scattering characteristics (Rossman *et al.* 1991).

2.1.2 Beryllium-copper alloy

Around 72% of all beryllium is used to produce beryllium-copper alloys (WHO 1990). While the alloy retains copper's desirable properties (corrosion resistance and thermal and electrical conductivity), addition of beryllium significantly increases the strength of the alloy. Few, if any, other types of copper alloy exhibit as great an increase in strength as beryllium-copper alloy. Because of the strength of this alloy, it can be used in many demanding applications, from military and commercial landing gear to oil field drill collars and drilling bit friction bushings (Rossman ***et al.*** 1991). Beryllium-copper alloys do not spark and are nonmagnetic. Non-sparking tools made of beryllium-copper alloy can therefore be used in explosive environments where sparks from steel-to-steel contact must be avoided (IARC 1993).

2.1.3 Other beryllium alloys

Beryllium-aluminum alloys have garnered increased attention particularly in the aerospace industry, because they are extremely lightweight, yet very strong (IARC 1993) (WHO 1990).

Beryllium-nickel alloys are used in some high-temperature applications because they have higher thermal conductivity and a greater hardness than beryllium-copper alloys (WHO 1990).

Beryllium-nickel-chromium alloys are used in dentistry as an alternative to gold because beryllium increases the porcelain-metal bond strength and facilitates castability (WHO 1990).

2.1.4 Beryllia ceramics

Beryllium oxide (BeO) ceramics exhibit many of the properties that are necessary for ceramic materials used in electronic packages. They are very effective electrical insulators, have the ability to be hermetically sealed, and have the mechanical properties suitable for mounting and protection of the electronic circuitry (Rossman ***et al.*** 1991). BeO ceramics have the highest thermal conductivity of the oxide ceramics. Together with their high heat capacity and electrical resistivity, this property allows BeO ceramics to be used as an electrical insulator in electronics and other applications that require thermal dissipation.

2.2 Production

Because of beryllium's increased importance in nuclear and aerospace technologies, U.S. production of beryllium has steadily increased. There are only two commercially important beryllium-containing minerals: beryl and bertrandite (Cunningham 1997).

Beryl ($3BeO{\cdot}Al_2O_3{\cdot}6SiO_2$), which contains around 11% beryllium oxide (up to 4% beryllium), is the predominant beryllium-containing mineral mined in the world. Beryl is found largely in Brazil and the former U.S.S.R. Impurities in beryl include alkali metals, alkaline-earth metals, iron, manganese, and phosphorus. Emeralds (chromium-containing

beryl), aquamarine (iron-containing beryl), and other semiprecious gems are examples of beryl at its purest gem quality (IARC 1993).

Bertrandite ($4BeO{\cdot}2SiO_2{\cdot}H_2O$) is the principal beryllium-containing mineral mined in the United States, accounting for approximately 85% of U.S. consumption. Bertrandite contains < 1% beryllium but can be efficiently processed into beryllium hydroxide.

Other compounds also are being studied to determine the commercial feasibility of extracting beryllium from them. Two main examples are phenakite ($2BeO{\cdot}SiO_2$) and chrysoberyl ($BeO{\cdot}Al_2O_3$). Phenakite is found in Canada, and chrysoberyl is found mostly in Texas (IARC 1993).

Table 2-2 shows the trend toward increased beryllium production (Cunningham 1997).

Table 2-2. United States production and use

Salient statistics	Metric tons of beryllium				
	1993	1994	1995	1996	1997[a]
Production, mine shipments	198	173	202	211	210
Imports for consumption, ore, and metal	8	53	32	20	45
Exports, metal	20	29	61	57	45
Consumption: apparent	183	198	198	204	205
Consumption: reported	196	174	227	234	230

Source: Cunningham (1997).
[a] Estimated.

2.3 Analysis

Analysis of beryllium started with spectroscopic, fluorometric, gamma activation, spectrophotometric, and automatic titrimetric techniques. Atomic absorption spectrometry currently is used to determine beryllium levels in biological and environmental samples. Inductively coupled plasma atomic emission spectrometry is now being used because of its high sensitivity and low level of interference (IARC 1993).

Table 2-3 defines analytical and detection limits for various assays to determine beryllium levels.

Table 2-3. Analytical procedures and detection limits for beryllium

Sample Matrix	Assay Procedure[a]	Limit of Detection	Reference
Aqueous samples, extracts, wastes	FLAA ICP (313 nm) GFAA	0.005 mg/L 0.3 µg/L 0.2 µg/L	U.S. EPA (1986a) U.S. EPA (1986b) U.S. EPA (1986c)
Oil, greases, waxes (organic extract)	FLAA ICP	0.005 mg/L 0.3 µg/L	U.S. EPA (1986a) U.S. EPA (1986b)
Sediments, sludges, soils	FLAA ICP (313 nm) GFAA	0.005 mg/L 0.3 µg/L 0.2 µg/L	U.S. EPA (1986a) U.S. EPA (1986b) U.S. EPA (1986c)
Tissue samples	FLAA	2 µg/L	Kleinman *et al*. (1989)
Urine	GFAA (untreated) GFAA (modify matrix with magnesium nitrate)	0.5 µg/L 0.05 µg/L	Angerer and Schaller (1985) Paschal and Bailey (1986)

Source: IARC (1993).
[a]FLAA: flame atomic absorption spectrometry; GFAA: graphite furnace atomic absorption spectrometry; ICP: inductively coupled argon plasma emission spectrometry.

2.4 Environmental occurrence

2.4.1 Soil

Beryllium is the 44th most abundant element in the Earth's crust (IARC 1993). Beryllium concentrations in the Earth's crust are estimated at 2.6 ppm.

Beryllium and beryllium compounds are widely distributed in soils. Through geochemical surveys, it is estimated that the lithosphere contains 6 mg Be/kg. Agricultural soils in the United States average 0.6 mg beryllium/kg (ranging from < 1 to 7 mg beryllium/kg). The rare geological sites that contain large deposits of beryllium evidently account for the relatively high overall lithospheric beryllium concentration (WHO 1990). Anthropogenic contributions to beryllium soil concentrations include coal ash and municipal waste combustor ash. Industrial waste also is a source of beryllium in the soil. Land burial is the most popular method of disposing of industrial waste generated from the processing or use of beryllium (ATSDR 1993).

In compliance with the Emergency Planning and Community Right-to-Know Act (EPCRA), 16 facilities reported their total beryllium land release as 47,428 lb. No underground injection values were reported (TRI 1996).

2.4.2 Water

Surface water concentrations of beryllium are usually in the nanograms per liter range. Seawater levels of beryllium are one tenth those of surface waters, varying from 3.5×10^{-8} to 22×10^{-8} ppm (Emsley 1998). Increased beryllium concentrations in water levels usually are due to industrial wastewater effluents (WHO 1990). Deposition of atmospheric beryllium also adds to water concentrations. However, the relative contributions of these sources cannot be assessed. Beryllium also can enter the water through the weathering of rocks and soils (ATSDR 1993).

The mean concentration of beryllium in 1,577 U.S. drinking-water samples was calculated at 190 ng/L (range 10 to 1,200 ng/L) (U.S. EPA 1980, cited in ATSDR 1993). A more recent survey of metals in the New York City drinking water did not detect any beryllium in the samples with a detection limit of 10 μg/L (10,000 ng/L) (Iwan 1987, cited in ATSDR 1993). U.S. EPA has set a standard where by the concentration of beryllium in drinking water may not exceed 4 μg/L.

In compliance with the EPCRA, 16 facilities reported their total beryllium water release as 32 lb (TRI 1996). The reportable quantity for release of beryllium into water is 1 lb.

2.4.3 Air

Although windblown dust and volcanic particles account for some of the natural atmospheric releases of beryllium, combustion of coal and fuel oil is the most likely source of environmental release. Coal combustion and fuel oil are estimated to account for 96% of the U.S. beryllium emission from all natural and anthropogenic sources. The average beryllium concentration in coal is between 1.8 and 2.2 μg/g of coal. Beryllium also occurs in the ash of many coals at concentrations of around 100 μg/g coal ash (IARC 1993). It is estimated that 10% to 30% of the beryllium contained in coal is released into the ambient atmosphere. Regulatory limits dictate that fuel oil can contain no more than 0.08 ppm beryllium. It is assumed that about 40% of beryllium contained in fuel oil is released into the atmosphere (ATSDR 1993).

The Toxic Release Inventory (U.S. EPA) listed 16 industrial facilities that produced, processed, or otherwise used beryllium in 1996. In compliance with EPCRA, 16 facilities reported their total beryllium air release as 1,254 lb (TRI 1996). The reportable quantity for release of beryllium into air is 1 lb.

Table 2-4 summarizes anthropogenic and natural sources of beryllium emissions into the atmosphere. The national emission standard for beryllium is 10 g/24 h per facility.

Table 2-4. Emissions of beryllium into the atmosphere

Emission source	Total U.S. production (10^6 metric tons/year)	Emission factor (g/ton)	Emissions (ton/year)
Natural			
Windblown dust	8.2	0.6	5
Volcanic particles	0.41	0.6	0.2
Total			**5.2**
Anthropogenic			
Coal combustion	640	0.28	180
Fuel oil combustion	148	0.048	7.1
Beryllium ore processing	0.008[a]	37.5[b]	0.3
Total			**187.4**

Source: ATSDR (1993; adapted from data provided by U.S. EPA 1987).
[a] The production of beryllium ore is expressed in equivalent tons of beryl; the emission factor of 23.5 is estimated. Production of 8,000 tons/year of beryl is equivalent to ≈400 tons/year of contained metal.
[b] Units are metric tons.

Atmospheric background concentrations of beryllium have been reported to be less than 0.1 and 0.2 ng/m^3. Air samples taken over 100 cities in the U.S. from 1964 to 1965 did not contain detectable amounts of beryllium. From 1977 to 1981, average air concentrations of beryllium were around the limit of detection (0.03 ng/m^3). From 1981 to 1986, beryllium concentrations at urban monitoring stations exceeded of 0.03 ng/m^3, ranging from 0.11 to 6.7 ng/m^3. Atmospheric concentrations of beryllium are higher around beryllium processing plants than in other areas. The concentration of beryllium in air near a Pennsylvania factory averaged 15.5 ng/m^3, with a maximum of 82.7 ng/m^3, whereas the background concentrations in several locations in the area averaged only 0.2 ng/m^3 (IARC 1993).

The average air concentration of beryllium in the United States is 0.03 ng/m^3, and the median concentration in cities is 0.2 ng/m^3. According to a survey by the National Air Surveillance Network, atmospheric concentrations of beryllium (between 1977 and 1981) were > 0.1 ng/m^3 in 50 U.S. cities, with the highest average being 0.4 ng/m^3 in Dallas, Texas, in 1979 (ATSDR 1993).

2.5 Environmental fate

2.5.1 Air

Beryllium is most likely emitted into the atmosphere as BeO. BeO is formed through ore processing (both bertrandite and beryl contain BeO) and in stack emissions in burning of coal and refuse. It is not known whether BeO reacts with sulfur or nitrogen oxides in the atmosphere. If this process does occur, wet deposition of beryllium will be accelerated. Rainwater in Fresno, California, contained beryllium (concentrations not quantified), indicating that transport of beryllium to soil and water occurs via wet transport (ATSDR 1993).

Stack emissions from coal combustion were studied to determine relative particle aerodynamic size, wind speed, and surface roughness. Most beryllium particles were of a

median aerodynamic diameter of < 2.5 μm (Gladney and Owens 1976, cited in ATSDR 1993), meaning that these particles could remain airborne for around 10 days.

2.5.2 Water

Concentrations of dissolved beryllium in natural waters are very low. The most likely reaction between beryllium compounds and water is hydrolysis to form beryllium hydroxide (BeOH), which has low solubility in the pH range of most natural water. Although other reactions might occur that would allow other, more soluble complexes to be formed, the pH range needed for these reactions is not found in most natural waters. Studies comparing sediment and water beryllium concentrations show that sediment has beryllium concentrations several orders of magnitude higher than water, indicating that beryllium is not present in a dissolved form in the water as insoluble complexes naturally settle into the sediment. However, at higher pH, soluble complexes could be formed, increasing solubility and mobility of beryllium in water (ATSDR 1993).

Beryllium will remain in ocean water for a few hundred years before it is removed from the aquatic phase through sedimentation or some other removal system (ATSDR 1993).

Bioaccumulation of beryllium in fish is not thought to occur, because uptake of beryllium from the water by aquatic animals is low. Though beryllium is toxic to warmwater fish in soft water, bioconcentration factors (BCFs) of 100 were reported in freshwater and marine plants, invertebrates, and fish. A BCF greater than 1,000 is required for significant bioaccumulation in aquatic organisms. BCFs for bottom-feeding animals may be higher. There is no evidence of beryllium biomagnification in food chains (ATSDR 1993).

2.5.3 Soil

Beryllium is expected to have low mobility in soil. Because of its similarity to aluminum, beryllium is thought to be adsorbed onto clay surfaces at low pH. Higher pH may result in increased mobility of beryllium in soils. Beryllium reactions that might occur in the soil are hydrolysis of soluble salts, anion exchange reaction, and complexation reactions with ligands present in the soil (ATSDR 1993).

2.6 Environmental exposure

Inhalation of beryllium resulting in lung deposition is the primary route of exposure. Over time, beryllium slowly enters the bloodstream and is eventually excreted by the kidneys. It takes months or years for inhaled beryllium to be removed by the body. Beryllium exposure also may occur if beryllium is ingested into the body through drinking water, contaminated foodstuffs, or smoking. Ingestion, however, is not thought to be an important mode of exposure, because only 1% of ingested beryllium enters the bloodstream. Dermal exposure can occur if beryllium enters through cuts in the skin (ATSDR 1993).

Whether through consumption of contaminated food or water or through inhalation, the entire U.S. population is exposed to beryllium. U.S. EPA and ATSDR have estimated the

daily beryllium intake for the general population from background environmental exposure to be 420 ng/day. People who work in beryllium manufacturing, fabricating, and reclaiming industries are exposed to higher levels of beryllium than the general public. Smokers also may be exposed to higher levels of beryllium, because cigarette smoke contains beryllium (ATSDR 1993).

2.6.1 Environmental sources of beryllium

Beryllium has been found in various foods and cigarettes. Table 2-5 summarizes food surveys done to determine beryllium concentrations.

Table 2-5. Beryllium concentrations in various foodstuffs

Food	Measurement	Value
Polished rice	dry weight (mg/kg)	0.08
Potatoes	dry weight (mg/kg)	0.17
Toasted bread	dry weight (mg/kg)	0.12
Tomatoes	dry weight (mg/kg)	0.24
Head lettuce	dry weight (mg/kg)	0.33
Beans	in ash (ppm)	0.01
Cabbage	in ash (ppm)	0.05
Hen eggs (yolk)	in ash (ppm)	0.01
Milk	in ash (ppm)	0.02
Mushrooms	in ash (ppm)	0.12
Nuts	in ash (ppm)	0.01 - 0.47
Tomatoes	in ash (ppm)	0.02
Baker's yeast	in ash (ppm)	0.02

Source: HSDB (1997)

Beryllium also was found in three brands of German cigarettes (0.47, 0.68, and 0.74 µg/cigarette) (WHO 1990). It is estimated that from 4.5% to 10% of the beryllium in a cigarette passes to the smoker through the tobacco smoke (HSDB 1997).

2.7 Occupational exposure

The highest levels of human exposure to beryllium are through occupational exposure. Occupational exposure may occur via inhalation or dermal contact if workers are exposed to beryllium dust or handle products containing beryllium. Occupational exposure may also lead to at-home exposure to beryllium through work garments. In personal monitoring studies in the workplace, it was noted that air concentration measurements from personal monitors mounted on clothing increased when the fabric load of beryllium increased (HSDB 1997).

As applications of beryllium and beryllium compounds have increased, more workers are exposed, from miners to workers at processing plants and factories that convert beryllium into alloys and chemicals. It has been estimated that over 800,000 workers have been exposed to beryllium (Cullen *et al*. 1986, cited in Meyer 1994). The National

Occupational Exposure Survey estimated that a total of 19,012 workers, including 1,778 women, might have been exposed to beryllium between 1980 to 1983 (NIOSH 1990). The following industries have the potential for occupational exposure to beryllium (WHO 1990):

ceramics
nonferrous foundries
sandblasting
nuclear control equipment
refractories
hazardous waste processing
engineering and scientific equipment
tool and die making
welding or flame cutting
automotive parts
golf club manufacture
electrical connectors
nonferrous smelters
aerospace
electronics
beryllium smelting or fabrication
dental equipment and supplies
mechanical measuring devices
soldering
metal plating
telecommunication equipment

2.7.1 Processing and manufacturing

Beryllium is released during the various processes involved in processing and manufacturing beryllium compounds. These include melting, casting, molding, grinding, buffing, welding, cutting, electroplating, milling, drilling, and baking (WHO 1990). Control measures were instituted in 1949 to limit high exposures to beryllium. In a sample of 2,627 air samples taken between 1950 and 1957, Breslin and Harris (1959, cited in IARC 1993) reported that 10% to 15% of the workers were exposed to beryllium concentrations greater than the standard Occupational Safety and Health Administration (OSHA) limit (2 $\mu g/m^3$).

Kriebel *et al.* (1988) calculated time-weighted average (TWA) air concentrations of beryllium in a U.S. refinery. This refinery is where most of the beryllium in the United States has been refined since 1934, with beryllium-copper alloys as its principal product. Before 1977, beryllium exposure levels at the plant were sometimes in excess of 100 $\mu g/m^3$. After 1977, exposure levels decreased so as not to exceed the permissible exposure level of 2 $\mu g/m^3$. Although there was some overlap in the plants surveyed, the median exposure for 297 white male workers in 1977 was 0.4 $\mu g/m^3$. The median cumulative exposure (with a mean of 17 years worked) was 65 $\mu g/m^3$ per year. Table 2-6 summarizes the data.

Table 2-6. Daily weighted average air concentrations (μg/m^3) of beryllium in a U.S. beryllium production plant for four time periods

Department	Approximate number of workers in 1943	Number of jobs in department	beryllium (air) concentration			
			1935–54	1955–64	1965–76	1977–83
Oxide	46	14	46	16	8.8	0.5
Arc furnace room	26	6	80	51	11	0.7
Detroit furnaces	24	4	51	51	33	NA
Foundry	27	5	19	19	13	NA
Melt and cast	105	6	18	18	7.6	1.1
Hot rolling	19	8	9.3	9.3	2.5	0.2
Cold rolling	29	8	9.2	5.7	2.5	0.2
Rod and wire	39	8	5.9	5.9	2.0	0.2
Annealing	10	5	13	13	5.7	0.1
Pickling	11	3	0.2	0.2	0.2	0.1
Machining, grinding	60	5	1.7	1.7	0.9	0.1
Maintenance	73	13	6.2	5.7	3.5	0.1
Inspection	12	7	1.6	1.6	0.9	0.1
Laundry	–	1	2.5	2.5	1.0	0.1
Laboratories, research and development	28	6	1.4	1.4	1.2	1.2
Store, shipping	20	3	3.6	3.6	2.0	0.1

Source: Kriebel *et al.* (1988, cited in IARC 1993).
NA = not applicable; these departments were not operational during 1977–83.

One of the most extensive studies done in the United States to determine occupational exposure levels of beryllium was the Rocky Flats Environmental Technology Sites (RFETS) studies. The RFETS are a part of the U.S. Department of Energy nuclear weapons complex. Beryllium use began in 1953, and beryllium production began in 1957. Barnard and Torma-Krajewski (1994, cited in Stange *et al.* 1996) analyzed two beryllium production buildings to determine beryllium levels between 1984 and 1986. From the random fixed-airhead samples from 1984 to 1986, the mean beryllium exposure level was 0.16 ± 0.33 μg/m^3 (95% CI = 0.10 - 0.22 μg/m^3). The mean beryllium exposure level in personal breathing-zone samples was 1.04 ± 1.25 μg/m^3 (95% CI = 0.79 - 1.29 μg/m^3). There was no correlation between the fixed-airhead and personal breathing-zone results ($r^2 = 0.029$). Table 2-7 summarizes the sampling data from the RFETS.

Table 2-7. Beryllium concentration in samples from two main beryllium production buildings at RFETS

Year	Fixed airhead		Personal breathing zone	
	Number of samples (random sample)	Mean (µg/m^3)	Number of samples	Mean (µg/m^3)
1970	308	0.306	–	–
1971	402	0.358	–	–
1972	430	0.358	–	–
1973	430	0.416	–	–
1974	416	0.228	–	–
1975	432	0.162	–	–
1976	431	0.105	–	–
1977	432	0.121	–	–
1978	431	0.134	–	–
1979	369	0.102	–	–
1980	410	0.156	–	–
1981	426	0.137	–	–
1982	432	0.163	–	–
1983	432	0.271	–	–
1984a	180	0.304	–	–
1984b	243	0.158	33	1.092
1985	396	0.163	51	1.195
1986a	242	0.159	33	0.779
1986b	48	0.039	29	0.092
1987	255	0.034	16	0.189
1988	310	0.045	–	–

Source: Barnard *et al*. (1996).

2.7.2 Machining

The National Institute of Occupational Safety and Health (NIOSH) conducted numerous air surveys to determine beryllium concentrations in various facilities. No detectable concentrations of beryllium were found in areas where machining of beryllium metal and alloys involved drilling, boring, cutting, and sanding (Gilles 1976; Bioana 1980; Lewis 1980, all cited in IARC 1993). During welding, air contamination depended on the type of welding process used and the concentration of beryllium in the compound being welded. The highest beryllium air emissions occurred in argon-arc welding (Bobrischev-Pushkin *et al.* 1975, cited in WHO 1990).

Kreiss *et al*. (1996) examined beryllium exposure measurements in a beryllia ceramics plant. Her group found that the daily weighted average (DWA) for machining processes exceeded that for any other occupation. Quarterly DWAs were estimated by a formula that incorporated average general area, full-shift area, and breathing zone measurements of beryllium. Table 2-8 summarizes these findings.

Table 2-8. Median of quarterly daily weighted averages (DWA) for a beryllia ceramics plant

Job	Dates of jobs	Median DWA ($\mu g/m^3$)	Number of DWA > 2.0 $\mu g/m^3$	Range ($\mu g/m^3$)
Jobs with DWAs over 2.0 $\mu g/m^3$				
Sawer/grinder	10/85 – 3/88	0.9	2	0.4 – 6.8
Lapper	4/88 – 3/92	0.6	2	0.2 – 2.1
Centerless grinder	4/88 – 3/92	0.5	1	0.1 – 8.2
Driller	4/88 – 3/92	0.3	2	0.1 – 4.9
Kiln operator	10/85 – 3/92	0.3	1	0.1 – 14.4
Dicer	4/88 – 3/92	0.1	1	0.1 – 2.2
Jobs with no DWAs over 2.0 $\mu g/m^3$				
Press setup operator	–	0.4	0	0.1 – 1.9
Janitor	–	0.3	0	0.1 – 1.0
Surface grinder	–	0.3	0	0.1 – 1.7
Material preparer	–	0.2	0	0.1 – 1.2
Green machinist	–	0.2	0	< 0.1 – 0.6
Tape operator	–	0.2	0	0.1 – 1.2
Small presser	–	0.1	0	< 0.1 – 0.8
Large presser	–	0.1	0	< 0.1 – 0.6
Isopresser	–	0.1	0	< 0.1 – 0.7
Engineering technician	–	0.1	0	< 0.1 - 0.6
Inspector	–	0.1	0	< 0.1 – 1.9
Front office employee	–	0.1	0	< 0.1 – 0.3
Metallizer	–	< 0.1	0	< 0.1 – 0.1

Source: Kreiss *et al*. (1996).

The median or quarterly DWA for machining processes was 0.9 $\mu g/m^3$, accounting for the majority of quarterly DWAs higher than the OSHA standard of 2.0 $\mu g/m^3$. Kreiss *et al.* (1996) calculated that 8.1% of the machining DWAs were above this OSHA standard.

2.7.3 Other occupational exposure scenarios

Dental laboratory technicians were found to be exposed to beryllium while processing beryllium-containing dental alloys. Dvivedi and Shen (1983, cited in WHO 1990) found that when exhaust extraction was used, beryllium exposure levels averaged 1.75 $\mu g/m^3$. Without exhaust extraction, however, beryllium exposure levels were as high as 74.3 $\mu g/m^3$.

OSHA also identified workers who grind, polish, and finish golf clubs containing a certain beryllium-copper alloy as occupationally exposed to beryllium. The average beryllium breathing-zone concentration of beryllium for these workers ranged from 2 to 14 μg/m^3 (OSHA, personal communication 1989, cited in WHO 1990).

2.8 Biological indices of exposure

Beryllium concentrations can be analyzed by various methods to determine exposure and body burden. While urine analysis may provide evidence of current exposure to beryllium compounds, analysis of blood, serum, or plasma can indicate the level of current exposure (Tsalev and Zaprianov 1984, cited in ATSDR 1993). Measured concentrations of beryllium in bodily fluids have decreased since 1983 probably as a result of better analytical techniques and more efficient ways of limiting beryllium contamination during collection and assay. Urine concentrations from non-occupationally exposed humans, identified by graphite furnace atomic absorption (GFAA), appear to have decreased, from 0.9 $\pm$ 0.4 μg/L (Grewal and Kearns 1977, cited in IARC 1993) to 0.13 μg/L (Paschal and Bailey 1986, cited in IARC 1993). Smoking appears to increase beryllium concentrations in urine. Apostoli *et al.* (1989, cited in IARC 1993) found that heavy smokers have beryllium urine levels (0.31 $\pm$ 0.17 μg/L) significantly higher than those of nonsmokers (0.20 $\pm$ 0.14 μg/L).

In a survey of 66 patients with chronic beryllium disease in the U.S. Beryllium Case Registry, beryllium concentrations ranged from 4 to 45,700 μg/kg dry lung tissue. Of the 66 patients, 82% had beryllium concentrations of more than 20 μg/kg dry weight. Beryllium levels ranging from 2 to 30 μg/kg dry lung tissue were found in 125 lung specimens from these patients during thoracic surgery (Sprince *et al.* 1976, cited in IARC 1993).

An exposure concentration of 2 μg/m^3 of beryllium in the air was found to correspond to beryllium concentrations in human urine and blood of about 7 μg/L and 4 μg/L, respectively. (Zorn *et al.* 1988, cited in IARC 1993).

Beryllium remains in major tissues for long periods, especially the bones and lymph nodes. Elimination of beryllium from the body can take months or years. Table 2-9 summarizes beryllium body burdens (HSDB 1997).

Table 2-9. Beryllium body burdens

Body site	Beryllium Concentration (µg/kg)
Total body burden	36
Soft tissue	24
Kidney	0.2
Liver	1.6
Muscle	0.75
Bone	3.0
Hair	6.0 - 20.0
Blood	0.02 - 3.0[a]
Urine	0.02 - 3.0[a]

Source: HSBD (1997)
[a] µg/L

2.9 Regulations

In 1980, the Consumer Product Safety Commission (CPSC) preliminarily determined that beryllium, beryllium oxide, and beryllium sulfate were not present in consumer products under its jurisdiction. Subsequently, public comment was solicited to verify the accuracy of this information; no comments were received. Pending receipt of new information, the CPSC plans no action on this chemical. In 1973, EPA promulgated a National Emissions Standard for Hazardous Air Pollutants (NESHAP) for extraction and production sites for beryllium and beryllium oxide and for beryllium rocket-motor firing. In 1980, EPA published a water quality criteria document on beryllium for the protection of human health under the Clean Water Act (CWA) and established regulations under the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) for releases of beryllium and beryllium compounds. These regulations were based on the inclusion of beryllium and its compounds on the EPA Carcinogen Assessment Group's list of potential carcinogens. The CERCLA final reportable quantity (RQ) is 10 lb for beryllium and beryllium dust and 1 lb for beryllium chloride and beryllium fluoride. RCRA mandates that wastes known to contain beryllium or beryllium compounds comply with handling and report/recordkeeping requirements. EPA does not plan to regulate beryllium in drinking water under the Safe Drinking Water Act. Beryllium and its compounds are also regulated under the Superfund Amendments and Reauthorization Act (SARA), which subjects them to reporting requirements. U.S. EPA regulations are summarized in Table 2-10.

FDA regulates beryllium in bottled water under the Federal Food, Drug and Cosmetics Act (FD&CA) (see Table 2-11).

The American Conference of Governmental Industrial Hygienists (ACGIH) has classified beryllium as A1, "a confirmed human carcinogen" (ACGIH 1992). NIOSH considers beryllium an occupational carcinogen. NIOSH recommended that exposure to beryllium and beryllium compounds should not exceed 0.5 µg/m^3 (NIOSH 1992). Current OSHA standards for workers exposed to beryllium are: 2 µg/m^3 eight-hr TWA, 5 µg/m^3 ceiling,

and 25 μg/m^3 maximum peak in 30 minutes (see Table 2-12). These standards were adopted by OSHA for toxic effects other than cancer. OSHA has proposed regulating occupational exposure to beryllium, based on its carcinogenicity as well as other toxic effects. OSHA regulates beryllium and certain beryllium compounds under the Hazard Communication Standard and as chemical hazards in laboratories.

Table 2-10. U.S. EPA regulations

U.S. EPA Regulations	
Regulatory action	Effect of regulation and other comments
40 CFR 51.160ff. – SUBPART I – Review of New Sources and Modifications. Promulgated: 51 FR 40669, 11/07/86. U.S. Codes: 101(b)(1), 110, 160-169, 171-178, and 301(a), 42 U.S.C. 7401(b)(1), 7410, 7470-7479, 7501-7508, and 7601(a)); sec. 129(a).	In accordance with the policy of section 101(b)(1) of the act and the purposes of section 160 of the Act, each applicable State implementation plan shall contain emission limitations and such other measures as may be necessary to prevent significant deterioration of air quality. Beryllium emissions must not exceed 0.0004 tons per year.
40 CFR 61 – PART 61 – NATIONAL EMISSION STANDARDS FOR HAZARDOUS AIR POLLUTANTS. Promulgated: 38 FR 8826, 04/06/73. U.S. Codes: 7401, 7412, 7414, 7416, 7601.	This part lists substances that, pursuant to section 112 of the CAA, have been designated as hazardous air pollutants, and applies to the owner or operator of any stationary source for which a standard is prescribed under this part.
40 CFR 61.01 ff. – Subpart A – Lists of pollutants and applicability of part 61. Promulgated: 59 FR 12429, 03/16/94. U.S. Code: 42 U.S.C. 7661.	Substances that, pursuant to section 112 of the CAA, have been designated as hazardous air pollutants. Substances for which a Federal Register notice has been published that included consideration of the serious health effects from ambient air exposure.
40 CFR 61.30 ff. – Subpart C – National Emission Standard for beryllium. Promulgated: 38 FR 8826, 04/06/73. U.S. Code: 7401, 7412, 7414, 7416, 7601. Emissions to the atmosphere from stationary sources subject to the provisions of this subpart shall not exceed 10 grams of beryllium over a 24-hr period (see paragraph [b] of 40 CFR 61.32 for exception to the rule).	The provisions of 40 CFR 61.30 are applicable to machine shops that process beryllium, beryllium oxides, or any alloy containing more than 5 wt. % beryllium, ceramic plants, incinerators, propellant plants that process beryllium ore, alloys, and waste.
40 CFR 61.41 ff. – Subpart D – National Emission Standard for beryllium Rocket Motor Firing. Promulgated: 50 FR 46294, 11/07/85.	The provisions of this subpart are applicable to rocket motor test sites. Emissions to the atmosphere from rocket-motor test sites shall not cause time-weighted atmospheric concentrations of beryllium to exceed 75 μg-min/m^3 of air within the limits of 10 to 60 minutes, accumulated during any 2 consecutive weeks, in any area in which an effect adverse to public health could occur. If combustion products from the firing of beryllium propellant are collected in a closed tank, emissions from such tank shall not exceed 2 g/h and a maximum of 10 grams per day.

U.S. EPA Regulations	
Regulatory action	Effect of regulation and other comments
40 CFR 63 – PART 63 – NATIONAL EMISSION STANDARDS FOR HAZARDOUS AIR POLLUTANTS FOR SOURCE CATEGORIES. Promulgated: 57 FR 61992, 12/29/92. U.S. Codes: 7401 et seq.; CAA.	Standards that regulate specific categories of stationary sources that emit (or have potential to emit) one or more hazardous air pollutants are listed in this part pursuant to section 112(b) of the CAA.
40 CFR 63.70 – Subpart D – Regulations Governing Compliance Extensions for Early Reductions of Hazardous Air Pollutants. Promulgated: 59 FR 53110, 10/21/94.	The provisions of this subpart apply to an owner/operator of an existing source wishing to obtain a compliance extension from a standard issued under section 112(d) of the CAA. Beryllium is listed as a high-risk pollutant with a weighting factor of 10.
40 CFR 63.800ff. – Subpart JJ – National Emission Standards for Wood Furniture Manufacturing Operations. Promulgated: 60 FR 62936, 12/07/95.	The provisions of this subpart apply to each facility that is engaged in the manufacture of wood furniture or wood furniture components and that is a major source as defined in 40 CFR 63.2. Beryllium salts and beryllium compounds are prohibited from use in cleaning and wash-off solvents.
40 CFR 116 – PART 116 – DESIGNATION OF HAZARDOUS SUBSTANCES. Promulgated: 43 FR 10474, 03/13/1978. U.S. Codes: 33 U.S.C. 1251 et seq.	This regulation designates hazardous substances under section 311(b)(2)(a) of the FWPCA. The regulation applies to discharge of the substances identified in table 116.4 to surface waters. Beryllium fluoride, chloride, and nitrate were classified in this section as hazardous substances.
40 CFR 117 – PART 117 – DETERMINATION OF REPORTABLE QUANTITIES FOR HAZARDOUS SUBSTANCES. Promulgated: 44 FR 50776, 08/29/79. U.S. Codes: FWPCA 311(b)(2)(A) and 501(a).	Discharges to water of amounts equal to or greater than the RQ must be reported to U.S. EPA. Reportable quantity (RQ) for environmental releases to water is 1 lb (0.454kg) for Beryllium fluoride, chloride, and nitrate.
40 CFR 122 – PART 122 – U.S. EPA ADMINISTERED PERMIT PROGRAMS: THE NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM. Promulgated: 48 FR 14153, 04/01/83. U.S. Code: 33 U.S.C. 1251 et seq., CWA.	Regulations cover basic U.S. EPA permitting requirements for effluent discharges from point sources to waters of the United States. Appendix D lists pollutants that must be identified by dischargers if expected to be present.
40 CFR 141 – PART 141 – NATIONAL PRIMARY DRINKING WATER REGULATIONS. Promulgated: 40 FR 59570, 12/24/75. U.S. Codes: U.S.C. 300.	To protect a safe drinking water supply, community and non-transient, non-community water systems must monitor for certain compounds listed.
40 CFR 141.21 ff. – SUBPART C – Monitoring and Analytical Requirements. Promulgated: 60 FR 34085, 06/29/95.	States that Atomic absorption (platform and furnace) and Inductively coupled plasma (along with mass spectrometry) should be used to analyze Beryllium levels in drinking water. Detection limits and RCLs are given.

U.S. EPA Regulations	
Regulatory action	Effect of regulation and other comments
40 CFR 141.31 ff. – Subpart D – Reporting, Public Notification and Record keeping. Promulgated: 59 FR 53110, 10/21/94.	A supplier of water shall report to the State the results of any test measurement or analysis required by this part. This part gives background information on several compounds with health concerns at certain levels of exposure. U.S. EPA has set the drinking water standard for beryllium at 0.004 ppm to protect against the risk of these adverse health effects.
40 CFR 141.50 ff. – Subpart F – Maximum Contaminant Level Goals. Promulgated: 50 FR 46901, 11/13/85.	The MCLG for beryllium in primary drinking water is 0.004 mg/L.
40 CFR 141.60 ff. – Subpart G – National Revised Primary Drinking Water Regulations: Maximum Contaminant Levels. Promulgated: 60 FR 33932, 06/29/95.	Revised maximum contaminant levels for beryllium in drinking water is 0.004 mg/L.
40 CFR 142 – PART 142 – NATIONAL PRIMARY DRINKING WATER REGULATIONS IMPLEMENTATION. Promulgated: 41 FR 2918, 01/20/1976. U.S. Code: 42 U.S.C. 300g, 300g-1, 300g-2, 300g-3, 300g-4, 300g-5, 300g-6, 300j-4, and 300j-9;	This part sets forth regulations for the implementation and enforcement of the national primary drinking water regulations contained in part 141 of this chapter.
40 CFR 172 – SUBPART B – Table of Hazardous Materials and Special Provisions. Promulgated: 61 FR 50623, 50624, 09/26/96. The reportable quantity for beryllium, beryllium chloride and beryllium compounds is 10 lb (4.54 kg). The reportable quantity for beryllium fluoride and beryllium nitrate is 1 lb (0.454 kg).	The Hazardous Materials Table in this section designates beryllium and beryllium compounds as hazardous materials for the purpose of transportation of those materials. beryllium's identification number is UN 1567; beryllium nitrate is UN 2464, and beryllium compounds is UN 1567.
40 CFR 192 – PART 192 – HEALTH AND ENVIRONMENTAL PROTECTION STANDARDS FOR URANIUM AND THORIUM MILL TAILINGS. Promulgated: 48 FR 602, 01/05/1983. U.S. Codes: 42 U.S.C. 2022, as added by the Uranium Mill Tailings Radiation Control Act of 1978. Appendix 1 lists beryllium and beryllium compounds as constituents that need to be monitored.	The provisions of this part control the residual radioactive material at designated processing or depository sites under section 108 of the Uranium Mill Tailings Radiation Control Act of 1978, and applies to the restoration of such sites following any use of the subsurface minerals under section 104(h) of the Uranium Mill Tailings Radiation Control Act of 1978.
40CFR192.40 ff. – Subpart E – Standards for Management of Thorium Byproduct Materials Pursuant to Section 84 of the Atomic Energy Act of 1954, as Amended. Promulgated: 48 FR 45947, 10/07/83.	RCRA Appendix VIII hazardous waste constituents are regulated by reference in this part.
40 CFR 228 – PART 228 – CRITERIA FOR THE MANAGEMENT OF DISPOSAL SITES FOR OCEAN DUMPING. Promulgated: 42 FR 2482, 01/11/1977. U.S. Codes: 33 U.S.C. 1412 and 1418.	The criteria of this part apply to the evaluation of proposed ocean dumping under Title I of the Act, and effective management of ocean disposal sites to prevent unreasonable degradation of the marine environment from all wastes being dumped in the ocean.

U.S. EPA Regulations	
Regulatory action	Effect of regulation and other comments
40 CFR 258 – PART 258 – CRITERIA FOR MUNICIPAL SOLID WASTE LANDFILLS. Promulgated: 56 FR 51016, 10/09/91. U.S. Codes: 33 U.S.C. 1345(d) and (e); 42 U.S.C. 6907(a)(3), 6912(a), 6944(a) and 6949a(c).	The provisions of this part establish minimum national criteria under RCRA, as amended, for all MSWLF units and under the CWA, as amended, for MSWLF that are used to dispose of sewage sludge. The criteria ensure the protection of human health and the environment. Suggested methods of detecting beryllium and beryllium compounds in sewage sludge are U.S. EPA methods 6010 (PQL = 3 mg/L), 7090 (PQL = 50 mg/L), and 7091 (PQL = 2 mg/L).
40 CFR 261 – PART 261 - IDENTIFICATION AND LISTING OF HAZARDOUS WASTE. Promulgated: 45 FR 33119, 05/19/80. U.S. Codes: 42 U.S.C. 6905, 6912(a), 6921, 6922, 6924(y) and 6938.	This part identifies those solid wastes which are subject to regulation as hazardous wastes under parts 262 through 265, 268, and parts 270, 271, and 124 of this chapter and which are subject to the notification requirements of section 3010 of RCRA. General exclusion levels for K061, K062, and F006 non-wastewater HTMR residues for beryllium is 0.010 mg/L.
40 CFR 261.30ff. – Subpart D – Lists of Hazardous Wastes. Promulgated: 55 FR 11863, 03/29/90.	The U.S. EPA Hazardous waste number for beryllium powder is P015.
40 CFR 264 – PART 264 – STANDARDS FOR OWNERS AND OPERATORS OF HAZARDOUS WASTE TREATMENT, STORAGE, AND DISPOSAL FACILITIES. Promulgated: 45 FR 33221, 05/19/80. U.S. Codes: 42 U.S.C. 6905, 6912(a), 6924, and 6925.	The purpose of this part is to establish minimum national standards that define the acceptable management of hazardous waste. The standards in this part apply to owners and operators of all facilities which treat, store, or dispose of hazardous waste, except as specifically provided otherwise in this part or part 261 of this chapter.
40 CFR 264.1200ff. – SUBPART EE – Hazardous Waste Munitions and Explosives Storage. Promulgated: 62 FR 6652, 02/12/97.	The requirements of this subpart apply to owners or operators, who store munitions and explosive hazardous wastes, except as §264.1 provides otherwise. The suggested method of detecting beryllium in groundwater is U.S. EPA method 6010 (PQL = 3 mg/L).
40 CFR 265.1200 ff. – SUBPART EE – Hazardous Waste Munitions and Explosives Storage. Promulgated: 62 FR 6653, 01/12/97.	The purpose of this subpart is to outline design and operating standards where munitions and explosive hazardous waste, including compounds containing beryllium and beryllium compounds, are stored.
40 CFR 266.100 ff. – Subpart H – Hazardous Waste Burned in Boilers and Industrial Furnaces. Promulgated: 56 FR 7208, 02/21/91.	Appendix V of Part 266 lists a risk specific dose of 4.2×10^{-3} $\mu g/m^3$ for beryllium.
40 CFR 268 – PART 268 – LAND DISPOSAL RESTRICTIONS. Promulgated: 62 FR 26019, 05/12/ 97. U. S. Codes: 42 U.S.C. 6905, 6912(a), 6921, and 6924.	This part identifies hazardous wastes that are restricted from land disposal and defines those limited circumstances under which an otherwise prohibited waste may continue to be land disposed.

U.S. EPA Regulations	
Regulatory action	Effect of regulation and other comments
40 CFR 268.40ff. – SUBPART D – Treatment Standards. Promulgated: 62 FR 32979, 06/17/97.	Prohibited waste identified in the table "Treatment Standards for Hazardous Wastes" may be land disposed only if it meets the requirements found in the table. Water disposal requires that it meat certain hazardous waste concentration requirements. beryllium wastewater standard is 0.082 mg/L while the non-wastewater standard is 0.014 mg/L.
40 CFR 302 – Part 302 – Designation, Reportable Quantities, And Notification. Promulgated: 50 FR 13474, 04/04/85. U.S. Codes: 42 U.S.C. 9602, 9603, and 9604; 33 U.S.C. 1321 and 1361. beryllium and beryllium compounds have a regulatory RQ of 1lb (0.454 kg) which was set by CERCLA. No final RQ was set because this is a broad category of compounds.	This part designates under section 102(a) of CERCLA 1980 those substances in the statutes referred to in section 101(14) of CERCLA, identifies reportable quantities for these substances, and sets forth the notification requirements for releases of these substances. This part also sets forth reportable quantities for hazardous substances designated under section 311(b)(2)(A) of the CWA.
40 CFR 372 – PART 372 – TOXIC CHEMICAL RELEASE REPORTING: COMMUNITY RIGHT-TO-KNOW. Promulgated: 53 FR 4525, 02/16/88. U.S. Codes: 42 U.S.C. 11013, 11028. Effective date for beryllium is 1/1/87.	This part sets forth requirements for the submission of information relating to the release of toxic chemicals under section 313 of Title III of SARA (1986). Information collected under this part is intended to inform the general public and the communities surrounding covered facilities about releases of toxic chemicals, to assist research, to aid in the development of regulations, guidelines, and standards.
40 CFR 401 – PART 401 – GENERAL PROVISIONS. Promulgated: 47 FR 24537, 06/04/82. U.S. Codes: 33 U.S.C. 1251 et seq.	The provisions of this part set forth the legal authority and general definitions which will apply to all regulations issued concerning specific classes and categories of point sources of industrial effluents under parts 402 through 699. In this section beryllium and beryllium compounds are identified as a toxic pollutant by the Federal Water Pollution Control Act.
40 CFR 403 – PART 403 – GENERAL PRETREATMENT REGULATIONS FOR EXISTING AND NEW SOURCES OF POLLUTION. Promulgated: 46 FR 9439, 01/28/81. U.S. Codes: Several sections of the FWPCA and the CWA of 1977 (Public Law 95-217).	Establishes responsibilities of federal, state, and local government; industry; and the public to implement National Pretreatment Standards to control pollutants that pass through POTWs and contaminate sewage sludge or interfere with treatment processes.
40 CFR 403.18 – Sec. 403.18 Modification of POTW Pretreatment Programs. Promulgated: 53 FR 40615, 10/17/88	Appendices list 65 Toxic Pollutants, including beryllium, (51 FR 20431, 06/04/86) and industrial categories subject to National Categorical Pretreatment Standards (51 FR 20429, 06/04/86).
40 CFR 421 – PART 421 – NONFERROUS METALS MANUFACTURING POINT SOURCE CATEGORY. Promulgated: 49 FR 8790, 03/08/84. U.S. Codes: 33 U.S.C. 1311, 1314(b), (c), (e), and (g), 1316(b) and (c), 1317(b) and (c), 1318, and 1361.	The provisions of this part apply to facilities producing primary metals from ore concentrates and recovering secondary metals from recycle wastes which discharge pollutants to waters of the U.S. or which introduce or may introduce pollutants into a POTW.

U.S. EPA Regulations	
Regulatory action	Effect of regulation and other comments
40 CFR 421.150 ff. – SUBPART O - Primary beryllium Subcategory. Promulgated: 50 FR 38346, 09/20/85.	The provisions of this subpart are applicable to discharges resulting from the production of beryllium by primary beryllium facilities processing beryllium ore concentrates or beryllium hydroxide raw materials. Effluent limitations are given in the subsequent sections.
40 CFR 423 – PART 423 – STEAM ELECTRIC POWER GENERATING POINT SOURCE CATEGORY. Promulgated: 47 FR 52304, 11/19/82. U.S. Codes: 33 U.S.C. 1311; 1314(b), (c), (e), and (g); 1316(b) and (c); 1317 (b) and (c); and 1361.	The provisions of this part apply to discharges resulting from the operation of a generating unit by an establishment generating electricity for distribution and sale which results from a process utilizing fossil-type or nuclear fuel in conjunction with a thermal cycle that uses the steam water system as the thermodynamic medium.
40 CFR 468 – PART 468 – COPPER FORMING POINT SOURCE CATEGORY. Promulgated: 48 FR 36957,08/15/83. U.S. Code: 33 U.S.C. 1311, 1314(b), (c), (e), and (g), 1316(b) and (c), 1317(b) and (c), and 1361.	The provisions of this part apply to discharges resulting from the manufacture of formed copper and copper alloy products.

Source: The regulations in this table have been updated through the 1998 Code of Federal Regulations 40 CFR, July 1, 1996; 21 CFR, April 1, 1996; 29 CFR, July 1, 1996

Table 2-11. FDA regulations

FDA Regulations	
Regulatory action	Effect of regulation and other comments
21CFR165-- PART 165--BEVERAGES. Promulgated: 60 FR 57124, 11/13/95 effective 5/13/96. U.S. Code: 21 U.S.C. 321, 341, 343, 343A, 348, 349, 371, 379e.	The regulations in subparts A and B govern the labeling and effective chemical substance limits for specific standardized beverages.
21CFR165.110 ff-- Subpart B--Requirements for Specific Standardized Beverages-- Bottled water: Allowable concentration of beryllium in bottled water is 0.004 mg/L. The levels for beryllium are stayed until further notice.	Allowable concentrations for inorganic substances, volatile organic chemicals (VOCs) and other chemical substances are given in this subpart.

Source: The regulations in this table have been updated through the 1998 Code of Federal Regulations 40 CFR, July 1, 1996; 21 CFR, April 1, 1996; 29 CFR, July 1, 1996

Table 2-12. OSHA regulations for beryllium and beryllium compounds

OSHA Regulations	
Regulatory action	Effect of regulation and other comments
29 CFR 1910.1000—Sec. 1910.1000 Air Contaminants. Promulgated: 58 FR 40191, 07/27/93. OSH Act: Air Contaminants.	As beryllium, PEL 2 μg/m^3 8-hr TWA; 5 μg/m^3 ceiling; 25 μg/m^3 maximum peak for 30 min.
29 CFR 1910.1200, 1915, 1917, 1918, 1926, 1928. Promulgated: 61 FR 9245, 03/07/96. OSH Act: Hazard Communication.	Requires chemical manufacturers and importers and all employers to assess chemical hazards and to provide information to employees. Hazard Communication Program to include labels, material safety data sheets, and worker training.
29 CFR 1910.1450—Sec. 1910.1450 Occupational Exposure to Hazardous Chemicals in Laboratories. Promulgated: 61 FR 5508, 02/13/96. OSH Act: Final rule for occupational exposure to hazardous chemicals in laboratories.	As select carcinogens (IARC Group 2A), beryllium and certain beryllium compounds are included as chemical hazards in laboratories. Employers are required to provide employee information and training and a Chemical Hygiene Plan.
29 CFR 1926.55(a)—Sec. 1926.55 Safety and Health Regulations for Construction. Promulgated: 39 FR 22801, 07/24/74. OSH Act: Final Standard (Construction Industry).	PEL 2 μg/m^3 8-hr TWA.

Source: The regulations in this table have been updated through the 1998 Code of Federal Regulations 40 CFR, July 1, 1996; 21 CFR, April 1, 1996; 29 CFR, July 1, 1996

3 Human Cancer Studies

Beryllium and beryllium compounds were classified as carcinogenic to humans when evaluated by IARC (1993). Since the IARC review, three new epidemiologic studies of cancer among beryllium-exposed workers (Rooney *et al.* 1993; Wing *et al*. 1993; Loomis and Wolf 1996) and one study describing an autopsy case-series of workers with chronic beryllium disease (Williams 1996) have been published. The quality of the epidemiologic evidence concerning beryllium has improved in the last decade. Nevertheless, the absence of quantitative information on exposures to beryllium remains an important limitation of the current literature. Four other reviews of epidemiologic studies, relevant to the carcinogenicity of beryllium, were also published after the IARC evaluation (Boffetta 1993; MacMahon 1994; Steenland *et al*. 1996; Hayes 1997). Most support the conclusions of the 1993 IARC monograph (Boffetta 1993; Steenland *et al*. 1996; Hayes 1997), but MacMahon (1994) criticized the conclusion that beryllium is carcinogenic, citing cigarette smoking as an alternative explanation. Interpretations of recent evidence on beryllium have also been offered in editorials and published letters (Saracci 1991; Eisenbud 1993; Steenland and Ward 1991; BISAC 1997; Vainio and Rice 1997).

This section summarizes the content and conclusions of the IARC Working Group's 1993 evaluation of beryllium and presents key findings of relevant epidemiologic studies published since that review.

3.1 IARC Evaluations

Human studies on the carcinogenicity of beryllium and beryllium compounds have been reviewed by four IARC Working Groups (IARC 1972, 1980, 1987, and 1993). The 1980 Working Group characterized the human evidence of carcinogenicity available at that time as limited. No new human studies were available when beryllium was next evaluated in 1987. The 1993 evaluation incorporated two cohort studies and a nested case-control study published since the previous review. After taking this new evidence into account, the Working Group classified beryllium and beryllium compounds as human carcinogens, based on sufficient evidence in epidemiologic studies of exposed workers.

The IARC Working Group summarized the human evidence of carcinogenicity in 1993 (IARC 1993). Early retrospective cohort mortality studies showed a consistent excess of deaths from lung cancer (Mancuso 1979; Mancuso 1980; Wagoner *et al*. 1980; all cited in IARC 1993).

The first study followed mortality through 1975 among a cohort of white men employed at two beryllium extraction, production, and fabrication facilities in the United States between 1942 and 1948. The standardized mortality ratio (SMR) for lung cancer was 1.8 (95% CI 1.2 - 2.7) among 1,222 men employed in one plant and 1.25 (95% CI 0.9 - 1.7) for 2,044 men in the other plant. The combined SMR for lung cancer in the two plants was 1.42 (95% CI 1.1 - 1.8) (Mancuso 1979; cited in IARC 1993). The excess of lung cancer was greatest for men employed during the period when exposures were highest,

before 1949, and increased with time since exposure: workers followed at least 15 years had lung cancer SMRs of 2.0 (95% CI 1.3 - 3.1) and 1.5 (95% CI 1.0 - 2.1) in the two plants. The SMRs cited in the IARC Working Group incorporate an adjustment for the lack of national mortality data for the years 1965-67. This study did not include analyses of mortality by job title or exposure category.

A subsequent re-analysis of mortality in the two plants by the same author expanded the period of employment to 1937-48, and used a cohort of viscose rayon workers, rather than the general population, as a referent group (Mancuso 1980; cited in IARC 1993). The SMR for lung cancer among the 3,685 workers in both plants was 1.40 ($P < 0.01$). The SMR for lung cancer was highest among men employed the longest in the beryllium plants, but did not increase steadily with duration of employment among men with shorter tenure: the lung cancer SMR was 1.38 (n = 52; $P < 0.05$) for $\leq$1 year, 1.06 (n = 14) for 1- 4 years, and 2.22 (n = 14; $P < 0.01$) for > 4 years (Mancuso 1980; cited in IARC 1993).

Wagoner *et al.* (1980; cited in IARC 1993) conducted an expanded study of mortality among workers at one of the two plants studied previously (Mancuso 1979, 1980), including men employed 1942-1967. Among the 3,055 workers, the SMR for lung cancer was 1.25 (95% CI 0.9 - 1.7). The Working Group noted that the average exposure in this cohort may have been lower than in previous studies because the study period extends across the year 1949, when levels of beryllium in workplaces were reduced markedly by a new exposure limit. The risk of lung cancer increased with latency, from 0.88 among workers with < 15 years latency, to 1.16 for 15 - 24 years' latency, and 1.68 (95% CI 1.0 - 2.6) for ≥ 25 years' latency. The investigators attempted to assess potential confounding by smoking using indirect adjustments. The IARC Working Group noted that these adjustments suggested the possibility of bias in opposite directions: estimates of smoking prevalence from a survey of a portion of the cohort suggested that smoking practices could have increased the workers' risk of lung cancer by 14% in the absence of any effect of beryllium, while local lung cancer rates suggested that the use of national rates in the analysis may have underestimated the risk by 19% (Wagoner *et al.* 1980; cited in IARC 1993).

Infante *et al.* (1980, cited in IARC 1993) analyzed the mortality of white men enrolled in a beryllium case registry with a diagnosis of chronic beryllium disease or acute beryllium-induced pneumonitis. The registry was established in 1952 to characterize the epidemiology and clinical features of beryllium -related diseases, and the participants had been employed in a variety of industries, primarily beryllium extraction and smelting, metal production, and fluorescent tube production. Among 421 white males enrolled between 1952 and 1975, there were 7 deaths from lung cancer, yielding an SMR of 2.12, based on 1952 to 67 national mortality rates. The Working Group estimated that adjustment for the gap in U.S. mortality data between 1968 and 1975 would alter the SMR to 1.93 (95% CI 0.8 - 4.0). Most of the lung cancer deaths (6 cases) occurred among men enrolled with a diagnosis of acute beryllium-induced pneumonitis; the corrected SMR for this group was 2.98 (95% CI 1.0 - 6.2). The Working Group noted

that exposures were likely to have been higher among workers with beryllium-related acute pneumonitis than among men with chronic beryllium disease (IARC 1993).

The 1993 IARC evaluation also included two later cohort studies. Ward *et al.* (1992) followed the mortality through 1988 of 9,225 male workers (8,905 white, 320 non-white) employed as early as 1935 at seven beryllium plants in the U.S.A., including the two studied previously. Mortality from all causes and all cancers was essentially as expected, while the SMR for lung cancer was 1.26 (95% CI 1.12 - 1.42) and for non-malignant respiratory disease the SMR was 1.48 (1.21 - 1.80). Lung cancer mortality increased with time since exposure (latency), but not with duration of employment. Although lung cancer mortality was highest in the oldest plant and in the 1940s, when exposures were highest, excess lung cancer was also observed in other plants and for workers hired in the 1940s. Mortality from cancers at sites other than the lung was not increased. The investigators performed adjustments based on the use of local, rather than national, death rates and on partial data on smoking in the cohort and concluded that neither could account for the excess risk of lung cancer (Ward *et al*. 1992).

Steenland and Ward (1991) expanded the analysis of mortality in the previously studied U.S. Beryllium Case Registry to include 689 women and men of all races enrolled 1952 to 1980 and extended the follow-up of mortality through 1988. The SMR for lung cancer was 2.00 (n = 28, 95% CI 1.33 - 2.89). This excess was greater in those who were entered into the Registry with acute beryllium pneumonitis (SMR 2.32, 95% CI 1.35 - 3.72). The prevalence of smoking among cohort members surveyed in 1965 was lower than average for the U.S. population, so the authors concluded that smoking was unlikely to explain the increased risk for lung cancer (Steenland and Ward 1991).

Two case-control studies were included in the IARC (1993) review. Hinds *et al.* (1985) used a computerized job-exposure matrix to assess occupational exposures in a population-based study of incident lung cancer in Hawaii. Between 1979 and 1982, 261 new cases of primary lung cancer were diagnosed among males (race not given). Lung cancer was associated with occupational exposure to beryllium (OR 1.62, 95% CI 1.04 - 2.51 and 1.57, 95% CI 0.81 - 3.01 for low and high beryllium exposures, respectively, relative to no exposure).

Carpenter *et al.* (1988) conducted a nested case-control study of 89 men and women with cancer of the central nervous system, each matched to four controls, among workers at two nuclear facilities at Oak Ridge, Tennessee. Exposures to 26 chemicals, including beryllium were assessed by job title and expert judgement. The odds ratio for "ever having been exposed to beryllium" was 1.5 (95% CI 0.6 - 3.9). The strength of the association increased with both presumed exposure level and latency, but the precision of the estimated ORs was limited.

The IARC Working Group emphasized several aspects of the most recent cohort studies in order to justify their conclusion that the environment of workers producing, refining and machining beryllium and beryllium alloys is causally related to lung cancer: 1) the statistical stability of the association; the consistency of the association across several

plants and populations; 2) the greater risk among workers hired before exposure controls were introduced; 3) the increasing risk with longer latency; 4) the increased risk in plants where the risk of beryllium-related non-malignant respiratory disease was highest, and 5) the increased risk among members of the Beryllium Case Registry with beryllium-related lung disease.

Key limitations of these studies noted by the Working Group are the absence of quantitative, individual measurements of exposure to beryllium and other occupational agents and the relatively low excess risk of lung cancer.

3.2 Current epidemiologic studies

Two case-control studies and two cohort studies published since the IARC review provide some additional information about the carcinogenicity of beryllium.

3.3 Case-control studies

Rooney *et al.* (1993) conducted a case-control study of prostate cancer incidence and mortality in 1946-86 among men employed by the United Kingdom Atomic Energy Authority (UKAEA). In this study, 136 men with prostate cancer were matched to 404 control men by age and calendar year of first employment, survival time, last place of employment, and monitoring for internal exposure to radionuclides. Individual information about social and demographic characteristics, work history, and internal exposures to radionuclides was abstracted from UKAEA records. Exposures to specific radionuclides and other potential hazards, including beryllium, were assessed by expert judgement based on work areas. A history of work in locations where beryllium was potentially present was found in 5% of the cases and 6% of the controls, yielding an odds ratio of 0.87 (95% CI 0.03 - 2.17)

The Children's Cancer Group (Buckley *et al.* 1998) conducted a case-control study of environmental and familial factors in the etiology of Ewing's sarcoma and osteosarcoma in children based on parental exposure to beryllium. Patients were identified in the registration data of the Children's Cancer Group. The osteosarcoma patients selected were less than 18 years of age and were diagnosed between January 1, 1982 and December 31, 1983. Children with Ewing's sarcoma were younger than 21 years and diagnosed between January 1, 1983 and July 30, 1985. Interviews with parents were conducted between October 1983 and February 1987. The studies were conducted separately, hence the different accrual periods and age eligibilities. However, the design and study questionnaires for each study were kept similar to facilitate comparisons. The parents of 152 children with osteosarcoma and 153 children with Ewing's sarcoma were interviewed by telephone, with controls obtained by random digit dialing, and matched to cases by age and race. This study did not find any important risk factors for either type of childhood bone tumor. No occupational category or specific exposure was associated with the occurrence of bone tumors. Although beryllium was of interest, no clear associations between maternal or paternal occupational exposures and osteosarcoma in offspring could be identified. There was no difference between cases and controls for maternal or paternal exposures to metals, welding, soldering, or mining and

manufacturing. For maternal exposure to metals, the OR for osteosarcoma was 3.50 (P = 0.11), and for Ewing's sarcoma, 1.12 (P = 0.81). For paternal exposure to metals, the OR for osteosarcoma was 0.74 (P = 0.34), and for Ewing's sarcoma, 1.09 (P = 0.77) (Buckley *et al.* 1998).

3.4 Cohort studies

Two recent cohort studies of U.S. nuclear workers also included workers exposed to beryllium. Wing *et al.* (1993) evaluated the association of all cancer with job titles and exposures to beryllium, mercury, and lead among white men employed at Oak Ridge National Laboratory in the United States. The primary goal of the study was to gauge whether other occupational exposures could explain previously-reported associations of cancer with exposure to ionizing radiation among the cohort. No information on the level of non-radiation exposures was available, but 609 workers were known to have worked with beryllium. Mortality from all cancers combined was increased 38% among these workers, who were almost exclusively nonsmokers. No data were presented for lung cancer or other specific cancers in relation to beryllium exposure.

Loomis and Wolf (1996) analyzed mortality among men and women of all races employed at the Y-12 nuclear materials production plant from 1947 and 1974 and followed through 1990. The plant was one of those studied previously by Carpenter *et al.* (1988); beryllium was known to have been used, but no quantitative measurements of exposure were available. Lung cancer mortality was elevated among all workers at the plant (SMR 1.17, 95% CI 1.01 - 1.34) and among the white males (SMR 1.20, 95% CI 1.04 - 1.38). The risk was highest among workers hired from 1947 to 54 and among those with 10 to 29 years latency and 5 to 19 years of employment. Lung cancer mortality was quantitatively associated with cumulative radiation dose in a previous study of the plant.

3.5 Other studies

Williams (1996) reported on a case-series of 30 workers in the United Kingdom who had died from chronic beryllium disease. The majority of the workers were fluorescent lamp workers and machinists who died from respiratory failure. Autopsies were conducted on 19 of the workers: most showed interstitial pulmonary fibrosis with varying degrees of cystic change, but no lung cancers were found.

3.6 Discussion

The quality of the epidemiologic evidence on the carcinogenicity of beryllium has improved substantially in the last decade. Early studies suggested an association of lung cancer with exposure to beryllium, but were limited by small numbers, short follow-up intervals, problems in estimating expected numbers of deaths due to missing national mortality data, and lack of direct measurements of exposure to beryllium and potential confounders. These problems have been addressed in recent studies. The remaining weakness of these studies is the absence of quantitative information on individual exposure; this is as likely to attenuate as to inflate observed risks.

The two cohort studies published from 1987 to 1993 strengthen the evidence for carcinogenicity. The study by Ward *et al.* (1992) represents a particularly significant advance relative to earlier efforts, with substantial increases in sample size and follow-up time, a larger number of plants, and use of appropriate referent mortality rates in the analysis. As in earlier research, the absence of information on beryllium exposure remained a key limitation in this study. Nevertheless, the results are consistent internally and externally, and the patterns of risk are consistent with a causal association between beryllium and lung cancer risk.

The results of cohort studies published after the 1993 IARC review (Wing *et al*. 1993; Loomis and Wolf 1996) are consistent with earlier findings, but add relatively little new evidence specifically concerning beryllium. Both studies focused on nuclear workers in facilities where beryllium was used in conjunction with other chemicals and where exposures to ionizing radiation were documented. One of the studies (Wing *et al*. 1993) examined the mortality of a group of workers known to have worked with BE and found evidence of increased mortality from cancer among them. However, neither study included quantitative information on beryllium exposures, which would play an important part in efforts to separate the effects of beryllium from those of radiation and other agents.

The population in the case-control study by Rooney *et al.* (1993) likewise included nuclear workers with exposures to multiple chemicals and ionizing radiation. This study's assessment of exposure to beryllium by expert judgement represents an improvement relative to other studies with no information about exposure. However, the study considered only prostate cancer, which has not been associated with beryllium exposures in previous studies. The negative results of this study for beryllium are therefore consistent with expectations.

The case-series study of individuals with chronic beryllium disease reported by Williams (1996) differs in design from earlier follow-up studies of participants in a beryllium disease registry (Infante *et al*. 1980; Steenland and Ward 1991). No lung cancer was identified among the beryllium workers studied by Williams. However, the study did not include information about age and follow-up time, which would be needed to calculate mortality rates and expected numbers of deaths. Given the small size of the series (n = 30), the expected number of lung cancer cases may have been close to zero. In addition, the series was limited to workers with chronic beryllium disease, which was associated with lower rates of lung cancer in earlier studies, relative to acute beryllium disease.

Critiques of the recent epidemiologic literature on beryllium and cancer have cited the inability to control directly for cigarette smoking in any of the studies as a critical limitation (MacMahon 1994; BISAC 1997). Confounding by smoking is a potential threat to validity in any study of the role of occupational exposures in lung cancer, particularly when the magnitude of the association is modest. In the case of beryllium, however, no evidence has been presented to indicate that the prevalence of smoking in any of the exposed cohorts was substantially greater than in the referent population. In the absence

of such evidence, arguments that smoking is the most likely explanation for the observed associations (MacMahon 1994) are speculative.

Tobacco smoke may, however, be of concern as a potential modifier of the effect of beryllium. For some occupational lung carcinogens, notably asbestos and radon, the risk of cancer is markedly increased among exposed smokers. It is not currently possible to evaluate this relationship for beryllium because of the absence of individual information on beryllium exposure and smoking.

Exposure to sulfuric acid mists has also been proposed as an alternative explanation for excess lung cancer among beryllium workers (BISAC 1997). Sulfuric acid has been designated as a *human carcinogen* by IARC and was used in one beryllium plant that had a large influence on the results of studies by Mancuso (1979; 1980) and Ward *et al.* (1992). However, excess lung cancer was also observed in facilities that did not employ the sulfuric acid process used in that plant (Wagoner 1980; Ward *et al*. 1992). Moreover, the finding that lung cancer risk is significantly increased among workers with beryllium disease and that the risk appears to increase with the intensity of beryllium exposure supports a conclusion that beryllium is causally related to lung cancer risk. Finally, although exposure to sulfuric acid mists is associated with laryngeal cancer, the evidence supporting a relationship to lung cancer is weak (Sathiakumar *et al.* 1997).

Thus, the epidemiologic evidence as a whole supports a conclusion that beryllium is carcinogenic to humans. Although the reported increases in cancer risk are relatively modest, they have been observed consistently in most locations studied. Small increases in risk may result from dilution of an effect by poor specificity in classifying exposure. Existing studies of populations exposed to beryllium have used relatively crude exposure classifications, generally treating all workers in a plant as exposed, although some may have had no contact with beryllium. Risks may be larger among truly-exposed workers. This interpretation is supported by the risk of lung cancer among individuals with beryllium-related disease, whose exposure to beryllium is known. In general, cancer risks do not appear to increase with duration of employment in beryllium-processing facilities. However, the temporal patterns of risk observed in studies of beryllium worker cohorts and persons with beryllium-related lung disease suggest that excess lung cancer may have been associated with intense, short-term exposures, rather than with long-term, low-level exposures. Epidemiologic studies of workers exposed to beryllium also suggest that the risk of cancer increases with time since exposure to beryllium (latency), a pattern that is consistent with a causal role.

Table 3-1. Current case-control studies of cancer

Reference	Study Design	Population	Exposure	Effects	Potential Confounders
Rooney *et al.* (1993) United Kingdom	Case-control	136 men with prostate cancer diagnosed from 1946 to 1986 and 404 matched controls, all employees of United Kingdom Atomic Energy Authority.	Individual work history and radiation exposure were abstracted from Atomic Energy Authority records. Exposure to beryllium was assessed by expert judgement, according to work location. Exposure levels were ranked as: none or unlikely; probable but relatively low level, or probable and relatively high level. If probable, calendar years and frequency of exposure recorded.	Risk of prostate cancer associated with working in places assessed to be potentially contaminated with beryllium RR=0.87 (0.30 - 2.17), relative to never having worked in a place potentially contaminated with relevant substance or radiation.	Multiple exposures (15 specific radionuclides, 6 metals, 3 groups of chemicals, 3 physical agents, 7 other types of radiation).
Buckley *et al.* (1998) U.S.A.	Case-control	152 children with osteosarcoma and 153 children with Ewing's sarcoma. Patients were identified in the registration data of the Children's Cancer Group. Patients with osteosarcoma who were younger than 18 years and diagnosed from January 1, 1982 to December 31, 1983 were selected. Children with Ewing's sarcoma were younger than 21 years and diagnosed from January 1, 1983 to July 30, 1985.	Parents of cases were interviewed by telephone. Controls were obtained by random digit dialing and matched to cases by age and race.	OR and *P*-value for occupational exposure of parents of children with osteosarcoma and Ewing's sarcoma compared with controls. Maternal exposure to metals: OR = 3.50, *P* = 0.11 for osteosarcoma; OR = 1.12, *P* = 0.81 for Ewing's disease. Paternal exposure to metals: OR = 0.74, *P* = 0.34 for osteosarcoma; OR = 1.09, *P* = 0.77 for Ewing's disease.	Results not presented separately for beryllium; instead classification was exposure to metals.

Table 3-2. Current cohort studies of cancer

Reference	Study Design	Population	Exposure	Effects	Potential Confounders
Wing *et al.* (1993) U.S.A.	Historical cohort	8,318 white male workers employed at Oak Ridge National Laboratory,	609 workers known to have worked with beryllium.	All cancer RR 1.38 (95% CI 0.95 - 2.00)	Ionizing radiation, other metals.
Loomis and Wolf (1996) U.S.A.	Historical cohort	8,116 men and women of all races employed at the Y-12 nuclear materials plant, 1947 to 74 and followed to 1990	Beryllium known to have been used in the plant	Lung cancer SMR 1.17 (95% CI 1.01 - 1.34) for all workers and 1.19 (95% CI 1.03 - 1.36) for white males. Excess brain and lymphopoietic among white males.	Ionizing radiation, other metals, solvents, cutting fluids, no adjustment for cigarette smoking.

4 Studies of Cancer in Experimental Animals

4.1 Inhalation studies in rats, hamsters, rabbits, and monkeys

Groups of 60 and 33 male Charles River rats and 30 Greenacres Controlled Flora rats (more than four weeks old) were exposed by inhalation to metallic beryllium in the form of beryl ore (containing 4.14% beryllium, 63.6% crystalline silica, 18.1% Al_2O_3, and lower concentrations of other metal salts; mean particle diameter, 0.64 μm) or bertrandite ore (1.4% beryllium, 63.9% SiO_2, 9.8% Al_2O_3, and lower concentrations of other metals salts; mean particle diameter, 0.27 μm). Chamber concentration was 15 mg/m^3 of dust, and animals were exposed for six hours per day, five days a week for up to 17 months. The beryl ore atmosphere contained 620 μg/m^3 beryllium, and the bertrandite ore atmosphere contained 210 μg/m^3 of beryllium. A third group of rats served as controls and was housed in inhalation chambers without exposure. Of animals killed after 12 months of exposure, 5/11 exposed to beryl ore had foci of squamous metaplasia or small epidermoid tumors. After 17 months, 18/19 had lung tumors (18 bronchiolar alveolar-cell tumors, 7 adenomas, 9 adenocarcinomas, and 4 epidermoid tumors). Exposure to bertrandite ore caused pulmonary granulomatous lesions and some proliferative changes, but lung tumors were not observed. Interpretation of this study was confounded by the presence of crystalline silica in the beryl ore sample and incomplete reporting (Wagner *et al.* 1969, cited in IARC 1993). Similar studies were conducted in Syrian golden hamsters and squirrel monkeys, but the IARC Working Group considered the interpretations questionable because of limited reporting of pathological findings and limited exposure durations (IARC 1993).

Male and female albino Wistar rats (27 per group) and male and female Sherman rats (109 per group) were exposed to aerosols of beryllium sulfate tetrahydrate at a beryllium concentration of 35.8 μg/m^3 for eight hours a day, 5.5 days a week for up to 180 days. Control groups of 69 male and female Wistar rats and 70 male and female Sherman rats were maintained without exposure. The exposed animals developed pulmonary tumors, eight with metastases, that included 18 adenomas, 5 squamous carcinomas, 24 acinous adenocarcinomas, 11 papillary adenocarcinomas, and 7 alveolar cell adenocarcinomas. No control animal had pulmonary tumors (Schepers *et al.* 1957). A similar study was conducted with a group of Sprague-Dawley rats (75 per sex) exposed to beryllium sulfate tetrahydrate at a mean atmospheric concentration of 34.25 ± 23.66 μg/m^3 for seven hours a day, five days a week for 72 weeks. An equal number of rats were exposed to an aerosol of distilled water and used as controls. All surviving exposed rats (43 per group) had alveolar adenocarcinomas. No tumors were found in control rats (Reeves *et al.* 1967, cited in IARC 1993).

Shorter beryllium inhalation exposure regimens also produced lung cancer in rats. Female rats (30 to 50 per group) were exposed to either beryllium oxide or beryllium chloride (concentrations of 0.8, 4, 30, or 400 μg/m^3) for one hour per day, five days per week for four months. A group of 160 females served as controls. In this study, only malignant epithelial cell lung tumors were evaluated. Beryllium exposure caused dose-dependant incidences of malignant epithelial lung tumors, and no lung tumors were observed in

control animals. The total duration of the experiment was not reported (Litvinov *et al.* 1984, cited in IARC 1993).

Three groups of rabbits (sex not specified) were exposed to aerosols of beryllium oxide at beryllium concentrations of 1 μg/L (five rabbits), 6 μg/L (six rabbits), or 30 μg/L (eight rabbits) for five hours per day, five days per week for 9 to 13 months. No control group was used. Lung tumors were not reported, but one of the animals exposed to 6 μg/L for over 11 months had an osteogenic sarcoma in the pubis (Dutra *et al.* 1951, cited in IARC 1993).

In a group of 16 rhesus monkeys (*Macaca mulatta*) exposed to beryllium sulfate aerosol at a beryllium concentration of 35 $\mu g/m^3$, primary anaplastic pulmonary tumors with adenomatous and epidermoid patterns were observed in three animals between six months and eight years after the beginning of exposure. Additional details were not reported (Vorwald 1967, cited in IARC 1993).

In more recent studies, groups of male and female Fischer 344/N rats received single nose-only exposures to beryllium metal sufficient to result in initial lung burdens of approximately 50, 150, or 450 μg of the metal. To this end, animals were exposed to beryllium at concentrations of 470 to 960 mg/m^3 for 10 to 41 minutes. Serial sacrifices were made from 8 to 450 days after the exposure. The target lung burden of 450 μg reduced survival. Beryllium inhalation caused an increased incidence of lung tumors in rats. The most prevalent tumor was bronchiolar/alveolar adenocarcinoma having alveolar, papillary, or tubular patterns, and other tumors included adenosquamous carcinomas and squamous cell carcinomas. Substantial lung tumor multiplicity also was observed (Finch *et al.* 1990a; Haley *et al.* 1990; Finch *et al.* 1991, 1994a, b; all cited in Finch *et al.* 1996).

Tumors were observed in groups of rats receiving initial lung burdens of beryllium metal of 40, 110, 360, and 430 μg by 14 months after exposure began. Approximately 64% of the rats had lung tumors during their lifetimes (Nickell-Brady *et al.* 1994, cited in Finch *et al.* 1996).

The relative susceptibility of A/J mice and C3H/HeJ mice to beryllium-induced pulmonary carcinogenesis was assessed. Mice were exposed to beryllium metal by inhalation to result in mean initial lung burdens of 47 μg beryllium in A/J mice and 64 μg in C3H/HeJ mice. Microscopic analysis of lungs revealed that the tumor incidence in A/J mice was elevated relative to controls (46% for exposed *vs.* 37% for controls), and the A/J mice exhibited greater lung tumor multiplicity. Overall, tumor incidences were lower in C3H/HeJ mice than in A/J mice, and beryllium exposure had little effect (tumor incidence was 5% in beryllium-exposed animals and 10% in controls). Results of statistical analyses of the data were not reported, nor were durations of beryllium exposures (Belinsky *et al.* 1992, Nikula *et al.* 1994, both cited in Finch *et al.* 1996).

Male F344/N rats received single nose-only inhalation exposures to beryllium metal at concentrations sufficient to result in lung burdens of 0.32, 1.8, 10, or 100 μg of beryllium. Rats were sacrificed at 8, 16, 40, 90, 210, and 365 days after exposure. One rat

in the 1.8-μg group, sacrificed after 365 days, had a pulmonary squamous-cell carcinoma. Because the single occurrence of a lung tumor was in an animal from a lower lung burden group, the authors concluded that the tumor was not caused by exposure to beryllium metal (Finch *et al.* 1994c).

4.2 Intratracheal instillation in rats

Female rats received a single intratracheal instillation of 50 μg of beryllium as beryllium hydroxide; then, 10 months later, they received a single instillation of an additional 25 μg. Of the animals sacrificed at 19 months, 13/25 had pulmonary tumors (6 adenomas and 7 carcinomas; one rat had both an epidermoid carcinoma and an adenocarcinoma) (Groth *et al.* 1980, cited in IARC 1993).

Male Wistar rats (10 weeks old) were instilled intratracheally with beryllium oxide once a week for 15 weeks. A group of 16 rats served as untreated controls. The animals were observed until natural death, and 6/30 had lung tumors (two malignant and four benign lung adenomas) (Ishinishi *et al.* 1980, cited in IARC 1993).

Eight groups of inbred albino rats (gender and initial number not specified) received weekly intratracheal instillations of "high-temperature-fired beryllium oxide" (2,000°C) or "low-temperature-fired beryllium oxide" (600°C) at doses of 0.036, 0.36, 3.6, or 18 mg/kg bw. A group of 300 untreated rats served as controls. The animals were observed until natural death. Beryllium calcined at 600°C caused a dose-related increase in the incidence of malignant lung tumors (3/69, 4%; 7/81, 9%; 18/79, 23%; and 8/26, 31%). The high-temperature-treated beryllium was associated with lower incidences of malignant lung tumors (0/76; 0/84; 2/77, 3%; 2/103, 2%). No tumors were found in 104 controls (Litvinov *et al.* 1983, cited in IARC 1993).

4.3 Effects of beryllium metal in p53 knockout mice

Experiments were conducted to assess the sensitivity of $p53^{+/-}$ knockout mice to the carcinogenic effects of metallic beryllium. The $p53^{+/-}$ mouse and other transgenic models are currently under investigation for utility in short-term tests for the assessment of carcinogenic potential (Finch *et al.* 1998b).

Mice of both sexes were exposed to air (negative control), metallic beryllium (target lung burden of 60 or 15 μg), or $^{239}PuO_2$, (target lung burden of 500 or 100 Bq ^{239}Pu) (positive control). Similar exposures of wild-type $p53^{+/+}$ (nontransgenic) mice also were conducted.
The incidences of lung neoplasms are shown in Table 4-1. Gender differences in pulmonary responses of transgenic mice were not apparent; hence, the sexes were pooled for statistical analysis.

Table 4-1. Incidence of mice with one or more pulmonary neoplasms following inhalation exposure to beryllium or Pu

Sex	Heterozygous $p53^{+/-}$ mice					Wild-type $p53^{+/+}$ mice	
	Air	$^{239}PuO_2$ (500 Bq)	$^{239}PuO_2$ (100 Bq)	beryllium (60 μg)	beryllium (15 μg)	$^{239}PuO_2$ (500 Bq)	beryllium (60 μg)
Male	0/15	1/15	6/15	2/15	0/15	5/15	0/15
Female	0/15	3/14	1/15	2/13	0/14	2/14	0/13
Combined	0/30[a, b, c]	4/29[a]	7/30[b]	4/28[c]	0/29	7/29	0/28[d]

Source: Finch *et al.* (1998a).
[a] Air vs. 500-Bq $^{239}PuO_2$ $p53^{+/-}$ mice, $P = 0.052$.
[b] Air vs. 100-Bq $^{239}PuO_2$ $p53^{+/-}$ mice, $P = 0.005$.
[c] Air vs. 60-μg beryllium $p53^{+/-}$ mice, $P = 0.048$.
[d] 60-μg beryllium $p53^{+/-}$ mice vs $p53^{+/+}$ mice, P=0.056.

For both the heterozygous ($p53^{+/-}$) and homozygous ($p53^{+/+}$) mice, lung-tumor responses to beryllium and to the positive control agent ($^{239}PuO_2$), were similar, but the latency period for tumor production was reduced in the heterozygous animals, suggesting an increased sensitivity in the transgenic animals.

The incidence of lung tumors in beryllium-exposed $p53^{+/-}$ mice was marginally higher than that of beryllium-exposed $p53^{+/+}$ mice ($P = 0.056$). Five primary lung neoplasms were observed in the four neoplasm-bearing heterozygous animals in the 60-μg group, while the wild-type animals with the same lung burden developed no tumors during the 22.5 months of the experiment. Heterozygotes exposed to the lower dose of beryllium metal had no lung tumors.

A number of nonpulmonary neoplasms (osteosarcoma, lymphoma, histeocytic sarcoma) also were observed during this experiment but these occurred with similar incidences in exposed and control animals. Therefore, the tumors could not be attributed to administration of either beryllium or $^{239}PuO_2$.

4.4 Intravenous injection in mice and rabbits

In a study reported as an abstract, Cloudman *et al.* (1949, cited in IARC 1993) administered 20 to 22 intravenous injections of either zinc beryllium silicate or beryllium oxide to mice (two injections per week). Beryllium administration caused malignant bone cancer in "some" mice. Similarly in another study (reported as an abstract) Gardner and Heslington (1946, cited in IARC 1993), intravenous administration of these beryllium salts to rabbits at total doses of 1 g caused malignant osteosarcomas, and some of the rabbits had visceral metastases. In a later study (Fodor 1977, cited in IARC 1993), intravenous administration of a beryllium oxide suspension (1% beryllium oxide in 5 mL of physiological saline) caused sarcomas (not otherwise described) in 21/29 (72%) of the animals. The IARC Working Group noted the lack of an appropriate control group and incomplete reporting of this study.

In another study, six groups comprising of 67 rabbits (mixed breeds and sexes) received intravenous injections of zinc beryllium silicate (total doses 1 to 2.1 g) or beryllium silicate (1 to 1.2 g). Injections were administered twice weekly, and the animals' survival was reduced. A group of 10 rabbits were injected with zinc silicate alone (1.2 g) and used as untreated controls. Beryllium exposure caused osteosarcomas in 7/21 animals that survived for more than 30 weeks. The earliest malignant tumor was detected at 32 weeks, and the latest tumor occurred at 83 weeks. No tumors were observed in the control group (Barnes *et al.* 1950, cited in IARC 1993).

In another rabbit study, intravenous injections of beryllium oxide caused osteosarcomas in 6/6 animals that survived for more than 11 months. In this study, rabbits received 360 to 700 mg of beryllium in 20 to 26 injections (three injections per week over six to nine weeks). Six animals survived for at least one year (the total number of animals in the study was not reported), and the first bone tumor was detected after 11.5 months. All six of the surviving animals had osteosarcomas (Dutra and Largent 1950, cited in IARC 1993).

Administration of total doses of 1g of beryllium phosphate, zinc beryllium silicate, or beryllium oxide in divided doses at one- to four-day intervals reduced survival of male and female rabbits, but 7/8 animals that survived for longer than 14 months had osteogenic sarcomas (Hoagland *et al.* 1950, cited in IARC 1993).

Osteosarcomas were produced by intravenous zinc beryllium silicate administration in 10/14 rabbits. Zinc beryllium silicate was administered twice weekly for 10 weeks (for a total dose of 1 g). Animals died or were sacrificed 28 to 57 weeks after the last injection. Tumors were detected 30 to 52 weeks after the last injection (Kelly *et al.* 1961, cited in IARC 1993).

A single intravenous dose of 1g of beryllium phosphate caused osteosarcomas in 2/4 rabbits within 18 months; no tumors were observed in rabbits that were given a single intravenous injection of 1 g of beryllium oxide (Araki *et al.* 1954, cited in IARC 1993). In a similar experiment, a single intravenous dose of 1g of beryllium oxide caused

osteosarcomas in 3/20 rabbits 15 to 18 months after administration (Komitowski 1968, cited in IARC 1993).

4.5 Intraperitoneal injection

Intraperitoneal administration of beryllium sulfate tetrahydrate at 0.02, 0.05, or 0.1 mg/mouse (three times per week for eight weeks) increased the incidences of lung tumors in A/J strain mice, but did not increase tumor multiplicity (Ashby *et al.* 1990, cited in IARC 1993). However, the IARC Working Group noted that the increased incidences were not statistically significant in Fisher's exact test (IARC 1993).

4.6 Implantation and/or injection into bone

After 1 to 43 injections of 10 mg of beryllium oxide as a 1% suspension into the marrow of the femur of rabbits, dosed animals exhibited chondromas, osteomas, chondrosarcomas, and osteochondrosarcomas. Injections were administered twice weekly for up to 22 weeks, and 26/55 (47%) of the animals had bone tumors. The average time between the last injection and the appearance of the tumor was 85 days (Yamaguchi 1963, cited in IARC 1993).

Intramedullary injection of one dose of zinc beryllium silicate powder (20 mg) into the upper end of the tibia of rabbits caused osteosarcomas in 4/12 animals 12 to 15 months after the injection (Tapp 1966, cited in IARC 1993). Implantation of 10 mg of zinc beryllium silicate, beryllium oxide, or beryllium silicate under the periosteum of the tibia also caused bone tumors after 10 to 25 months (Tapp 1969, cited in IARC 1993).

Intramedullary administration of beryllium oxide, beryllium carbonate, and beryllium acetylacetonate to rabbits caused bone tumors within 10 to 17 months (Komitowski 1974, Matsuura 1974, both cited in IARC 1993). Intramedullary administration of either beryllium stearate and beryllium laurate in rabbits did not cause bone tumors (Matsuura 1974, cited in IARC 1993). The doses of beryllium salts administered in the study were not given.

Single intraosseous injections of 0.5 mL of a suspension of 1 g of zinc beryllium silicate in 15 mL of distilled water and gelatin, to yield 33 mg beryllium, caused osteogenic sarcomas in 45/65 rabbits that survived more than four months after the injection. Radiographic examinations indicated that the initial sarcomatous changes occurred after three months (Mazabraud 1975, cited in IARC 1993).

Three groups of male rabbits received implants of pellets of hydroxypropylcellulose mixed with beryllium oxide into the distal metaphysis of the femur as follows: group 1, into the internal callus one week after a fracture (300 mg); group 2, into the bone marrow cavity at a dose of 300 mg; group 3, into the bone marrow cavity at a dose of 50 mg. After 56 weeks, osteosarcomas had developed in 10/10 animals in group 1, 7/10 in group 2, and 1/10 in group 3 (Hiruma 1991, cited in IARC 1993).

4.7 Summary

The results of carcinogenesis studies in experimental animals and reviewed by IARC are summarized in Table 4-2. These studies provide evidence that beryllium and beryllium compounds are carcinogenic to rats, mice, and rabbits. Results of animal experiments have shown consistent increases in lung cancers in rats, mice, and rabbits chronically exposed to beryllium and beryllium compounds by inhalation or intratracheal instillation. Osteocarcinomas have been produced in mice and rabbits exposed to various beryllium salts by intravenous injection or implantation into the bone. IARC has concluded there is sufficient evidence of carcinogenicity in experimental animals for beryllium and beryllium compounds. This conclusion is affirmed by evidence from more recent studies in mice and rats.

Table 4-2. Animal carcinogenesis studies of beryllium metal, alloys, ores, and compounds

Species, strain, and sex	Chemical and physical form	Exposure route, dosage, and regimen	Results and comments*	Reference
Beryllium metal				
Rat, Wistar, F	beryllium metal (100%) 1 to 2.5 μm in saline	intratracheal instillation: 0.5 or 2.5 mg (diameter 1 – 2 μm) in saline x 1 occasion	treated: lung adenomas/adenocarcinomas (first tumor at 8 – 10 mo): low dose 2/21, high dose 9/16 ($P < 0.008$) controls: no tumors	Groth *et al.* (1980)
Rabbit, n.s., n.s.	beryllium metal "finely divided"	Intravenous injection: 40 mg x 1 occasion	of 24 subjects: 9 died with liver necrosis within 7 d and 10 more within 1 mo, 2 died with pulmonary infections, 2 had "characteristic bone sarcomata," and 1 was unaffected controls: no controls	Barnes (1950 [letter])
Beryllium alloys				
Rat, Wistar, F	Be 99%:Cr Be 62%:Al 38% Be 04%: Cu Be 02%:Ni 98% Be 24%: Cu 0.4%:Co 96%	intratracheal instillation: 0.5 or 2.5 mg (diameter 1 – 2 μm) in saline x 1 occasion	treated: lung adenomas/adenocarcinomas (first tumor at 8 – 10 mo): Be:Cr, low dose 7/20, high dose 9/26 ($P < 0.008$), Be:Al, low dose 1/21, high dose 4/24 ($P < 0.008$); other alloys, no tumors controls: no tumors	Groth *et al.* (1980)
Beryllium ores				
Rat, Greenacres Controlled Flora and Charles River Caesarian, n.s.	beryl ore (diam. 0.64 μm) = 210 μg/m^3 Be Bertrandite ore (diam. 0.27 μm) = 620 μg/m^3 Be	inhalation: dust, 15 mg/m^3/6 h/d, 5 d/wk, (up to) 17 mo	beryl ore: after 12 mo; 5/11 squamous metaplasia or small epidermoid tumors; after 17 mo, 18/19 lung tumors (18 bronchiolar alveolar-cell tumors [BACs]), 7 adenomas, 9 adenocarcinomas, and 4 epidermoid tumors) bertrandite ore: granulomas, but no tumors controls: no lesions of any type (IARC noted high crystalline silica content of bertrandite and incomplete reporting)	Wagner *et al.* (1969)
Hamster, Syrian golden, n.s.	beryl ore (diam. 0.64 μm) = 210 μg/m^3 Be Bertrandite ore (diam. 0.27 μm) = 620 μg/m^3 Be	inhalation: dust, 15 mg/m^3 for 6 h/d, 5 d/wk, (up to) 17 mo	beryl ore and bertrandite ore: atypical proliferations in lungs after 12 mo (some thought to be BACs); lesions bigger and more adenomatous after 17 mo in the beryl ore group controls: no pulmonary lesions (IARC noted high crystalline silica content of bertrandite and incomplete reporting)	Wagner *et al.* (1969)

Species, strain, and sex	Chemical and physical form	Exposure route, dosage, and regimen	Results and comments*	Reference
Monkey, *Saimiri sciurea*, M	Beryl ore (diam. 0.64 µm) = 210 µg/m^3 beryllium Bertrandite ore (diam. 0.27 µm) = 620 µg/m^3 beryllium	inhalation: dust, 15 mg/m^3 6 h/d, 5 d/wk, (up to) 23 mo	beryl ore and bertrandite ore: death rate exceeded controls by 11%; some bronchiolar inflammation noted in treated groups; no tumors observed controls: no pulmonary lesions (IARC noted incomplete reporting and limited duration of study)	Wagner *et al.* (1969)
Beryllium compounds				
Rat, Long-Evans (BLU:LE), M and F	beryllium sulfate	oral: 5 ppm (5 mg/L) in drinking water (also contained 5 ppm chromium [III] acetate, 50 ppm zinc acetate, 5 ppm copper acetate, 10 ppm manganese chloride, 1 ppm cobalt chloride, and 1 ppm sodium molybdate) given *ad libitum* until natural death	treated and controls: 20% to 30%, of both groups died from pneumonia; "no significant difference in tumor incidence was observed between treated and control groups." (IARC noted that the dose was too low for an evaluation of carcinogenicity)	Schroeder & Mitchner (1975)
Rat, Wistar, M and F Rat, Sherman M and F	beryllium sulfate tetrahydrate	inhalation: aerosol, 35.8 µg/m^3 8 h/d, 5.5 d/wk, 180 d and (those surviving) then placed in normal air for up to 72 wk	treated: 76 lung tumors found, 8 metastatic: 8 adenomas, 5 squamous cell carcinomas, 24 acinous adenocarcinomas, 11 papillary adenocarcinomas, and 7 alveolar-cell adenocarcinomas controls: no lung tumors (IARC noted incomplete reporting of the study)	Schepers *et al.* (1957)
Rat, Sprague-Dawley CD, M and F	beryllium sulfate tetrahydrate (diam. 0.12 µm)	inhalation: aerosol, 34 µg/m^3, 7 h/d, 5 d/wk, 72 wk	treated: 1st lung tumor seen at 9 mo; all surviving 13 mo or more had tumors (some multiple) and all were alveolar adenocarcinomas controls: no lung tumors (IARC noted incomplete reporting of the study)	Reeves *et al.* (1967)
Rat, albino, F	beryllium oxide or beryllium chloride	inhalation: aerosol, 0.8, 4, 30, or 400 µg/m^3, 1 h/d, 5 d/wk, 16 wk	treated: malignant epithelial lung tumors were scored: respectively, for doses): beryllium oxide: 3/44, 4/39, 6/26, and 8/21; beryllium chloride: 1/44, 2/42, 8/24, and 11/19 controls: no lung tumors	Litvinov *et al.* (1984)
Rabbit, n.s, n.s.	beryllium oxide (diam. 0.29 µm)	inhalation: aerosol, 1, 6, or 30 µg/L, 5 h/d, 5 d/wk, 36 – 72 wk	treated: 1 metastatic osteogenic sarcoma was observed in an animal exposed to 6 µg for 235 d controls: no controls (IARC noted the small number of animals and limited study duration)	Dutra *et al.* (1951)

Species, strain, and sex	Chemical and physical form	Exposure route, dosage, and regimen	Results and comments*	Reference
Monkey, Rhesus (*Macaca mulatta*), n.s.	beryllium sulfate	inhalation: aerosol, 35 µg/m^3, "for a long time"	treated: 3 animals developed primary anaplastic pulmonary tumors with adenomatous and epidermoid patterns between 6 mo and 8 yr after exposure controls: no controls	Vorwald (1967)
Rat, Wistar-derived, F	beryllium hydroxide	intratracheal instillation: 50 µg Be in distilled water x 1 occasion, followed (after 40 wk) by another 2.5 µg	treated: animals were sacrificed after 64 wk; 13/25 had pulmonary tumors (6 adenomas and 7 adenocarcinomas) and 1 had both epidermoid carcinoma and adenocarcinoma controls: no untreated controls (IARC noted the lack of an appropriate control group)	Groth *et al.* (1980)
Rats, Wistar, n.s.	beryllium oxide (low-fired, 900°C) arsenic trioxide	intratracheal instillation: 1 mg/wk as Be (or As), 15 wk and then observed for life	treated: beryllium oxide: lung tumors: 1 squamous-cell carcinoma, 1 adenocarcinoma, and 4 adenomas ("3 suspected of malignancy") arsenic trioxide: 1 squamous-cell carcinoma controls: no lung tumors	Ishinishi *et al.* (1980)
Rats, inbred albino, n.s.	beryllium oxide (l) (low-fired, 600°C) beryllium oxide (h) (high-fired, 2,000°C)	intratracheal instillation: single doses of 0.04, 0.4, 4.0 and 18 mg/kg bw and then observed for life	treated: malignant epithelial lung tumors (respectively, for doses): BeO (l): 0/76, 0/84, 2/77, and 2/103 BeO(h): 3/69, 7/81, 18/79 and 8/26 controls: no lung tumors	Litvinov *et al.* (1983)
Monkey, *Macaca mulatta*, n.s.	beryllium oxide ("particles" in saline)	intrabronchial intubation and/or (n.s.) bronchomural injection, single dose n.s.	treated: "1st bronchogenic tumor detected about 4.5 yr after treatment; at about 5.5 yr, 2 monkeys developed highly neoplastic tumors with adenomatous and epidermoid patterns"	Vorwald (1967)
Mouse, n.s., n.s.	zinc beryllium silicate (8.4 mg Zn, 0.26 mg Be) zinc silicate (2.8 mg Zn) beryllium oxide (1.5 mg Be)	intravenous injection: 20 – 22 injections (2/wk)	treated: "some mice receiving Zn Be silicate developed bone tumours" controls: no tumors	Cloudman *et al.* (1949 [abstract])
Rabbit, n.s., n.s.	zinc beryllium silicate (diameter $\leq$3 µm) beryllium oxide (diameter $\leq$3 µm)	intravenous injection: 20 doses totaling 1 g/6 wk	treated: Zn Be silicate: "all 7 surviving rabbits developed malignant osteosarcomas (4 of them metastatic)"; BeO: "1 rabbit, sacrificed at 1 yr, had a malignant osteosarcoma" controls: "no such tumors were induced by administration of 65 other minerals in the same way"	Gardner and Heslington (1946 [abstract])
Rabbit, n.s., n.s.	zinc beryllium silicate (550 mg Zn, 17 mg Be) zinc silicate (390 mg Zn) beryllium oxide (390 mg Be)	intravenous injection: 20 – 22 injections (2/wk)	treated: "4 of 5 rabbits given Zn Be silicate and surviving past 1 yr developed bone tumors, 3 with metastases" controls: n.s.	Cloudman *et al.* (1949 [abstract])

Species, strain, and sex	Chemical and physical form	Exposure route, dosage, and regimen	Results and comments*	Reference
Rabbit, n.s, n.s.	zinc beryllium silicate (2% BeO) (diameter $\leq$5 µm) Beryllium silicate (diameter $\leq$5 µm)	intravenous injection: at various concentrations in water (1.0, 1.2, or 2.0 g total), in 6 – 10 injections, 2/wk	treated: Zn Be silicate, Be silicate: 7/21 rabbits injected with Be silicates (surviving 30 wk) developed bone sarcomas; earliest malignant tumor seen at 32 wk and latest at 83 wk controls: no tumors found in rabbits injected with Zn silicate (IARC noted survival was poor in the study)	Barnes *et al.* (1950)
Rabbit, n.s., M and F	beryllium oxide (highly purified) (diameter $\leq$1 µm) calcined phosphor (containing beryllium oxide, zinc oxide, and silica in M ratio of 1:1:1) (diameter $\leq$5 µm)	intravenous injection: Be oxide total 360 – 700 mg Be/rabbit in 20 – 26 injections and phosphor total 64 – 90 mg Be/ rabbit in 17 – 25 injections, 3/wk, x 6 – 9 wk	treated: BeO: 6/6 (surviving) rabbits had osteosarcomas (some primary, some metastatic, and some multiple) after 1 yr; phosphor: 2/3 (surviving) rabbits had osteosarcomas after 1 yr controls: "about 50 untreated rabbits, kept for similar periods, developed no tumor" (IARC noted small group sizes, limited reporting, and incomplete observations)	Dutra and Largent (1950)
Rabbit, n.s., M&F	beryllium phosphate zinc beryllium silicate (2.3% BeO) zinc beryllium silicate (14% BeO) beryllium oxide	intravenous injection: 1% suspension in saline, at 1- or 4-d intervals, to deliver a total of 1 g of compound per rabbit	treated: 7/8 surviving rabbits developed osteogenic sarcomas; Be phosphate; 1 survivor received only 100 mg and had no tumor; Zn Be silicate (2.3% BeO): 3 had tumors; Zn Be silicate (14% BeO): 3 with tumors; BeO: 1 had a tumor controls: n.s. (IARC noted small group sizes and lack of appropriate controls)	Hoagland *et al.* (1950)
Rabbit, n.s., n.s.	beryllium phosphate beryllium oxide beryllium oxide mixed with zinc oxide, manganese oxide, and/or silicon oxide	intravenous injection: single doses of 1 g per animal	treated: Be phosphate: 2/4 rabbits had osteosarcomas within 18 mo; BeO: no tumors found in 3 rabbits; BeO mixed with other oxides: 9/31 developed osteosarcomas controls: n.s. (IARC noted small group sizes, lack of appropriate controls, and incomplete observations)	Araki *et al.* (1954)
Rabbit, n.s., M	zinc beryllium silicate (3.4% BeO)	intravenous injection: 2/wk, 10 wk, for a total dose of 1 g (33.6 mg BeO)	treated: 5 rabbits developed osteogenic sarcomas after 9 to 11 mo controls: n.s. (IARC noted small group size and lack of appropriate controls)	Janes *et al.* (1954)
Rabbit, n.s., n.s.	zinc beryllium silicate (diameter 1 – 3 µm)	intravenous injection: 2/wk, 10 wk, for a total dose of 1 g	treated: rabbits died or were killed 28 – 57 wk after last injection; osteogenic sarcomas developed in 10/14 rabbits after 30 – 52 wk controls: n.s. (IARC noted small group size and lack of appropriate controls)	Kelly *et al.* (1961)
Rabbit, n.s., n.s.	beryllium oxide	intravenous injection: BeO in a 1% saline suspension, x 1 occasion, for a total dose of 1 g	treated: osteosarcomas were induced in 3/20 rabbits 15 – 18 mo after injection controls: n.s. (IARC noted the lack of appropriate controls)	Komitowski (1968)

Species, strain, and sex	Chemical and physical form	Exposure route, dosage, and regimen	Results and comments*	Reference
Rabbit, n.s., n.s.	beryllium oxide	intravenous injection: BeO in a 1% saline suspension, 1/wk, 25 wk	treated: sarcomas were induced in 21/29 rabbits surviving to "the end of the experiment" controls: n.s. (IARC noted the lack of appropriate controls and incomplete reporting)	Fodor (1977)
Mouse, A/J, M	beryllium sulfate tetrahydrate (purity $\geq$ 99%) suspended in water	intraperitoneal injection: maximum total dose of 0.02, 0.05, or 0.1 mg/mouse 3/wk, 8 wk	treated: authors stated treatment produced significant (X^2 analysis) increases in lung tumor incidences at total dose of 1.2 and 2.4 mg/mouse without a significant increase in tumor multiplicity controls: water only; tumor incidence n.s. (IARC noted that the increases in tumor incidence were not significant using Fisher's exact test)	Ashby *et al.* (1990)
Rabbit, n.s., n.s.	beryllium oxide	injection into bone: 10-mg doses (1% in saline), injected into the bone marrow of the femur, 2/wk for up to 23 wk	treated: 1/55 rabbits had a chondroma, 3/55 had osteomas, 15/55 had chondrosarcomas, and 7/55 had osteochondrosarcomas after 1 to 2 yr; the average period between last injection and tumor occurrence was 85 days controls: n.s.	Yamaguchi (1963)
Rabbit, n.s., n.s.	zinc beryllium silicate (powder, diameter $\leq$ 5 μm)	implantation into bone: 20 mg given as a single intramedullary injection into the right tibia; as a control, Zn oxide injected into the left tibia	treated: at 15 – 20 mo after implantation, 4/12 had osteogenic sarcomas (3 metastasized), 4/12 were killed at 15 – 20 mo with no evidence (clinical or radiological) of tumors, and 4/12 had died from in intercurrent infections controls: no effect was seen from Zn oxide	Tapp (1966)
Rabbit, n.s., n.s.	zinc beryllium silicate beryllium oxide beryllium silicate	implantation into bone: 10 mg implanted on a single occasion under the periosteum of the right tibia; as a control, Zn oxide or Zn silicate implanted on the left side	treated: Zn Be silicate: 1/6 rabbits developed a metastatic, osteogenic sarcoma; BeO: 2/6 had metastatic, osteogenic sarcomas; and Be silicate: 1/6 had an osteogenic sarcoma (the tumors were observed in these rabbits 10 – 25 months after implantation controls: no effect was seen from Zn oxide	Tapp (1969)
Rabbit, n.s., n.s.	beryllium oxide (diameter ~4 μm)	injection into bone: intramedullary injection in gelatin into the femur (amount and schedule, n.s.)	treated: 5/20 rabbits osteogenic sarcomas within 2nd yr; the 1st tumor was observed 13 mo after injection controls: n.s. (IARC noted the lack of appropriate controls and incomplete reporting)	Komitowski (1974)

Species, strain, and sex	Chemical and physical form	Exposure route, dosage, and regimen	Results and comments*	Reference
Rabbit, n.s., n.s.	beryllium carbonate beryllium acetate beryllium acetylacetonate beryllium laurate beryllium stearate	injection into bone: intramedullary injection (amounts, placement, and schedule, n.s.)	treated: Be carbonate: 30/173 developed osteosarcomas 10 – 13 mo after implantation; Be acetate: n.s.; Be acetylacetonate: 1/10 (that survived 13 mo) developed an osteosarcoma; Be laurate: n.s.; and Be stearate: n.s. controls: n.s. (IARC noted small group sizes, except for Be carbonate, and incomplete reporting)	Matsuura (1974)
Rabbit, Fauve de Bourgogne, n.s.	zinc beryllium silicate	injection into bone: 1 g (33 mg Be) in gelatin suspension injected x 1 occasion into the tibial or femoral metaphysis	treated: 45/65 rabbits surviving more than 4 mo after injection developed osteogenic sarcomas; radiographic examination showed that the earliest sarcomatous changes occurred within 3 mo of injection controls: n.s. (IARC noted the lack of appropriate controls)	Mazabraud (1975)
Rabbit, n.s., n.s.	beryllium oxide	implantation into bone: pellets of hydroxypropylcellulose mixed with BeO implanted into the distal metaphysis of the femur according to experimental group: (1) internal callus artificial fracture at 300 mg, (2) bone marrow cavity at 300 mg, (3) bone marrow cavity at 50 mg, and (4) untreated	treated: group (1): 56 weeks post implantation, osteosarcomas had developed in 10/10 rabbits; these tumors appeared significantly earlier than those in other groups; group (2): 7/10 had osteosarcomas; group (3): 1/10 had osteosarcomas; (for all groups: 80% of rabbits with primaries had lung metastases as well) controls: n.s.	Hiruma (1981)
Mouse, SENECAR, M&F	beryllium sulfate (purity n.s.)	intraperitoneal injection (followed by) dermal applications of 12-*O*-tetradecanoylphorbol 13-acetate (TPA) co-treatment: in saline, 0, 0.01, 0.1, 1.0, 5.0, or 10.0 µg/mouse; 1 wk after Be sulfate injection, TPA applied, dermally, 2/wk for 26 wk; a positive control group was dosed with 50.5 µg/mouse benzo[a]pyrene followed by TPA treatment	treated: "failed to induce a significant number of mouse skin papillomas"	Nesnow (1985)

Source: IARC (1993).

M = males; F = females; n.s. = not specified. *****Significant increase (Fisher's exact test, 1-tailed).

5 Genotoxicity

5.1 Prokaryotic systems

5.1.1 Induction of mutations in Salmonella typhimurium

Beryllium compounds (beryllium chloride, beryllium nitrate, beryllium sulfate) were not mutagenic when tested in a variety of *Salmonella* tester strains, in the presence or absence of exogenous metabolic activation (IARC 1993) (Appendix A, Table 19).

Beryllium sulfate was not mutagenic when tested in five *S. typhimurium* strains, in the presence or absence of metabolic activation by S9 liver homogenate (Ashby *et al.* 1990). A review of the literature by these authors, indicates that a number of earlier *Salmonella* studies on beryllium sulfate and beryllium nitrate failed to detect mutagenic activity. In these studies, TA1530, TA1535, TA1536, TA1537, TA1538, TA98, and TA100 strains of *S. typhimurium* were tested at beryllium sulfate concentrations that ranged from 25 to 5,000 μg/plate. The LT2 and TA100 strains of *S. typhimurium* were tested with beryllium nitrate at a concentration of 10^{-4} to 10^{-1} M.

Beryllium was non-mutagenic to *S. typhimurium* strains TA100 and TA98 at concentrations of > 5,000 μg/plate (beryllium chloride), > 5,000 μg/plate (beryllium nitrate), and > 0.43 μg/plate (beryllium oxide), in the presence and absence of S9 rat liver homogenate (Kuroda et al. 1991).

5.1.2 Induction of mutation in Escherichia coli

Beryllium chloride induced a forward mutation in one test with *E. coli*, in the absence of exogenous metabolic activation, but tested negative with beryllium sulfate for differential toxicity with or without exogenous metabolic activation (IARC 1993) (Appendix A, Table 19).

5.1.3 Induction of differential toxicity in Bacillus subtilis rec *assay*

Beryllium chloride (375, 750, and 1,500 μg/disk), beryllium nitrate (375, 750, and 1,500 μg/disk), and beryllium oxide (0.1 μg/disk) were tested in the *B. subtilis rec* assay. Evidence of a weak DNA-damaging effect was noted for beryllium chloride and beryllium nitrate. Beryllium oxide was negative in the *rec* assay, which was attributed to the incomplete solubility of the compound in water (Kuroda *et al.* 1991).

Beryllium compounds (beryllium nitrate, beryllium sulfate, beryllium oxide) were found to be DNA damaging and tested positive in the *B. subtilis rec* assays, in the absence of exogenous metabolic activation (IARC 1993) (Appendix A, Table 19).

5.1.4 Induction of mutation in Saccharomyces cerevisiae

Beryllium sulfate failed to induce mitotic recombination in *S. cerevisiae*, in the presence or absence of exogenous metabolic activation (IARC 1993) (Appendix A, Table 19).

5.2 Mammalian systems

5.2.1 In vitro *assays*

5.2.1.1 hprt *locus forward mutation test*

Beryllium chloride was positive in the *hprt locus* gene mutation test in Chinese hamster lung V79 cells in the absence of exogenous metabolic activation (IARC 1993) (Appendix A, Table 19).

5.2.1.2 Mammalian cell transformation assays

Beryllium compounds in the absence of exogenous metabolic activation, were found to be mutagenic causing cell transformations in murine, Syrian hamster embryo cells, rat embryo cells (beryllium sulfate), and rat tracheal epithelial cells (beryllium oxide) (IARC 1993) (Appendix A, Table 19).

5.2.1.3 Sister chromatid exchanges (SCEs)

Beryllium chloride (31 to 250 μg/mL), beryllium nitrate (31 to 500 μg/mL), and beryllium oxide (0.02 to 0.09 μg/mL) were tested for induction of SCEs in Chinese hamster lung V79 cells. Beryllium chloride and beryllium nitrate induced significant SCEs in the presence of S9 rat liver homogenate. Beryllium oxide tested negative for induction of SCEs (Kuroda *et al.* 1991).

Beryllium compounds were found to damage chromosomes and tested positive for SCEs in Chinese hamster lung V79 cells (0.05 and 0.25 μg/mL beryllium nitrate), Syrian hamster embryo cells (beryllium sulfate), and human lymphocytes (0.05 μg/mL beryllium sulfate); in the absence of exogenous metabolic activation (IARC 1993) (Appendix A, Table 19).

5.2.1.4 Chromosomal aberrations tests

In studies reviewed by IARC (1993), beryllium compounds (beryllium nitrate, beryllium sulfate, beryllium oxide) were found to damage chromosomes and tested positive for chromosomal aberrations in swine lymphocytes (beryllium chloride), Chinese golden hamster ovary cells (beryllium sulfate), Syrian hamster embryo cells (beryllium sulfate), and human lymphocytes (beryllium sulfate); in the absence of exogenous metabolic activation (Appendix A, Table 19).

When beryllium sulfate (0.2 and 1.0 mM) was tested for the induction of chromosomal aberrations in Chinese hamster ovary cells, it yielded equivocal results (Brooks *et al.* 1989). Using Chinese hamster lung cells, Ashby *et al.* (1990) failed to note any evidence of a clastogenic response for beryllium sulfate (0.078, 0.156, 0.313, 0.625 μg/mL), either in the presence or absence of an Aroclor-induced S9 rat liver homogenate.

5.2.1.5 DNA damage/repair tests

DNA single strand breaks

Beryllium oxide was found to damage DNA and tested positive for DNA single strand breaks in rat tracheal epithelial cells (IARC 1993) (Appendix A, Table 19).

Unscheduled DNA synthesis

Beryllium sulfate was found to be DNA damaging and tested positive for unscheduled DNA synthesis (UDS) in primary rat hepatocytes (IARC 1993) (Appendix A, Table 19).

5.2.2 In vivo *assays*

5.2.2.1 Host-mediated assay

Beryllium sulfate was not mutagenic in *S. typhimurium* and *S. cerevisiae* host-mediated assays in mice (IARC 1993) (Appendix A, Table 19).

5.2.2.2 Micronucleus test

Ashby *et al.* (1990) performed an analysis of micronuclei induction using beryllium sulfate administered by gavage in saline at doses of 1.45 g/kg or 2.3 g/kg. $BeSO_4$ failed to induce micronucleated polychromatic erythrocytes (MPE) in the bone marrow of male CBA mice.

5.2.2.3 Oncogene transformation assays

Nickell-Brady *et al.* (1994) examined pulmonary adenocarcinomas induced by beryllium metal for the presence of genetic alteration in the K-*ras*, *p53,* and c-*raf*-1 genes. No K-*ras* codon 12, 13, or 61 mutations were seen in 24 lung tumors examined by direct sequencing. Using a more sensitive assay that detects mutant alleles at a sensitivity of $1x10^{-3}$, K-*ras* codon 12 GGT-GTT transversions were found in 2 of 12 adenocarcinomas. The researchers suggested "these activations were a late and rare event, possibly stemming from genomic instability during tumor progression." Nuclear immunoreactivity of *p53* was not observed in any beryllium-induced tumor, nor were any mutations detected within exons 5-8 of the *p53* gene. No rearrangements of the c-*raf*-1 protooncogene were detected by Southern blot analysis. The authors concluded that the mechanisms underlying the development of beryllium-induced lung cancer in rats did not involve gene dysfunctions commonly associated with human non-small-cell lung cancer.

5.3 Summary

Beryllium compounds were not mutagenic when tested in a variety of *Salmonella* tester strains. However, beryllium compounds were positive for *hprt locus* gene mutation in hamster cells and caused cell transformations in mammalian cells *in vitro*. Beryllium compounds also induced genetic alteration in the K-*ras* gene, without affecting *p53* or rearrangements of the c-*raf*-1 protooncogene, in beryllium-induced tumor cells. Beryllium compounds are clastogenic, inducing differential toxicity in *B. subtilis*; SCEs in hamster, rat, and human cells, *in vitro*; chromosomal aberrations in swine, hamster, and human cells, *in vitro*; and single strand chromosomal breaks and UDS in rat cells, *in*

vitro. However, beryllium compounds tested equivocally for the induction of forward mutation in *E. coli* and failed to induce mitotic recombination in *S. cerevisiae, in vitro,* or micronuclei in mice, *in vivo*.

6 Other Relevant Data

6.1 Absorption, distribution, metabolism and excretion

Data available to the IARC Working Group concerning absorption, distribution, metabolism, and excretion indicated that beryllium, when administered orally, beryllium is absorbed from the gastrointestinal tracts of mice, rats, dogs, and monkeys. After oral administration of carrier-free ^{7}Be as a chloride, 0.6% of the dose was estimated to be absorbed in monkeys, although the urinary excretion was reported to be 3.71%. Beryllium was excreted in the urine of these species for two days post-administration (Furchner *et al.* 1973, cited in IARC 1993).

Continuous inhalation of beryllium sulfate by rats resulted in development of a lung burden plateau after approximately 36 weeks (Reeves and Vorwald 1967, cited in IARC 1993). Clearance from lungs included accumulation of beryllium in the tracheobronchial lymph nodes, where concentrations reached peak values at 52 weeks after cessation of inhalation exposure. Deposition in other organ systems was not reported. In a later study, however, Zorn *et al.* (1977, cited in IARC 1993) reported that inhalation (nose-only) of aqueous aerosols of beryllium chloride and beryllium sulfate by rats resulted in approximately 13.5% of the dose being deposited in the skeleton.

When dogs inhaled aerosols of beryllium oxide calcined at 500°C (low-fired) or 1,000°C (high-fired), clearance from the lung followed first-order kinetics. Clearance half-time was 240 days for high-fired beryllium oxide and 64 days for the low-fired compound. Beryllium was distributed to the skeleton, tracheobronchial lymph nodes, liver, and blood. Both gastrointestinal and urinary excretions of beryllium were reported (Finch *et al.* 1990b, cited in IARC 1993).

During inhalation carcinogenicity studies of beryl ore dusts (described in Section 4), Wagner *et al.* (1969, cited in IARC 1993) reported elevated levels of beryllium in skeletons of rats, hamsters, and monkeys.

Like inhaled beryllium, parenterally administered beryllium salts lead to accumulation of the metal in the skeletal system. One day after intramuscular injection of beryllium chloride to rats, the highest concentrations of beryllium were detected in skeleton, liver, kidney, lungs, and spleen. After 64 days, skeletal and splenic beryllium concentrations were still higher, indicating continued deposition in these tissues, while concentrations in other tissues were reduced (Crowley *et al.* 1949). Similar results were reported in a comparative study for rats, and, to a lesser extent, for rabbits (Scott *et al.* 1950, cited in IARC 1993).

Twenty-four hours after intravenous administration of beryllium chloride (at pH 2) to rats, nearly half (47%) the administered dose was excreted in the urine and 43% was detected in bone. Only 4% of the administered dose remained in the liver, and 0.1% was recovered from the spleen (Klemperer *et al.* 1952, cited in IARC 1993).

After intravenous administration of beryllium sulfate to rats, circulating beryllium in the plasma was largely bound to plasma globulins, and a small part of the dose remained in a low-molecular-weight form (Vacher and Stoner 1968, cited in IARC 1993). Similar binding of beryllium to plasma proteins has been demonstrated for guinea pigs (Stiefel *et al.* 1980, cited in IARC 1993). When beryllium chloride was added to normal plasma (*in vitro*), only 2.5% was dialyzable, indicating a high level of binding to macromolecules. Other beryllium salts, however, were more readily dialyzable from plasma (citrate, 62%; maleate, 30%; bicarbonate, 10%). Feldman *et al.* (1953, cited in IARC 1993) concluded that at plasma concentrations in excess 10^{-7} mol/L, most of the beryllium present is in a nondialyzable phosphate state, with the smaller, dialyzable portion being mainly citrate. A low-affinity binding site for beryllium also was observed on the outer cell surface of human and guinea pig lymphocytes, and a higher-affinity binding site was detected in the cell nucleus (Skilleter and Price 1984, cited in IARC 1993).

After beryllium sulfate was repeatedly administered intraperitoneally to rats, beryllium was found concentrated in the cells of the proximal convoluted tubules (Berry *et al.* 1987, 1989, cited in IARC 1993). Beryllium accumulated in hepatic lysosomes where it was dissociated to the ionic form (Be^{2+}) by lysozymes and then became detectable in proximal nuclei of rats (Levi-Setti *et al.* 1988, Magos 1991, both cited in IARC 1993). Beryllium exhibited an affinity for nuclei isolated from rat liver, but was not bound to DNA or histones, only to a highly phosphorylated, non-histone protein fraction (Witschi and Aldridge 1968, Parker and Stevens 1979, both cited in IARC 1993).

Snow (1992) reviewed the effects of beryllium on cellular immunity and nucleic acid metabolism and suggested that a number of biological activities of beryllium resemble those attributed to metals known to be carcinogenic such as nickel and chromium. For example, all elicit strong immune responses in the respiratory system, and all affect enzymes involved in nucleotide metabolism and can decrease the fidelity of DNA replication *in vitro*. Epidemiological studies of occupational exposures have not generally benefited from reliable bio-exposure data. Although beryllium can be measured in blood or urine (see section 2), temporal relationships are unclear; current or recent exposure levels are not distinguishable because urinary excretion of beryllium can continue for several years following a known exposure (Klemperer *et al*. 1951, De Nardi *et al*. 1953, both cited in Leonard and Bernard 1993).

6.2 Binding to nucleoproteins and interference with DNA synthesis

Experimental studies in guinea pigs have demonstrated that ionized beryllium can bind to nucleic acids (Lansdown 1995, Leonard and Lauwerys 1987). In addition to binding to nucleoproteins, beryllium compounds (beryllium chloride and beryllium sulfate) affect certain enzymes (DNA and RNA polymerases, deoxythymidine kinase, and deoxythymidylate deaminase) needed for DNA synthesis. These effects can produce infidelity in DNA replication *in vitro* that may be manifested as genetic transformations in microorganisms and mammalian cells (Leonard and Lauwerys 1987).

6.3 Summary

After administration by inhalation, beryllium compounds are absorbed into the systemic circulation in studies involving mice, rats, guinea pigs, dogs, and monkeys. Pharmacokinetic analysis of beryllium compounds administered either by inhalation or intratracheally provided evidence that these beryllium compounds accumulate in the lung. Beryllium also accumulates in the bone after administration by inhalation or injection. Clearance from the bone is slower than from other organs. Absorbed beryllium is excreted by both gastrointestinal and urinary routes. Beryllium can bind to nucleic acids and affects certain enzymes needed for DNA synthesis.

7 References

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BERYLLIUM AND BERYLLIUM COMPOUNDS

Beryllium and beryllium compounds were considered by previous Working Groups, in 1971, 1979 and 1987 (IARC, 1972, 1980, 1987a). New data have since become available, and these are included in the present monograph and have been taken into consideration in the evaluation. The agents considered herein include (a) metallic beryllium, (b) beryllium-aluminium and -copper alloys and (c) some beryllium compounds.

1. Exposure Data

1.1 Chemical and physical data and analysis

1.1.1 *Synonyms, trade names and molecular formulae*

Synonyms, trade names and molecular formulae for beryllium, beryllium-aluminium and -copper alloys and certain beryllium compounds are presented in Table 1. The list is not exhaustive, nor does it comprise necessarily the most commercially important beryllium-containing substances; rather, it indicates the range of beryllium compounds available.

1.1.2 *Chemical and physical properties of the pure substances*

Selected chemical and physical properties of beryllium, beryllium-aluminium and -copper alloys and the beryllium compounds covered in this monograph are presented in Table 2.

The French chemist Vauquelin discovered beryllium in 1798 as the oxide, while analysing emerald to prove an analogous composition (Newland, 1984). The metallic element was first isolated in independent experiments by Wöhler (1828) and Bussy (1828), who called it ‘glucinium’ owing to the sweet taste of its salts; that name is still used in the French chemical literature. Wöhler’s name ‘beryllium’ was officially recognized by IUPAC in 1957(WHO, 1990). The atomic weight and common valence of beryllium were originally the subject of much controversy but were correctly predicted by Mendeleev to be 9 and +2, respectively (Everest, 1973).

Beryllium is the lightest of all solid, chemically stable substances and has an unusually high melting-point. It has a very low density and a very high strength-to-weight ratio. Beryllium is lighter than aluminium but is more than 40% more rigid than steel. It has excellent electrical and thermal conductivities. Its only markedly adverse feature is relatively pronounced brittleness, which has restricted the use of metallic beryllium to specialized applications (WHO, 1990).

Table 1. Synonyms (Chemical Abstracts Service (CAS) names are in italics), trade names and atomic or molecular formulae of beryllium and beryllium compounds

Chemical name	CAS Reg. No[a]	Synonyms and trade names	Formula
Beryllium metal	7440-41-7	*Beryllium*; beryllium-9; beryllium element; beryllium metallic; glucinium; glucinum	Be
Beryllium-aluminium alloy[b]	12770-50-2	*Alluminium alloy, nonbase, Al,Be*; aluminium-beryllium alloy	Al.Be
Beryllium-copper alloy[c]	11133-98-5	*Copper alloy; base, Cu,Be*; copper-beryllium alloy	Be.Cu
Beryl	1302-52-9	Beryllium aluminosilicate; beryllium aluminium silicate	$Al_2Be_3(SiO_3)_6$
Beryllium chloride	7787-47-5	Beryllium dichloride	$BeCl_2$
Beryllium fluoride	7787-49-7 (12323-05-6)	Beryllium difluoride	BeF_2
Beryllium hydroxide	13327-32-7 (1304-49-0)	Beryllium dihydroxide	$Be(OH)_2$
Beryllium sulfate	13510-49-1	*Sulfuric acid, beryllium salt (1:1)*	$BeSO_4$
Beryllium sulfate tetrahydrate	7787-56-6	*Sulfuric acid, beryllium salt (1:1), tetrahydrate*	$BeSO_4.4H_2O$
Beryllium oxide	1304-56-9	Beryllia; beryllium monoxide Thermalox™	BeO
Beryllium carbonate basic[d]	1319-43-3	*Carbonic acid, beryllium salt, mixture with beryllium hydroxide (Be(OH)$_2$)*	$BeCO_3.Be(HO)_2$
Beryllium nitrate	13597-99-4	Beryllium dinitrate; *nitric acid*, *beryllium salt*	$Be(NO_3)_2$
Beryllium nitrate trihydrate	7787-55-5	*Nitric acid, beryllium salt, trihydrate*	$Be(NO_3)_2.3H_2O$
Beryllium nitrate tetrahydrate	13510-48-0	Beryllium dinitrate tetrahydrate; *nitric acid, beryllium salt, tetrahydrate*	$Be(NO_3)_2.4H_2O$
Beryllium phosphate	13598-15-7	*Phosphoric acid, beryllium salt(1:1)*	$BeHPO_4$
Beryllium silicate[e]	13598-00-0	Phenazite; *phenakite*	$Be_2(SiO_4)$
Zinc beryllium silicate	39413-47-3 (63089-82-7)	*Silicic acid, beryllium zinc salt*	Unspecified

[a]Replaced CAS Registry numbers are shown in parentheses.

[b]Related compound registered by CAS is beryllium alloy, base, Be,Al historically (Lockalloy), Al (24-44%).Be (56-76%) [12604-81-8; replaced Registry No., 12665-28-0]; 60 beryllium-aluminium alloys are registered with CAS numbers, with different percentages of the two elements.

[c]Related compound registered by CAS is beryllium alloy, base, Be,Cu [39348-30-6]; 111 beryllium-copper alloys are registered with CAS numbers, with different percentages of the two elements.

[d]CAS name and Registry number shown were selected as being closest to the formula given by Lide (1991). Related compounds registered by CAS are: bis[carbonato(2)]dihydroxytriberyllium, $(BeCO_3)_2.Be(OH)_2$ [66104-24-3]; carbonic acid, beryllium salt (1:1), tetra-hydrate, $BeCO_3.4H_2O$ [60883-64-9]; carbonic acid, beryllium salt (1:1), $BeCO_3$ [13106-47-3]; and bis[carbonato(2-)]oxodiberyllium, $(CO_3)_2Be_2O$ [66104-25-4].

[e]Related compounds registered by CAS are: bertrandite, $Be_4(OH)_2O(SiO_3)_2$ [12161-82-9]; beryllium silicate, formula unspecified [58500-38-2]; silicic acid (H_2SiO_3), beryllium salt (1:1), $Be(SiO_3)$ [14902-94-4]; silicic acid (H_4SiO_4), beryllium salt (1:2), $Be_2(SiO_4)$ [15191-85-2]

Table 2. Physical properties of pure beryllium and beryllium compounds

Chemical name	Relative atomic/ molecular mass	Melting-point (°C)	Typical physical description	Density (g/cm^3)	Solubility
Beryllium metal	9.0122	1287	Grey, close-packed, hexagonal, brittle metal	1.85 (20 °C)	Soluble in most dilute acids and alkali; decomposes in hot water; insoluble in mercury and cold water
Beryllium chloride	79.92	399.2	Colourless to slightly yellow, orthorhombic, deliquescent crystal	1.899 (25 °C)	Soluble in water, ethanol, diethyl ether and pyridine; slightly soluble in benzene, carbon disulfide and chloroform; insoluble in acetone, ammonia and toluene
Beryllium fluoride	47.01	555	Colourless or white, amorphous, hygroscopic solid	1.986	Soluble in water, sulfuric acid, mixture of ethanol and diethyl ether; slightly soluble in ethanol; insoluble in hydrofluoric acid
Beryllium hydroxide	43.03	138 (dec.[a])	White, amorphous, amphoteric powder	1.92	Soluble in hot concentrated acids and alkali; slightly soluble in dilute alkali; insoluble in water
Beryllium sulfate	105.07	550 (dec.)	Colourless crystal	2.443	Forms soluble tetrahydrate in hot water; insoluble in cold water
Beryllium sulfate tetrahydrate	177.14	NR	Colourless, tetragonal crystal	1.713	Soluble in water; slightly soluble in concentrated sulfuric acid; insoluble in ethanol
Beryllium oxide	25.01	2530	Colourless to white, hexagonal crystal or amorphous, amphoteric powder	3.01 (20 °C)	Soluble in concentrated acids and alkali; insoluble in water
Beryllium carbonate	69.02	NR	NR	NR	Soluble in acids and alkali; insoluble in cold water; decomposes in hot water
Beryllium carbonate, basic	112.05	NR	White powder		Soluble in acids and alkali; insoluble in cold water; decomposes in hot water
Beryllium nitrate, trihydrate	187.97	60	White to faintly yellowish, deliquescent mass	1.56	Very soluble in water and ethanol
Beryllium phosphate	104.99	NR	NR	NR	Slightly soluble in water

Table 2 (contd)

Chemical name	Relative atomic/ molecular mass	Melting-point (°C)	Typical physical description	Density (g/cm^3)	Solubility
Beryllium silicate	110.11	NR	Triclinic, colourless crystal	3.0	Insoluble in acids
Zinc beryllium silicate	Unspecified	NR	Crystalline solid	NR	NR

From Ballance *et al.* (1978); Walsh & Rees (1978); IARC (1980); Sax & Lewis (1987); Lewis (1988); Budavari (1989); Lide (1991); Aldrich Chemical Co. (1992). NR, not reported; dec., decomposes

[a]Decomposes to beryllium oxide (Sax & Lewis, 1987).

Natural beryllium is 100% ^{9}Be isotope; four unstable isotopes with mass numbers of 6, 7, 8 and 10 have been made artificially. Because of its low atomic number, beryllium is very permeable to X-rays. Neutron emission after bombardment with α or γ rays is the most important of its nuclear physical properties, and beryllium can be used as a neutron source. Moreover, its low neutron absorptiveness and high-scattering cross-section make it a suitable moderator and reflector in structural materials in nuclear facilities; while most other metals absorb neutrons emitted during the fission of nuclear fuel, beryllium atoms only reduce the energy of such neutrons and reflect them back into the fission zone (Ballance *et al.*, 1978; Newland, 1984; WHO, 1990).

The chemical properties of beryllium differ considerably from those of the other alkaline earths, but it has a number of chemical properties in common with aluminium. Like aluminium, beryllium is amphoteric and shows very high affinity for oxygen; on exposure to air or water vapour, a thin film of beryllium oxide forms on the surface of the bare metal, rendering the metal highly resistant to corrosion, to hot and cold water and to oxidizing acids. Dichromate in water enhances this resistance by forming a protective film of chromate, similar to that formed on aluminium. In powder form, beryllium is readily oxidized in moist air and burns with a temperature of about 4500 °C when ignited in oxygen (Newland, 1984; Petzow *et al.*, 1985; WHO, 1990).

Cationic beryllium salts are hydrolysed in water; they form insoluble hydroxides or hydrated complexes at pH values between 5 and 8 and form beryllates above a pH of 8 (Reeves, 1986).

1.1.3 *Technical products and impurities*

Beryllium metal—purities: technical or nuclear grade, 98-> 99.5%; Grade A, 99.87%; Grade AA, 99.96%; distilled grade, > 99.99%; forms: single crystals, flakes, powders, plates, sheets, foils, wires, rods (Sax & Lewis, 1987; Alfa Products, 1990; CERAC, Inc., 1991; Aldrich Chemical Co., 1992; Atomergic Chemetals Corp., undated; D.F. Goldsmith Chemical & Metal Corp., undated); impurities vary with the production method (see section 1.2.1 and Tables 5 and 6).

Beryllium-aluminium alloy—composition limits for one alloy (%): Be, 4.5-6.0; Si, 0.2; Fe, 0.2; Mg, 0.5, Mn, 0.02; Cr, 0.02; Ni, 0.02; Ti, 0.02; Zn, 0.1; Cu, 0.05 (KBAlloys, 1985)

Beryllium-copper alloy—composition limits for one alloy (Alloy 20C or C82500) (%): Be, 2.0-2.25; Co, 0.35-0.65; total unnamed elements, 0.5 max; Cu, remainder (Stonehouse & Zenczak, 1991)

Beryllium chloride—purities: 97-99.5%; impurities (mg/kg): Al, 50; Fe, 100; Si, 30; Cd, 10; Ni, 120; Cu, 10; Co, 10; Zn, 10; Cr, 10; Mn, 10; Mg, 150 (Kawecki Berylco Industries, 1968; Alfa Products, 1990; CERAC, Inc., 1991; Strem Chemicals, 1992; Fluka Chemie AG, 1993)

Beryllium fluoride—purity: 99.5%; impurities (mg/kg): Al, 75; Fe, 75; Ni, 40; Cu, 10 (Kawecki Berylco Industries, 1968; CERAC, Inc., 1991; D.F. Goldsmith Chemical & Metal Corp., undated)

Beryllium hydroxide—contains different levels of several impurities depending on whether it is made from beryl ore or bertrandite ore (IARC, 1980)

Beryllium sulfate tetrahydrate—purities: 98.3-99.99%; impurities (%): chloride, Ca, Cd, Co, Cu, Fe, Ni, Pb and Zn, all < 0.005; K, Na, < 0.01 (Alfa Products, 1990; Aldrich Chemical Co., 1992; Fluka Chemie AG, 1993).

Beryllium oxide—purities: 99-99.99% (Alfa Products, 1990; CERAC, Inc., 1991; Aldrich Chemical Co., 1992; Strem Chemicals, 1992). The purity of beryllia is critical to its thermal conductivity: as the purity drops below 99.5%, thermal conductivity drops off rapidly. Impurities (mg/kg): Al, 46; Fe, 32; Cr, 8; Mn, < 2; Ni, 9; B, 2; Ca, 31; Co, < 1; Cu, 3; Si, 1861; Mg, 922; Li, 2; Zn, < 20; Ti, 5; Na, 173; Ag, < 1; Mo, < 3; Pb, 2. Silicon and magnesium silicates are added to beryllia powder as sintering aids (Brush Wellman, undated)

Beryllium carbonate—impurities (mg/kg): Al, 30; Fe, 100; Si, 150 (IARC, 1980)

Beryllium nitrate (trihydrate)**—**purity: 99.5% (D.F. Goldsmith Chemical & Metal Corp., undated); impurities (mg/kg): Al, 20; Fe, 30; Si, 50; Na, 20 (Kawecki Berylco Industries, 1968)

Impurities that occur in beryllium compounds that have been the subjects of previous monographs are: cadmium (IARC, 1987b), chromium (IARC, 1990a), cobalt (IARC, 1991), lead (IARC, 1987c), nickel (IARC, 1990b) and silica (IARC, 1987d).

1.1.4 *Analysis*

Beryllium metal

Selected methods for the determination of beryllium and beryllium compounds in various media are presented in Table 3. Other methods have been reviewed (IARC, 1980; Agency for Toxic Substances and Disease Registry, 1988; WHO, 1990).

Table 3. Methods for the analysis of beryllium and beryllium compounds (as Be)

Sample matrix	Sample preparation	Assay procedure	Limit of detection	Reference
Air[a]	Collect on membrane filter; dissolve in nitric acid	FLAA	0.08 μg/m^3; 0.002 μg/mL	Kleinman *et al.* (1989a)
	Collect sample on cellulose ester membrane filter; add nitric and sulfuric acids; heat; cool; evaporate to dryness; add sodium sulfate/sulfuric acid solution; heat	GFAA	0.005 µg/sample	Eller (1987) (Method 7102)
	Collect sample on cellulose ester membrane filter; ash with nitric:perchloric acid solution (4:1) v:v; heat; repeat; heat to dryness; dilute with nitric:perchloric acid solution (4:1)	ICP	1 μg/sample	Eller (1984) (Method 7300)
Water, ground- and surface	Acidify with nitric and hydrochloric acids (Method 3005)	FLAA ICP (313 nm)	0.005 mg/L 0.3 μg/L	US Environmental Protection Agency (1986a) (Method 6010)

Table 3. (contd)

Sample matrix	Sample preparation	Assay procedure	Limit of detection	Reference
Aqueous Samples, extracts, wastes	Acidify with nitric acid; heat and evaporate to low volume; cool; add nitric acid; reheat and reflux with hydrochloric acid (Method 3010)	FLAA ICP (313 nm)	0.005 mg/L 0.3 μg/L	US Environmental Protection Agency (1986a,b) (Methods 6010 and 7090)
Oils, greases, waxes (organic extract)	Dissolve in xylene or methyl iso-butyl ketone (Method 3040)	FLAA ICP (313 nm)	0.005 mg/L 0.3 μg/L	US Environmental Protection Agency (1986a) (Method 6010)
Sediments, sludges, soils	Digest with nitric acid and hydrogen peroxide; reflux with nitric acid Method (3050)	FLAA ICP (313 nm)	0.005 mg/L 0.3 μg/L	US Environmental Protection Agency (1986a) (Method 6010)
Aqueous samples, extracts, wastes	Acidify with nitric acid; evapo-rate to low volume; cool; add nitric acid; heat to complete digestion (Method 3010)	GFAA	0.2 μg/L	US Environmental Protection Agency (1986a,c) (Method 7091)
Sediments, sludges, soils	Digest with nitric acid and hydrogen peroxide; reflux with nitric acid Method (3050)	GFAA	0.2 μg/L	US Environmental Protection Agency (1986a,c) (Method 7091)
Tissue samples	Ash in hot concentrated nitric acid	FLAA	2 μg/L	Kleinman *et al.* (1989b)
Urine	Inject untreated samples directly into a pretreated graphite tube; follow standard addition method	GFAA	0.5 μg/L	Angerer & Schaller (1985)
	Modify matrix with magnesium nitrate; follow platform technique	GFAA	0.05 μg/L	Paschal & Bailey

FLAA, flame atomic absorption spectrometry; GFAA, graphite furnace atomic absorption spectrometry; ICP, inductively coupled argon plasma emission spectrometry

[a] [Digestion with a solution of nitric acid:perchloric acid:sulfuric acid and addition of several drops of hydrofluoric acid are currently recommended in sample preparation. Detection limits can be reduced to 0.001 μg/mL and sensitivity to 0.0001 μg/mL.]

Methods used up to the 1960s included spectroscopic, fluorometric, gamma activation, spectrophotometric and automatic titrimetric techniques (Ballance *et al.*, 1978). The main deficiency of spectrophotometric methods lies in the nonspecificity of the complexing agents used to form coloured complexes with beryllium. The limit of detection of these methods was about 100 ng/sample. The fluorimetric method, which is based on fluorescent dyes (preferably morin), has a very low limit of detection, 0.02 ng/sample; its sensitivity is exceeded only by that of the gas chromatographic method. The fluorimetric method may, however, be subject to error unless several time-consuming, cumbersome processing steps are undertaken prior to analysis (WHO, 1990).

Atomic absorption spectrometry is a rapid, very convenient method for analysing biological and environmental samples. The limit of detection for the flame technique is 2-10 μg/L and lower when the sample is concentrated before analysis (WHO, 1990). The graphite furnace method is much more sensitive, with a detection limit of approximately 0.1 μg/L. Blood, urine and tissue samples can be analysed by this technique with or without digestion of the biological matrix (see Table 3).

Inductively coupled plasma atomic emission spectrometry has been introduced to determine beryllium directly in a variety of biological and environmental matrices, because of its high sensitivity and low level of interference. Owing to its high sensitivity and specificity, gas chromatography is also used for determining beryllium in environmental and biological media, particularly at ultratrace levels. Beryllium can be converted into a volatile form by chelation with trifluoroacetylacetone before injection into the chromatographic column (WHO, 1990).

1.2 Production and use

1.2.1 *Production*

More than 40 beryllium-bearing minerals are known, but only two are of economic significance. The first beryllium mineral to be exploited commercially was beryl ($3BeO.Al_2O_3.6SiO_2$), an aluminosilicate (WHO, 1990). The largest deposits of beryl are found in Brazil and the former USSR (Petkof, 1982; Stonehouse & Zenczak, 1991). Beryl ore contains about 11% beryllium oxide (up to 4% beryllium) and is often obtained as a by-product of feldspar quarrying (for typical ore composition, see Table 17). In addition to the other major components, aluminium oxide and silicon dioxide, the principal impurities in the ores include alkali metals, alkaline-earth metals, iron, manganese and phosphorus. In its purest gem quality, it occurs as emerald (chromium-containing beryl), aquamarine (iron-containing beryl) and some other semiprecious stones (Petzow *et al.*, 1985; WHO, 1990).

The other mineral of economic significance, bertrandite ($4BeO.2SiO_2.H_2O$), is a beryllium silicate hydrate. Although bertrandite ore contains less than 1% beryllium, it became economically important in the late 1960s because it can be processed to beryllium hydroxide highly efficiently. Bertrandite mined in the USA accounts for about 85% of US consumption of beryllium ore. The total world reserves of beryllium that can be recovered by mining bertrandite are estimated at 200 000 tonnes (Petzow *et al.*, 1985; WHO, 1990).

Known deposits of other beryllium-containing minerals are being studied for possible commercialization. Most notable among these are phenakite ($2BeO.SiO_2$) at Yellowknife, Northwest Territory, Canada, the chrysoberyl ($BeO.Al_2O_3$) deposits of the Seward Peninsula, Alaska, and the Sierra Blanca deposits near El Paso, Texas, USA (Stonehouse & Zenczak, 1991).

Beryllium production started in some industrialized countries around 1916. Beryllium gained commercial importance in the early 1930s, following the realization that beryllium-copper alloys are extraordinarily hard, resistant to corrosion, non-magnetic, do not spark and withstand high temperatures. In addition, the nuclear and thermal properties and high specific modulus of beryllium metal made it attractive for nuclear and aerospace

applications, including weapons. The latter use is the main reason why reliable data on the production and consumption of beryllium have been scarce and incomplete. Considerable fluctuations in the supply and demand of beryllium result from variations in government programmes in armaments, nuclear energy and aerospace. For example, the demand for beryllium in the USA that was created by the programme for development of the atomic bomb was about equivalent to total world demand up to 1940 (WHO, 1990).

Production in the rest of the world paralleled those fluctuations in the beryllium market, with 222 tonnes produced in 1965, 320 tonnes in 1969 and 144 tonnes in 1974. Data on US production are now available, and world production of beryllium as beryl is shown in Table 4. If production from bertrandite is included, the USA appears to be the world's largest producer of beryllium raw materials (WHO, 1990).

(*a*) *Processing of beryl and bertrandite*

The first step in the processing of beryl ore is normally hand-sorting to select beryl crystals containing at least 10% beryllium oxide (Ballance *et al.*, 1978) on the basis of shape and colour (Powers, 1991).

Two commercial methods have been used to process beryl to beryllium hydroxide: the fluoride process and the sulfate process. In the *fluoride process*, which was discontinued in the 1970s, beryl was sintered together with sodium hexafluorosilicate, or the less expensive sodium fluoroferrate, at 700-800 °C to convert beryllium oxide to a water-soluble salt, sodium beryllium tetrafluoride (Na_2BeF_4). The reaction product was then leached with water at room temperature and precipitated from the purified solution with caustic soda as beryllium hydroxide (Petzow *et al.*, 1985; WHO, 1990).

The *sulfate process*, the only process currently used, involves either alkali or heat treatment of beryl. With alkali treatment, which was discontinued in the 1960s, finely ground beryl was heated until fusion or sintered below the melting-point with suitable alkalis, such as hydroxides and carbonates of sodium, potassium and calcium. With heat treatment, which has been used since the 1970s, beryl is melted without additives and quenched with water; the water insoluble portion, a solid solution with silicon dioxide, is reheated to 900 °C to render a total of 90-95% of the beryl soluble. Heat-treated or alkali-treated beryl is then extracted with sulfuric acid and carried through several additional purification steps to produce a fine-grained, readily filtered beryllium hydroxide (Petzow *et al.*, 1985; WHO, 1990).

The beryllium-poor bertrandite ores (≤ 0.5-0.8% BeO) mined in the USA since 1960 cannot be smelted economically by conventional methods, and a less complicated procedure has been developed in which a very pure beryllium hydroxide is produced by liquid-liquid extraction. This so-called 'SX-carbonate process' involves direct leaching of bertrandite ore with sulfuric acid, extraction of the sulfuric acid leachate with di(2-ethylhexyl)phosphoric acid in kerosene, stripping of beryllium from the organic phase with aqueous ammonium carbonate, and, through a series of heat, hydrolysis and precipitation steps, production of beryllium hydroxide (Petzow *et al.*,1985; WHO,1990). Beryllium hydroxide is the starting material for the production of beryllium, beryllia and beryllium alloys. For further processing, it is ignited to form the oxide (BeO) or converted to the fluoride (BeF_2) (WHO, 1990).

Table 4. World production of beryl (tonnes)

Country	1980	1981	1982	1983	1984	1986	1987	1988	1989	1990	1991[a]
Argentina	31	7	6	24[b]	15[a]	50	46	39	89[c]	85[a]	80
Brazil[d]	550	854[c]	1062	1252[a,c]	1252	907[c]	1000	913	800	850[a]	850
Madagascar	10	10	10	10	10	50 kg	35 kg	3 kg	154 kg	150 kg[c]	3
Mozambique	20	18	15	15[a]	15	1	ND	ND	ND	ND	ND
Portugal	19	18	19	18	18	ND	4	4	4	4	4
Rwanda	108	59	69	33	36	ND	ND	ND	ND	ND	ND
Republic of South Africa	ND	122	58	22	ND	3	135 kg	72 kg	ND	1[c]	1
Russia[a]	1800	1800	1800	1900	1900	1900	2000	2000	2000	1600	1300
USA[e]	6756[c]	6653[c]	4945	6046	5470[c]	5927	5499	5313	4592	4548	4339[c]
Zimbabwe	9	42	52	50[a]	50	103	83	33	46	28[c]	30
World[f]	9319	9597	8051	9375	8772	8891	8632	8302	7532	7119	6607

From Kramer (1985a, 1991a, 1992a) [somefigures are estimates]; beryl has also been produced in China, perhaps in Bolivia and Namibia and in small amounts in Nepal, but the available information is inadequate to formulate reliable estimates of production. ND, no data

[a]Estimated

[b]Preliminary

[c]Revised

[d]Export data for 1980–84

[e]Includes bertrandite ore calculated as equivalent to beryl containing 11% BeO

[f]Totals are not the sum of the columns, because world values are revised figures.

(*b*) *Beryllium metal*

The chief difficulties involved in the production of beryllium metal are the reactivity and high melting-point of the metal and the extreme stability of the oxide. Of the many possible methods of producing beryllium, two have been used in industry: fusion electrolysis and reduction of halides by metals. The only industrial process currently in use, developed in the 1930s, is reduction of beryllium fluoride with magnesium. The reaction is started by heating a mixture of relatively coarse-grained beryllium fluoride and magnesium in a graphite crucible. At a temperature of about 1300 °C, the reaction produces a mixture of beryllium pebbles and magnesium fluoride (Petzow *et al.*, 1985).

All practical electrolytic methods of production are based on decomposition of beryllium fluoride, beryllium oxide or beryllium chloride mixed with halides of the alkali metals or alkaline-earth metals. Several methods for the electrolysis of beryllium fluoride were developed in the 1920s. Electrolysis was carried out at above the melting-point of beryllium, at 1290-1400 °C; these methods are now obsolete. Electrolysis of beryllium chloride can be carried out at temperatures so low that the metal neither melts nor oxidizes. The beryllium is obtained as solid flakes, which are separated by washing out the electrolyte. This method was used in France, Japan, the United Kingdom and the former USSR (Petzow *et al.*, 1985).

Beryllium pebbles or flakes still contain many impurities and must be refined before they can be used to fabricate structural pieces. The main impurities in electrolytically produced beryllium are sodium and chloride; the main impurities in beryllium produced by the magnesium reduction process are magnesium and magnesium fluoride. Other impurities include beryllium oxide, carbon and metals, the most important being aluminium, iron and silicon (Petzow *et al.*, 1985). Beryllium is available mainly as block and rolled sheet and, to a lesser extent, as extruded bar, wire and near net shapes (Smugeresky, 1986).

Several commercial grades of beryllium are produced for specific uses: structural, nuclear, instrument, optical and electronic (Smugeresky, 1986). Commercial grades of beryllium are refined exclusively by vacuum melting in beryllium oxide or magnesium oxide crucibles and casting in graphite ingot moulds. The melting of magnesium-reduced beryllium in a high vacuum produces a metal of a purity comparable to that of electrolytic beryllium. Melting the electrolytic flakes in a vacuum further reduces the content of halides and low-boiling metals. A very pure grade of beryllium, particularly with respect to the content of oxide, aluminium, iron, silicon, carbon and halides, can be produced by electrolytic refining (SR flakes) (Ballance *et al.*, 1978; Petzow *et al.*, 1985).

(*c*) *Beryllium-aluminium alloy*

Beryllium-aluminium alloys (originally termed ‘lockalloy’ by the inventors, who were working for the Lockheed Co.) exhibit high bend ductility and high strength and are weldable and easy to machine. A major factor in their successful development was the preparation of a relatively fine, two-phase microstructure by a gas atomization process with quenching into water. The resultant powders are dried, then hot degassed, hot compacted and extruded to bars, from which thin sheet and thin-section extrusion are produced. Lockalloys were produced commercially from the late 1960s until 1975 (Lewis, 1988). The

one remaining US manufacturer currently produces beryllium-aluminium alloys under the trade name AlBeMet™ (Brush Wellman, 1992).

(*d*) *Beryllium-copper alloy*

Alloys with copper are the most important beryllium alloys. Copper-beryllium master alloy is manufactured commercially by an arc-furnace method in which beryllium oxide is reduced by carbon in the presence of molten copper at 1800-2000 °C; the resulting alloy typically contains 4.0-4.25 wt % beryllium. The master alloy is then melted together with virgin copper or copper scrap to produce the desired alloy, which is usually cast into billets (Ballance *et al.*, 1978; Stonehouse & Zenczak, 1991).

(*e*) *Beryllium chloride*

Beryllium chloride can be prepared either directly from beryl by the chloride process or by chlorination of beryllium oxide under reducing conditions. Beryllium chloride is purified by distillation in a stream of hydrogen, followed by fractional condensation (Petzow *et al.*, 1985).

(*f*) *Beryllium fluoride*

In the production of beryllium fluoride, beryllium hydroxide is dissolved in an ammonium hydrogen fluoride solution to produce ammonium tetrafluoroberyllate. Impurities can be precipitated as hydroxides. Upon concentration, ammonium tetrafluoro-beryllate crystallizes from solution and is separated; after heating, it dissociates into ammonium fluoride and beryllium fluoride (Petzow *et al.*, 1985).

(*g*) *Beryllium hydroxide*

Beryllium hydroxide exists in three forms. By adding alkali to a beryllium salt solution to make a slightly basic pH, a gelatinous beryllium hydroxide is produced. Aging of this amorphous product results in a metastable tetragonal crystalline form, which, after months of standing, is transformed into a stable, orthorhombic crystalline form. The orthorhombic modification is also precipitated by hydrolysis from a hot sodium beryllate solution containing more than 5 g/L beryllium. Granular beryllium hydroxide is the readily filtered product from sulfate extraction processing of beryl (Walsh & Rees, 1978).

(*h*) *Beryllium sulfate*

Beryllium sulfate can be obtained by heating beryllium sulfate dihydrate in air to 400 °C and from the reaction of beryl ore or beryllium oxide with sulfuric acid (Walsh & Rees, 1978; Petzow *et al.*, 1985).

(*i*) *Beryllium sulfate tetrahydrate*

Beryllium sulfate tetrahydrate is produced commercially in a highly purified state by fractional crystallization from a beryllium sulfate solution obtained by reacting beryllium hydroxide with sulfuric acid. The tetrahydrate crystallizes from the aqueous solution in well-developed crystals (Walsh & Rees, 1978; Petzow *et al.*, 1985).

(*j*) *Beryllium oxide*

Beryllium oxide is produced by the following processes: beryllium hydroxide is first converted to high-purity beryllium sulfate tetrahydrate, as described above. This salt is

calcined at carefully controlled temperatures, between 1150 and 1450 °C, selected to give the properties of the beryllium oxide powders required by individual beryllia ceramic fabricators. Alternatively, beryllium hydroxide may be purified first and then calcined directly to beryllium oxide powder (Walsh & Rees, 1978). In another process, beryl ore is fused with sodium silicic fluoride at 700-800 °C, with conversion to sodium fluoroberyllate and precipitation by means of caustic soda from the purified leached solution as beryllium hydroxide, from which the anhydrous chloride can be obtained by reaction with carbon and chlorine at 800 °C (US National Library of Medicine, 1992).

Today, practically all of the beryllium oxide produced commercially is calcined at temperatures of 1000 °C or higher and is referred to as 'high-fired'. Beryllium oxide that is calcined at temperatures lower than 1000 °C is referred to as 'low-fired'; it consists of poorly crystallized, small particles which are more reactive and more soluble in dilute acid than those of high-fired beryllium oxide (Finch *et al.*, 1988).

(*k*) *Beryllium carbonate*

Basic beryllium carbonate is formed in the reaction of beryllium salt solutions with alkali metal or ammonium carbonate solutions. If excess ammonium carbonate is used, a readily filtered precipitate of variable composition is formed on boiling. This salt is a suitable starting material for the preparation of beryllium salts of all types. Gentle calcining causes ammonia to escape, leaving beryllium basic carbonate. Further heating drives off the carbon dioxide to produce beryllium hydroxide (Petzow *et al.*, 1985).

(*l*) *Beryllium nitrate*

Beryllium nitrate trihydrate is prepared by crystallizing a solution of beryllium hydroxide or carbonate that has been treated with a slight excess of concentrated nitric acid; the dihydrates and monohydrates are also formed, depending on the concentration of the acid used. The anhydrous form may be obtained by treating an ethyl acetate solution of beryllium chloride with dinitrogen tetroxide but not by dehydration of one of the hydrated species; the latter operation results in thermal decomposition of the nitrate, with evolution of nitrous fumes (Drury *et al.*, 1978).

(*m*) *Beryllium phosphate*

Beryllium phosphate can be produced by the reaction of disodium hydrophosphate with a beryllium salt solution or by reaction of beryllium hydroxide solution with phosphoric acid (Mellor, 1946).

(*n*) *Beryllium silicate*

No information was available to the Working Group.

(*o*) *Zinc beryllium silicate*

No information was available to the Working Group.

1.2.2 *Use*

Typical use patterns for beryllium, beryllium alloys and beryllium compounds in the USA are presented in Table 5.

Table 5. Use patterns for beryllium in the USA (%)

Use category	1985	1987	1990	1991	1992
Metal and alloy in nuclear reactor and in military and aerospace applications	40	40	23	29	29
Alloy and oxide in electrical equipment	36	35	17	19	20
Alloy in oxide in electronic components	17	17	35	47	45
Alloy, metal and oxide in other applications	7	8	25	5	6

From Kramer (1985b, 1987, 1990, 1991b, 1992b)

(*a*) *Beryllium metal*

Some of the typical uses of beryllium metal are: structural material in space technology; moderator and reflector of neutrons in nuclear reactors; source of neutrons when bombarded with α particles; special windows for X-ray tubes; in gyroscopes, computer parts, inertial guidance systems; additives in solid propellant rocket fuels; beryllium-copper alloys; heat-sink material in low-weight, high-performance aircraft brakes; scanning mirrors and large mirror components of satellite optical systems; hardening of copper; and in developmental brass alloys (Sax & Lewis, 1987; WHO, 1990).

(*b*) *Beryllium-aluminium alloy*

The use of beryllium in alloys is based on a combination of properties that beryllium confers on other metals. Low density combined with strength, high melting-point, resistance to oxidation and a high modulus of elasticity make beryllium alloys light-weight materials that can withstand high acceleration and centrifugal forces. Most metals, however, form very brittle compounds with beryllium, and this and the low solubility of most elements in solid beryllium are the reasons why beryllium-rich alloys have not found extensive use (WHO, 1990). Historically, the only alloy with a high beryllium content was lockalloy, which contained 62% beryllium and 38% aluminium (Petzow *et al.*, 1985). Recently, Brush Wellman (1992) introduced a family of beryllium-aluminium alloys containing 20-60% beryllium and sold as AlBeMet™.

Aluminium-beryllium alloys are used mainly to save weight, reduce life-cycle cost and increase reliability in aerospace structures of advanced design. Small additions of beryllium to aluminium impart high strength, thermal stability and unusual resistance to oxidation (Lewis, 1988; WHO, 1990). These alloys are also used in computer information storage devices.

(*c*) *Beryllium-copper alloy*

The principal uses of beryllium stem from the discovery in the 1920s that the addition of only 2% beryllium to copper results in an alloy six times stronger than copper. Beryllium-copper alloys withstand high temperatures, are extraordinarily hard, are resistant to corrosion, do not spark and are non-magnetic. These alloys are used in many critical moving parts of aircraft engines and in key components of precision instruments, electrical relays and switches. An alloy containing 25% beryllium has limited application in camera

shutters. Beryllium-copper hammers, wrenches and other tools are used in petroleum refineries where sparks from steel against steel might cause explosions (Newland, 1984). A representative use for beryllium-copper alloys in the electronics industry is in integrated circuit sockets and electronic connectors (Stonehouse & Zenczak, 1991). These alloys are also used in sports equipment (e.g., golf clubs).

(*d*) *Beryllium chloride*

Beryllium chloride has been used as a raw material in the electrolytic production of beryllium and as the starting material for synthesis of organoberyllium compounds (Petzow *et al.*, 1985).

(*e*) *Beryllium fluoride*

Beryllium floride is used as an intermediate in the preparation of beryllium and beryllium alloys. It was used as an additive to welding and soldering fluxes because it dissolves metal oxides readily; it was also used in nuclear reactors and glass manufacture (Petzow *et al.*, 1985; Sax & Lewis, 1987). It is being investigated for use in fibre optic cables because of its low absorbance of ultraviolet radiation.

(*f*) *Beryllium hydroxide*

Beryllium hydroxide is used as an intermediate in the manufacture of beryllium and beryllium oxide (Budavari, 1989).

(*g*) *Beryllium sulfate tetrahydrate*

Beryllium sulfate tetrahydrate is used as an intermediate in the production of beryllium oxide powder for ceramics (Walsh & Rees, 1978).

(*h*) *Beryllium oxide*

Beryllium oxide has an extremely high melting-point, very high thermal conductivity, low thermal expansion and high electrical resistance. It can either be moulded or applied as a coating to a metal or other base; through the process of sintering (1480 °C), a hard, compact mass with a smooth glassy surface is formed. The ceramic properties of sintered beryllium oxide make it suitable for the production or protection of materials to be used at high temperatures in corrosive environments. Beryllium oxide ceramics have the highest thermal conductivity of the oxide ceramics (Newland, 1984; WHO, 1990). They are also used as dental materials (ceramic crowns).

Specific applications include: transistor mountings, semiconductor packages and microelectronic substrates. Transparency to microwaves has led to its use as windows, radomes and antennae in microwave devices; it is also used in high-power laser tubes. Its low density and other properties make it attractive for aerospace and military applications, such as gyroscopes and armour; general refractory uses include thermocouple sheaths and crucibles. It is also used as an additive to glass, ceramics and plastics; in the preparation of beryllium compounds; as a catalyst for organic reactions; and in nuclear reactor fuels and moderators (Livey, 1986; Sax & Lewis, 1987; US Environmental Protection Agency, 1987; Budavari, 1989).

(*i*) *Beryllium nitrate*

Beryllium nitrate was used until the late 1960s for stiffening incandescent gas mantles (Petzow *et al.*, 1985).

(*j*) *Beryllium phosphate*

Beryllium phosphate is not known to be produced commercially.

(*k*) *Beryllium silicate*

Beryllium silicate is not known to be produced commercially.

(*l*) *Zinc beryllium silicate*

Zinc beryllium silicate is not known to be produced or used commercially at present. It was used until about 1950 as a fluorescent lamp phosphor (WHO, 1990).

1.3 Occurrence

The environmental occurrence of beryllium has been reviewed extensively (Agency for Toxic Substances and Disease Registry, 1988; WHO, 1990).

1.3.1 *Natural occurrence*

Beryllium is the forty-fourth most abundant element in the Earth's crust (Drury *et al.*, 1978; Reeves, 1986), with an average content of about 6 mg/kg. It occurs in rocks and minerals (mica schist, granite, pegmatite and argillite) at concentrations of 0.038-11.4 mg/kg (Drury *et al.*, 1978). The most highly enriched beryllium deposits are found in granitic pegmatites, in which independent beryllium minerals crystallize (WHO, 1990).

Some 40 beryllium-containing minerals have been identified. Only ores containing beryl ($3BeO.Al_2O_3.6SiO_2$) and bertrandite ($4BeO.2SiO_2.H_2O$) have achieved commercial significance (Drury *et al.*, 1978). The most important environmental source of beryllium is the burning of coal. Coals contain 1.8-2.2 mg beryllium/kg dry weight (US Environmental Protection Agency, 1987), and beryllium occurs in the ash of many coals at concentrations of about 100 mg/kg (WHO, 1990). These waste products could represent an extensive beryllium reserve. The beryllium content of fuel oils has been estimated to be less than 0.1 ppm (Drury *et al.*, 1978).

1.3.2 *Occupational exposure*

The range of industrial processes in which occupational exposure to beryllium occurs has expanded over the past two decades: The number of uses has increased, and the occupational settings have diversified. It is used in many manufacturing industries (see above) and in a growing industry for recycling and processing. Nonsiliceous mineral slag used for sand blasting is also frequently contaminated with beryllium. Potential exposure settings are summarized in Table 6.

Table 6. Industries and trades in which there is potential exposure to beryllium

Ceramics
Electrical connectors
Nonferrous foundries
Nonferrous smelters
Sandblasting
Aerospace
Nuclear control equipment
Electronics
Refractories
Beryllium smelting or fabrication
Hazardous waste processing
Dental equipment and supplies
Engineering and scientific equipment
Mechanical measuring devices
Tool and die making
Soldering
Welding or flame cutting
Metal plating
Automotive parts
Telecommunication equipment
Golf club manufacture

From Cullen *et al.* (1986); WHO (1990)

The US Occupational Safety and Health Administration summarized data on occupational exposure to beryllium for the period 1 June 1979 to 31 January 1984 (Table 7), based on inspections of work places. Exposure levels in excess of the threshold limit value of 2 μg/m^3 were found mainly in the traditional beryllium industry but also in high technology industries.

(*a*) *Processing and manufacturing*

Substances to which potential exposure occurs during ore processing include ore dust, silicon dioxide fumes and acid mists and fumes of beryllium sulfate; those during beryllium oxide production include fumes of lead sulfide, copper sulfide and sulfur trioxide and dusts of beryllium oxide; those during production of beryllium metal include acid fluoride mists, fumes and dusts of beryllium ammonium fluoride, beryllium fluoride, hydrogen fluoride, ammonium fluoride, beryllium metal and beryllium oxide; and those during production of beryllium-copper alloy include beryllium oxide, copper and beryllium-copper alloy dusts and fumes. Machining potentially involves exposure to respirable particles of beryllium alloys in the absence of adequate controls (Laskin *et al.*, 1950; Preuss, 1988). Exposure concentrations in various industries have been reviewed (WHO, 1990).

Table 7. Occupational exposure to beryllium compounds (1 June 1979 to 31 January 1984)

Type of industry	No. of samples in which beryllium is detected	No. of samples ≥ 0.5 μg/m^3 [a]	No. of samples ≥ 2 μg/m^3 [b]
Traditional[c]	25	16	9
High-technology[d]	3	3	2
Secondary process[e]	5	1	0
Dental laboratory	1	0	0
Total	34	20	11

From Cullen *et al.* (1986)

[a]Criterion of the US National Institute for Occupational Safety and Health

[b]Standard of the US Occupational Safety and Health Administration

[c]Including particulate blasting, shipbuilding and repair, nonferrous foundries, nonclay refractories, beryllium machining and fabrication and metalworking

[d]Including the semiconductor industry, precision electronics industry and spacecraft and missile manufacture

[e]Including secondary nonferrous smelters, nonferrous foundries and hazardous waste reclamation

Although there are few quantitative data on exposure to beryllium before 1947, there seems to be little doubt that extremely high concentrations were encountered in the work place (US National Institute for Occupational Safety and Health, 1972). In the USA, concentrations greater than 1000 μg/m^3 were not uncommon in beryllium extraction facilities (Eisenbud & Lisson, 1983). Exposures measured in December 1946 (by the filter-paper dust sampler method) ranged from 110 to 4710 μg/m^3 in the furnace area of a beryllium extraction plant (Laskin *et al.*, 1950). Concentrations of 590-43 300 μg/m^3 were found in a beryllium-copper alloy plant in Lorain, Ohio, USA, monitored by the Atomic Energy Commission in 1947 and 1948 (Zielinski, 1961). After institution of control measures in 1949 in a new beryllium-copper alloy production plant in Elmore, Ohio, the limit of 2 μg/m^3 was considerably exceeded between 1953 and 1960, with time-weighted average values of 3.8-9.5 μg/m^3 in 1953, 6.8-19.1 μg/m^3 in 1956 and 23.1-54.6 μg/m^3 in 1960 (Zielinski, 1961; US National Institute for Occupational Safety and Health, 1972). In the same beryllium-copper alloy plant, a new furnace was installed between 1960 and 1966. Concentrations ranged from < 0.1 μg/m^3 in the mixing areas to 1050 μg/m^3 in the oxide areas in 1960 and from 0.2 μg/m^3 in the saw area to 249 μg/m^3 in the arc furnace area in 1966. Five-day average beryllium concentrations in this plant were 60.3 μg/m^3 in 1960 and 18.1 μg/m^3 in 1966 (see Table 8) (Cholak *et al.*, 1967)

In a summary of beryllium concentrations in 2627 air samples taken during 1950-57 in two US beryllium production plants, Breslin and Harris (1959) reported that 10-15% of workers were exposed to concentrations greater than 2 μg/m^3 and that the average concentration in each plant in many operations was 10 μg/m^3. Exposures may have been higher in plants that were not monitored by the Atomic Energy Commission (US National Institute for Occupational Safety and Health, 1972).

Table 8. Concentrations of beryllium in air at a number of locations in a beryllium-copper alloy plant in Ohio (USA) during two cycles of air monitoring six years apart

Location	Year	Beryllium concentration (μg/m^3) of air per 2-h period		
		Average	Median	Range
Oxide area	1960	149.4	72.5	0.4-1050.0
	1966	10.7	8.1	0.8-29.3
Arc furnace area	1960	87.6	50.0	22.1-502.0
	1966	25.9	36.9	7.7-249.0
Mixing area	1960	21.6	14.4	< 0.1-452.0
	1966	20.0	14.7	5.9-88.5
Casting area	1960	39.8	14.6	0.2-535.0
	1966	25.4	20.5	8.5-210.5
Fisher furnace area	1960	40.8	28.8	0.2-340.0
	1966	7.3	5.5	1.5-37.8
Saw area	1960	25.6	21.1	< 2.5-92.5
in rolling mill	1966	5.7	4.0	0.2-18.4
Cropping area	1960	52.8	33.6	14.0-399.0
Ajax furnace area[a]	1966	14.4	11.1	4.6-87.5
All areas	1960	60.3	28.4	< 0.1-1050.0
	1966	18.1	11.4	0.2-249.0

From Cholak *et al.* (1967)

[a]Approximately same area as cropping area in 1960

The US Atomic Energy Commission presented exposure data from five major beryllium-processing plants for various periods during 1950-61. Up to 40-75% of the daily weighted average exposures exceeded 2 μg/m^3 (US National Institute for Occupational Safety and Health, 1972).

[The Working Group noted the uncertainty of the representativeness for exposure of workers of air monitoring data obtained in the 1940s, 1950s and 1960s.]

In the early 1970s in a beryllium extraction and processing plant in northeastern USA, peak concentrations up to 1310 μg/m^3 were observed (Kanarek *et al.*, 1973). Follow-up analyses in 1974 showed a significant decrease (Sprince *et al.*, 1978).

The US National Institute for Occupational Safety and Health conducted several surveys of air in different beryllium plants in the USA. In a beryllium production plant, concentrations of 0.3-160 μg/m^3 were found in 1971, the high values occurring in powdering operations (H.M. Donaldson, 1971; cited in WHO, 1990). In another beryllium production plant, the concentrations of airborne beryllium in 1972 rarely exceeded the threshold limit value of 2 μg/m^3 (H.M. Donaldson & P.J. Shuler, 1972; cited in WHO, 1990). Beryllium concentrations in 50 personal samples collected at a secondary copper smelter in 1982-83 ranged between < 0.2 and 0.5 μg/m^3 (Cherniak & Kominsky, 1984). In 1983, the

concentrations of beryllium in 121 personal air samples obtained in the refinery and manufacturing melt areas of a precious metals refinery ranged from 0.22 to 42 μg/m^3 (mean, 1.4 μg/m^3) (K.P. McManus *et al.*, 1986; cited in WHO, 1990). Concentrations in the beryllium shop of another plant in 1985 ranged from < 0.2 to 7.2 μg/m^3 and exceeded 0.5 μg/m^3 in 6/33 breathing-zone samples (Gunter & Thoburn, 1986).

Kriebel *et al.* (1988a) described the beryllium concentrations in a plant in which most of the beryllium refined in the USA since 1934 has been produced, the principal product always having been beryllium-copper alloys (containing ≤ 2-4% beryllium). Table 9 summarizes the daily weighted average concentrations in 16 departments in four periods. The concentrations were high for many years, with some estimated to have been in excess of 100 μg/m^3; as late as 1975, average exposures to beryllium in some jobs were greater than 10 μg/m^3. After about 1977, the levels were in compliance with the permissible exposure limit of 2 μg/m^3. The median cumulative exposure of 297 white male workers surveyed in 1977 was 65 μg/m^3-years; their median exposure was 0.4 μg/m^3, and the mean number of years worked was 17. [The Working Group noted that there was some overlap in the plants surveyed.]

Table 9. Daily weighted average concentrations of beryllium (μg/m^3) in 16 departments[a] in a US beryllium production plant in four periods

Department	Approximate no. of workers in 1943	No. of jobs in department	Period			
			1935-54	1955-64	1965-76	1977-83
Oxide	46	14	46	16	8.8	0.5
Arc furnace room	26	6	80	51	11	0.7
Detroit furnaces	24	4	51	51	33	NA
Foundry	27	5	19	19	13	NA
Melt and cast	105	6	18	18	7.6	1.1
Hot rolling	19	8	9.3	9.3	2.5	0.2
Cold rolling	29	8	9.2	9.7	2.5	0.2
Rod and wire	39	8	5.9	5.9	2.0	0.2
Annealing	10	5	13	13	5.7	0.1
Pickling	11	3	0.2	0.2	0.2	0.1
Machining, grinding	60	5	1.7	1.7	0.9	0.1
Maintenance	73	13	6.2	5.7	3.5	0.1
Inspection	12	7	1.6	1.6	0.9	0.1
Laundry	–	1	2.5	3.5	1.0	0.1
Laboratories, research and development	28	6	1.4	1.4	1.2	0.2
Stores, shipping	20	3	3.6	3.6	2.0	0.1
Total	529	102				

From Kriebel *et al.* (1988a); NA, not applicable; these departments were not operational during 1977-83.
[a]Smaller departments were grouped for presentation.

(*b*) *Machining and use*

Personal air samples taken at US factories in which machining of beryllium metal and alloys involved drilling, boring, cutting and sanding did not contain any detectable amount of beryllium (Gilles, 1976; Boiana, 1980; Lewis, 1980). In a US boat factory in which workers were engaged in grid blasting, beryllium concentrations of 6-134 μg/m^3 were measured (Love & Donohue, 1983). Breathing-zone air samples taken from workers during grinding, polishing, cutting and welding of beryllium-containing alloys in a German metal processing plant contained < 0.1-11.7 μg/m^3 beryllium in total dust; 0.1-10.0 μg/m^3 during hand cutting; 1.4-11.7 μg/m^3 during automatic cutting; 2.1-3.63 μg/m^3 during welding without exhaust extraction; and 1.12-1.34 μg/m^3 during welding with exhaust extraction (Minkwitz *et al.*, 1983; WHO, 1990).

Dental laboratory technicians were exposed to < 2 μg/m^3 beryllium in the breathing zone during the processing of beryllium-containing dental alloys in the USA when exhaust ventilation was used (Dvivedi & Shen, 1983). Air measurements in three dental laboratories in Italy where melting and finishing of dental prostheses were carried out revealed beryllium concentrations in the breathing area in the range of 0.04-1.7 μg/m^3. The mean concentration of beryllium in the urine of 46 dental technicians (0.34 μg/L; range, 0.05-1.7) was higher than that of non-occupationally exposed subjects (mean, 0.26 μg/L; range, < 0.03-0.8) (Apostoli *et al.*, 1989a). [The Working Group noted that the smoking habits of the technicians were not defined.]

1.3.3 *Air*

The major source of atmospheric beryllium is combustion of coal, and its most prevalent chemical form is probably beryllium oxide, mainly bound to particles smaller than 1 μm (WHO, 1990). In earlier reports, average atmospheric background concentrations of beryllium were reported to be less than 0.1 (Bowen, 1966) and 0.2 ng/m^3 (Sussmann *et al.*, 1959). The air of over 100 cities in the USA, sampled in 1964-65, did not contain detectable amounts of beryllium (detection limit, 0.1 ng/m^3) (Drury *et al.*, 1978). Annual average background concentrations during 1977-81 throughout the USA were around the detection limit of 0.03 ng/m^3. Annual averages at urban monitoring stations where concentrations exceeded 0.1 ng/m^3 ranged between 0.11 and 6.7 ng/m^3 during 1981-86 (US Environmental Protection Agency, 1987; WHO, 1990). These data are similar to those found in other countries: Ikebe *et al.* (1986) found an average of 0.042 ng/m^3 in 76 air samples collected in 17 Japanese cities between 1977 and 1980; the highest values were found in Tokyo (0.22 ng/m^3) and in an industrial area in Kitakyushu (0.21 ng/m^3). R. Freise and G.W. Israel (1987, cited in WHO, 1990) found annual mean values in Berlin (Germany) of 0.2-0.33 ng/m^3. A concentration of 0.06 ng/m^3 was measured in a residential area, an office area and the inner city area of Frankfurt, whereas 0.02 ng/m^3 was measured in a rural area near Frankfurt (Müller, 1979).

Atmospheric concentrations of beryllium in the vicinity of beryllium processing plants are often higher than those elsewhere. A mean concentration of 15.5 ng/m^3 and a maximum concentration of 82.7 ng/m^3 were reported near a Pennsylvania (USA) factory, whereas background levels in several locations in the area averaged only 0.2 ng/m^3 (Sussman *et al.*, 1959).

The average concentration of beryllium in air 400 m from a beryllium extracting and processing plant in the former USSR, which was not equipped with emission control devices, was 1 μg/m^3; at 1000 m, it was 10-100 ng/m^3. Between 500 and 1500 m from a mechanical beryllium-finishing plant with operational filter facilities, no beryllium was detected in air [detection limit not given] (Izmerov, 1985). Bencko *et al.* (1980) reported beryllium concentrations of 3.9-16.8 ng/m^3 (average, 8.4 ng/m^3) in the vicinity of a power (coal) plant in former Czechoslovakia.

1.3.4 *Tobacco smoke*

In a German study of three brands of cigarettes [origin of tobaccos and number of samples not given], 0.47-0.75 μg beryllium was found per cigarette. Less than 10% of the beryllium content (0.011-0.074 μg/cigarette) was released into mainstream smoke during smoking (Zorn & Diem, 1974).

1.3.5 *Water*

*B*eryllium concentrations in surface waters are usually in the range 0.01-0.1 μg/L (WHO, 1990). The concentrations in 15 major US river basins ranged from 0.01 to 1.22 μg/L, with a mean of 0.19 μg/L (Safe Drinking Water Committee, 1977). Water samples taken from various areas near the Seward Peninsula in Alaska contained beryllium concentrations of 0.034-2.4 μg/L (Gosink, 1976). Surface water in eastern USA and Siberia contained beryllium at concentrations ranging from 0.1 to 0.9 μg/L (Safe Drinking Water Committee, 1977). Groundwater samples from Germany contained < 5-9 ng/L, with a mean of 8 ng/L; beryllium concentrations in seawater were 10 times lower than those in surface water (Reichert, 1974).Concentrations of 0.2-0.9 ng/L (mean, 0.5) (Merrill *et al.*, 1960) and 2 ng/L (Meehan & Smythe,1967)were reported in the Pacific Ocean. Measures and Edmond (1982) found still lower concentrations, 0.04-0.06 ng/L, in the mixed layer—up to about 500 m.

In a survey of 380 US drinking-water sources in 1962-67, beryllium was found in only 1.1% of samples, at concentrations ranging from 20 to 170 ng/L (mean, 100) (Safe Drinking Water Committee, 1977). Sauer and Lieser (1986) found beryllium at 27 ± 8 ng/L in drinking-water samples from Germany.

1.3.6 *Soils*

Beryllium occurs in most soils. Drury *et al.* (1978) reported an average of 6 mg/kg (range, 0.1-4.0) worldwide and 0.04-1.45 mg/kg in Kenya. Of 847 samples of agricultural soils collected at a depth of 20 cm throughout the USA, 66% contained < 1 mg/kg, 22% between 1 and 2 mg/kg and 12% between 2 and 7 mg/kg (Shacklette *et al.*, 1971). The mean beryllium concentration in 27 soil profiles (with 129 horizons) of uncontaminated soil from various locations in Japan was 1.31 mg/kg (Asami & Fukazawa, 1985).

In some small, unpolluted areas in which rocks contain large amounts of beryllium, the overlying soils show relatively high beryllium concentrations; e.g., soils in the Lost River Valley, Alaska, USA, contained up to 300 mg/kg, with an average of 60 mg/kg (WHO, 1990).

1.3.7 *Food*

Only limited, variable data are available on beryllium contents of food (WHO, 1990). The concentrations in various foods collected in New South Wales, Australia, ranged from 10 to 470 μg/kg ash weight (0.07-1175 μg/kg fresh weight); the highest concentrations were found in peanut shells (Meehan & Smythe, 1967).

Owing to the limited data, the daily human intake of beryllium from food has not been determined. In a study in the United Kingdom (Hamilton & Minsky, 1973), the average total dietary intake was estimated to be < 15 μg/day. The US Environmental Protection Agency (1987) estimated a total daily consumption of about 420 ng, most of which came from food (120 ng/day) and drinking-water (300 ng/day); air and dust reportedly contributed very little to the total intake of beryllium.

1.3.8 *Human tissues and secretions*

The measured concentrations of beryllium in body fluids and tissues have diminished substantially over the past 10 years, probably as a consequence of improved analytical techniques, including better procedures for minimizing beryllium contamination during collection and assay. The validity of the data reported in the older literature is therefore somewhat doubtful.

Sprince *et al.* (1976) analysed specimens taken at autopsy from patients without granulomatous disease and found less than 20 μg/kg dry weight of beryllium in lung tissue (mean, 5 μg/kg; range, 3-10; six cases) and mediastinal lymph nodes (mean, 11 μg/kg; range, 6-19; seven cases). These concentrations are within the range of 90% of the values of 2-30 μg/kg dry lung tissue found in 125 lung specimens obtained during thoracic surgery (Baumgardt *et al.*, 1986).

Caroli *et al.* (1988) analysed different parts of lung tissue from 12 subjects in an urban area of Rome (Italy), who were nonsmokers, 50 or more years old and had not been occupationally exposed to beryllium during their lifetime. The overall mean of 5 μg/kg fresh weight indicates a smaller concentration range than those above, which were expressed in dry weight.

In a survey of 66 patients with beryllium disease in the US Beryllium Case Registry, the concentrations of beryllium ranged from 4 to 45 700 μg/kg dried tissue; 82% of the patients had concentrations of more than 20 μg/kg dry weight. Peripheral lymph-node specimens from five patients contained 2-490 μg/kg beryllium and mediastinal specimens, 56-8500 μg/kg (Sprince *et al.*, 1976).

Beryllium concentrations in urine specimens from non-occupationally exposed subjects are summarized in Table 10. The mean beryllium concentration in blood from 20 non-occupationally exposed German subjects was 0.9 μg/L (SD, 0.5) (Stiefel *et al.*, 1980).

Smoking appears to influence the concentration beryllium in urine: the beryllium concentration in the urine of heavy smokers (0.31 ± 0.17 μg/L) was significantly greater than that of nonsmokers (0.20 ± 0.14 μg/L) (Apostoli *et al.*, 1989b).

An exposure concentration of 2 $\mu g/m^3$ beryllium in air was found to correspond to about 7 μg/L in urine and about 4 μg/L in blood (Zorn *et al.*, 1988).

Table 10. Urinary concentrations of beryllium, identified by graphite furnace atomic absorption, in specimens from non-occupationally exposed subjects

Country	No. of subjects	Concentration (μg/L; mean ± SD)	Reference
USA	120	0.9 ± 0.4	Grewal & Kearns (1977)
Italy	56	0.6 ± 0.2	C. Minoia *et al.* (1985; cited by Apostoli *et al.*, 1989b)
USA	NR	0.13	Paschal & Baily (1986)
Italy	163	0.24 ± 0.16 (range, <0.03-0.8)	Apostoli *et al.* (1989b)
Italy	579	0.4 (range, < 0.02-0.82)	Minoia *et al.* (1990)

Modified from Apostoli *et al.* (1989b); NR, not reported

1.4 Regulatory status and guidelines

Occupational exposure limits and guidelines for beryllium and beryllium compounds established in different parts of the world are given in Table 11.

Table 11. Occupational exposure limits and guidelines for beryllium and beryllium compounds

Country or region	Year	Concentration (μg/m^3)	Interpretation[a]
Argentina	1991	2	TWA, potential carcinogen
Australia	1990	2	TWA, probable human carcinogen
Belgium	1990	2	TWA, probable human carcinogen
Bulgaria	1984	1	TWA
China	1979	1	TWA
Denmark	1992	1	TWA[b]
Finland	1990	0	Suspected of having carcinogenic potential
France	1990	2	TWA, carcinogen
Germany	1992	0	A2[c]
Hungary	1990	1	STEL, probable human carcinogen, irritant, sensitizer
Indonesia	1978	2	TWA
Italy	1978	2	TWA
Japan	1991	2	TWA, probable human carcinogen
Korea, Republic of	1983	2	TWA
Mexico	1984	2	TWA
Netherlands	1986	2	TWA
Poland	1985	1	TWA

Table 11. (contd)

Country or region	Year	Concentration ($\mu g/m^3$)	Interpretation[a]
Romania	1975	1	STEL
Sweden	1991	2	TWA, causes cancer, sensitizer
Switzerland	1990	2	TWA, inhalable dust, absorbed through skin
Taiwan	1981	2	TWA
United Kingdom	1994	2 (proposal)	STEL
USA			
OSHA	1989	2	TWA (PEL)
		5	Ceiling
		25	Max
NIOSH	1990	0.5	TWA, carcinogens (REL)
ACGIH	1992	2	TWA, A2[d] (TLV)
Venezuela	1978	2	TWA
		25	Ceiling

From Arbeidsinspectie (1986); Cook (1987); US Occupational Safety and Health Administration (OSHA) (1989); Arbetarskyddsstyrelsens (1991); Institut National de Recherche et de Sécurité (1990); US National Institute for Occupational Safety and Health (1990); International Labour Office (1991); American Conference of Governmental Industrial Hygienists (ACGIH) (1992); Anon. (1992); Arbejdstilsynet (1992); Deutsche Forschungsgemeinschaft (1992); UNEP (1993).

[a]The concentrations given may or may not have regulatory or legal status in the various countries; for interpretation of the values, the original references or other authoritative sources should be consulted. TWA, time-weighted average; STEL, short-term exposure limit; Max, acceptable maximal peak (of 30-min maximal duration) above the acceptable ceiling concentration for an 8-h shift; PEL, proposed exposure limit; REL, recommended exposure limit; TLV, threshold limit value

[b]Beryllium and beryllium compounds are on a list of dangerous compounds but not classified for carcinogenic effect.

[c]Compounds which in the Commission's opinion have proven so far to be unmistakably carcinogenic in animal experimentation only; namely under conditions which are comparable to those for possible exposure of a human being at the workplace, or from which such comparability can be deduced

[d]Suspected human carcinogen; chemical substance, or substances associated with industrial processes, which are suspected of inducing cancer, on the basis of either limited epidemiological evidence or demonstration of carcinogenesis in one or more animal species by appropriate methods

Stationary sources (extraction plants, ceramic plants, foundries, incinerators and propellant plants for the processing of beryllium ore, beryllium, beryllium oxide, beryllium alloys and beryllium-containing waste; machine shops for the processing of beryllium, beryllium oxide and any alloy containing more than 5% beryllium by weight) are subject to the US national emission standard for beryllium, which is 0.01 $\mu g/m^3$ (30-day average) in ambient air for those production facilities which qualify for regulation through ambient air monitoring. Other facilities must meet a total site emission limit of 10 g per 24 h (US Environmental Protection Agency, 1992).

In the European Economic Community, beryllium and beryllium compounds are not permitted in cosmetic products (Commission of the European Communities, 1991a, 1992). Waste (except domestic waste) containing or contaminated by beryllium and beryllium compounds is classified as hazardous waste (effective date, 12 December 1993) (Commission of the European Communities, 1991b). Member States must take the necessary steps to limit the introduction of beryllium and its compounds into groundwater (effective date, 26 January 1982) (Commission of the European Communities, 1980). Beryllium and beryllium compounds (except aluminium beryllium silicates) are classified as very toxic and irritant (effective date, 1 July 1992) (Commission of the European Communities, 1991c).

2. Studies of Cancer in Humans

Beryllium was considered previously by three working groups (IARC, 1972, 1980, 1987). The first group (IARC, 1972) found the four epidemiological studies available at that time (Hardy *et al.*, 1967; Stoeckle *et al.*, 1969; Mancuso & El-Attar, 1969; Mancuso, 1970) not to provide evidence of the existence of a possible relationship between exposure to beryllium compounds and the occurrence of cancer in man. The second working roup (IARC, 1980) reviewed four subsequent cohort studies (Infante *et al.*, 1980; Mancuso, 1979, 1980; Wagoner *et al.*, 1980) and concluded that the evidence for an increased risk for lung cancer from occupational exposure to beryllium was limited. No new study was available at the time of the third review (IARC, 1987).

2.1 Cohort studies (see Table 12, p. 70)

Mancuso (1979) conducted a retrospective cohort mortality study of workers employed in two beryllium extraction, production and fabrication facilities in the USA: one in Lorain, Ohio, and the other in Reading, Pennsylvania (see Table 13, p. 71, for description). The cohort was limited to workers who had been employed for at least three months during 1942-48. Observed and expected numbers of deaths were compared using a modified life-table analysis. Expected deaths were calculated on the basis of five-year mortality rates for the general white male population of the USA, except that the author did not have access to the actual national mortality rates for 1968-75 and calculated expected deaths for that period by applying US mortality rates for 1965-67. As a consequence of this extrapolation, expected lung cancer death rates for the 1968-75 period were underestimated by a factor of 10% (Saracci, 1985). The standardized mortality ratio (SMR) for lung cancer among the 1222 workers in the Ohio plant was 2.00 (1.8 with Saracci's adjustment; 95% confidence interval [CI], 1.2-2.7); that among the 2044 workers at the Pennsylvania plant was 1.37 (1.25 with Saracci's adjustment; 95% CI, 0.9-1.7). The combined lung cancer SMR (with Saracci's adjustment) for the two plants was 1.42 (95% CI, 1.1-1.8). A consistently greater excess of lung cancer was seen in the two plants among workers who were followed for 15 or more years since first employment; the SMRs (with Saracci's adjustment) were 2.0 (95% CI, 1.3-3.1) for the Ohio plant and 1.5 (95% CI, 1.0-2.1) for the Pennsylvania plant. In the combined cohort, the excess of lung cancer was limited to workers who had been employed for less than five years and followed for 15 or more years since first employment. [The

Working Group noted that no analysis of risk by job title or exposure category was conducted. The period of initial employment of the study cohort preceded the imposition by the US Atomic Energy Commission in 1949 of a 2 μg/m^3 8-h time-weighted average limit for occupational exposure to beryllium and a ceiling limit of 25 μg/m^3, applicable to all beryllium facilities under contract to the Commission (Preuss, 1988).] A study of the beryllium alloy plant in Lorain, Ohio, conducted in 1947-48 by the US Atomic Energy Commission (Zielinski, 1961), showed concentrations of beryllium ranging from 411 μg/m^3 in the general air surrounding the mixing operation to 43 300 μg/m^3 in the breathing zone of alloy operatives. Control measures were introduced throughout US plants after 1949, and exposure levels in beryllium facilities were reduced markedly. Extraction plants, for example, were able to maintain exposure levels of 2 μg/m^3 or less, while certain foundry operations had air concentrations consistently in excess of 2 μg/m^3, with maximal values greater than 1000 μg/m^3 during the period 1968-72 in the Pennsylvania plant (Wagoner *et al.*, 1980).

Mancuso (1980) re-analysed mortality in the same Ohio and Pennsylvania beryllium extraction and processing plants, but extended the period of employment of the study cohort to 1937-48 and used as a comparison group viscose rayon industry workers employed at one company during 1938-48. Mortality was followed up through 1976. Among the 3685 cohort members from the two beryllium plants, 80 lung cancer deaths were observed, whereas 57.1 were expected on the basis of the total mortality experience of the viscose rayon workers (SMR, 1.40; $p < 0.01$) and 50.6 deaths were expected on the basis of the mortality experience of viscose rayon workers employed in a single department of the industry (SMR, 1.58; $p < 0.01$). [The Working Group noted that use of the latter reference cohort may introduce a selection bias into the analysis, since the mortality experience of workers who never change departments while employed in the industry may differ from that of the total workforce of the industry, for non-occupational reasons.] Lung cancer SMRs were calculated by duration of employment in comparison with the entire group of viscose rayon employees; these values were 1.38 ($p < 0.05$; 52 observed deaths) for one year or less of employment, 1.06 (14 observed deaths) for more than one year to four years or less, and 2.22 ($p < 0.01$; 14 observed deaths) for more than four years' employment.

Wagoner *et al.* (1980) expanded the cohort mortality study of the same Pennsylvania plant analysed by Mancuso (1979, 1980) to include workers employed at some time during 1942-67 and followed them up to 1 January 1976. [This interval extends across the year 1949 when, as previously noted, the Atomic Energy Commission standard of 2 μg/m^3 was introduced and a substantial reduction in exposure to beryllium subsequently occurred (US National Institute for Occupational Safety and Health, 1972).] They also used 1965-67 national lung cancer mortality rates to calculate expected lung cancer deaths for the period 1968-75. [The adjustment of Saracci (1985) is thus appropriate in considering these results.] Wagoner *et al.* (1980) observed 47 lung cancer deaths among the 3055 workers in the study cohort, whereas 37.7 were expected (with Saracci's adjustment) on the basis of national mortality experience, yielding an SMR of 1.25 (95% CI, 0.9-1.7). When lung cancer SMRs were calculated by latency, the SMRs were 0.88 (9 deaths) for < 15 years' latency, 1.16 (18 deaths) for 15-24 years' latency and 1.68 (20 deaths) for ≥ 25 years' latency, the 95% CI for latter SMR being 1.0-2.6. Within latency categories, there was no pattern of increasing (or decreasing) SMR by duration of employment, dichotomized into less than five and five

years or more. Analysis by duration yields an unstable estimate for longer duration strata owing to small numbers: for ≥ 5 years, the SMR is 1.1 (seven deaths) and the 95% CI is 0.4-2.3 (Saracci, 1985). A decline in risk for death from chronic beryllium disease was seen in relation to the same categories of length of employment. The potential for confounding of the SMR by a different distribution of smoking habits in the US population and in the beryllium cohort was calculated on the basis of a 1968 medical survey, in which detailed smoking histories of workers at the Pennsylvania plant were obtained, and of the 1964-65 Health Interview Survey of a probability sample of the US population, in which current and past smoking habits were queried. The overall calculations suggest that reported differences in smoking habits were sufficient to increase the lung cancer risk among the beryllium workers by 14%, in the absence of beryllium exposure; however, as also discussed by Wagoner *et al.* (1980), the white male age-adjusted rate for lung cancer mortality in the county in which the Pennsylvania plant was located (31.8/100 000) was lower than the average annual white male age-adjusted mortality rate for the USA as a whole (38.0/100 000). Wagoner *et al.* (1980) calculated that the risk for mortality from lung cancer in the beryllium cohort, if adjusted for differences in mortality between the County and the USA and for residential stability of cohort members, was underestimated by a factor up to 19%. [The Working Group noted that these two factors—smoking distribution and lower regional lung cancer mortality—bias the SMR estimate in opposite directions.]

Infante *et al.* (1980) analysed the mortality experience of white males entered into the Beryllium Case Registry while alive, with a diagnosis of chronic beryllium disease or acute beryllium-related pneumonitis. The Beryllium Case Registry was established in 1952 to collect date on the epidemiology, diagnosis, clinical features, course and complications of beryllium-related diseases. Individuals who were entered into the Registry were categorized as having either acute beryllium-induced pneumonitis or chronic systemic beryllium diseases (Sprinze & Kazemi, 1980). Individuals who were referred to the Registry for evaluation of beryllium-related diseases were employed in a variety of occupations, but most worked in beryllium extraction and smelting, metal production and fluorescent tube production. A total of 421 white males who entered the Registry alive between July 1952 and December 1975 were followed through to 31 December 1975. Seven deaths from lung cancer were observed and 3.3 were expected, based on national mortality rates for the period 1952-67 (SMR, 2.12, not significant). Since published vital statistics were not available for the period 1968-75, national mortality rates for 1965-67 were applied to 1968-75. If the number of expected deaths is increased by 10%, the expected value becomes [3.63], and the adjusted SMR is [1.93; 95% CI, 0.8-4.0]. For men who were entered into the Registry with a diagnosis of beryllium-related acute pneumonitis, the SMR (with Saracci's adjustment) for lung cancer is 2.86 (95% CI, 1.0-6.2; six cases). For those who were entered with a diagnosis of chronic beryllium disease, one lung cancer death was observed, with 1.52 expected (SMR, 0.66; 95% CI, 0.1-3.7). [The Working Group noted the small expected number of lung cancer deaths, particularly among workers with chronic lung disease, and the relatively short follow-up time for those workers who were entered into the Registry after 1965 (≤ 10 years). Chronic beryllium disease results from hypersensitivity to beryllium and may occur at much lower exposures than acute beryllium pneumonitis. A small number of the cases occurred among people living near the plants but who were not occupationally exposed.]

An extended analysis of mortality among people entered into the Beryllium Case Registry was reported by Steenland and Ward (1991).The study cohort, which now included women (34% of the cohort) and men of all races, numbered 689 people who were alive at entry into the Registry between July 1952 and the end of 1980. Mortality follow-up was extended through 1988 [actual US death rates were available for comparison for all years, eliminating the need for Saracci's adjustment in this and the report of Ward *et al.* (1992)]. Excess mortality was found for all cancers (SMR, 1.51; 95% CI, 1.17-1.91; 70 observed deaths), due primarily to an excess of lung cancer (SMR, 2.00; 95% CI, 1.33-2.89; 28 observed deaths); there were also excess deaths from nonmalignant respiratory disease (SMR, 34.23; 95% CI, 29.1-40.0; 158 observed deaths) and all causes of deaths (SMR, 2.19; 95% CI, 1.17-1.91; 428 observed deaths). The SMR for lung cancer was greater among cohort members with acute beryllium pneumonitis (SMR, 2.32; 95% CI, 1.35-3.72; 17 cases) than among those with chronic beryllium disease (SMR, 1.57; 95% CI, 0.75-2.89; 10 cases) (one death was due to disease of unknown type). The SMRs for nonmalignant respiratory disease were 10 times higher in the chronic disease group (SMR, 68.6) than in the acute disease group (SMR, 6.6). The SMRs for lung cancer varied little by time since first exposure (SMR, 1.95; 95% CI, 0.94-3.59 for $\leq$ 20 years since first exposure; 2.03; 95% CI, 1.20-3.21 for > 20 years) or by duration of exposure. [The Working Group presumed that duration of exposure to beryllium was determined by duration of employment in a beryllium plant, although this is not specified in the published report.] Taking into account the distribution of smoking habits among 32% of the cohort members questioned in 1965 and from a national survey of the US population studied in 1965, Steenland and Ward (1991) concluded that the study cohort smoked less (current smokers, 26%) than the US referent population (39%) in 1965 and that, if the 32% sample were representative of the entire cohort, smoking was unlikely to be a confounder of the observed excess lung cancer. Selection bias was diminished in this study because: people who died before entry into the Registry were excluded; only five individuals who had cancer before entry into the Registry were found in a review of Registry records, and none of these had lung cancer; and if patients with lung cancer had entered the Registry preferentially, the follow-up interval on these subjects would have been short, whereas only three of the 28 observed lung cancer deaths occurred within five years of entry into the Registry. [The Working Group noted that the results of this Beryllium Case Registry cohort study yield a higher lung cancer SMR than was found in other studies of beryllium-exposed workers, particularly among those who were entered with acute beryllium pneumonitis and who could therefore be assumed to have had a higher intensity of exposure to beryllium. This finding is consistent with the assumption that the risk for lung cancer is proportional to the intensity of exposure to beryllium. Furthermore, it provides indirect evidence that beryllium, rather than smoking, explains the findings, as people with acute pneumonitis were unlikely to smoke more than workers with chronic beryllium disease.]

Ward *et al.* (1992) reported the results of a cohort mortality study of 9225 male workers (8905 white, 320 non-white) employed by two companies at seven beryllium plants in Ohio and Pennsylvania. The results are summarized in Tables 12-16 (pp. 70-73). [Two of these plants (in Lorain, OH, and Reading, PA) are the same as those studied by Mancuso (1979, 1980) and Wagoner *et al.* (1980) (see Table 13).] Workers had to have worked for at least two days between 1940 and 1969 to qualify for entry into the study cohort. Mortality

Table 12. Cohort studies of lung cancer in beryllium workers

Reference	Cohort or plant location	Period of employment	Termination of follow-up	Comparison population	SMR	95% CI	Lung cancers observed
Mancuso (1979)	Lorain, OH	1942–48	1974	US white males	1.8[a]	1.2–2.7	25
	Reading, PA	1942–48	1975		1.25[a]	0.9–1.7	40
	Combined				1.42[a]	1.1–1.8	65
Mancuso (1980)	Lorain, OH Reading, PA	1937–48	1976	Viscose rayon workers	1.40	[1.1–1.7]	80
Wagoner *et al.* (1980)	Reading, PA	1942–67	1975	US white males	1.25[a]	0.9–1.7	47
Infante *et al.* (1980)	Beryllium Case Registry	Entry into Registry 1952–75	1975	US white males	[1.93]	[0.8–4.0]	7
				Acute pneumonitis	2.86[a]	1.0–6.2	6
				Chronic beryllium disease	0.66[a]	0.1–3.7	1
Steenland & Ward (1991)	Beryllium Case Registry	Entry into Registry 1952–80	1988	US men and women (all races)	2.00	1.33–2.89	28
				Acute pneumonitis	2.32	1.35–3.72	17
				Chronic beryllium disease	1.57	0.75–2.89	10
Ward *et al.* (1992)	Seven beryllium processing plants	1940–69	1988	US males, all races	1.26	1.12–1.42	280

SMR, standardized mortality ratio; CI, confidence interval; [ ], calculated by the Working Group
[a]With Saracci's adjustment

follow-up was extended through to 1988 and was analysed using standard modified life-table methods. The influence of local differences in mortality was evaluated by comparing SMRs derived from national and from local county mortality rates. The effect of the dissimilar distribution of smoking habits between beryllium workers and the US population was also evaluated. In the total cohort of 9225 workers, there were 3240 deaths (35% of the total) and 269 235 person-years of follow-up, of which 52% were person-years at risk 15 years or more after first employment in the beryllium industry. The SMR for all causes was 1.05 (95% CI, 1.01-1.08), that for all cancers was 1.06 (95% CI, 0.99-1.44), and that for nonmalignant respiratory disease was 1.48 (95% CI, 1.21-1.80). With the exception of that for cancer of the respiratory system, none of the SMRs for cancers at specific sites was significantly different from 1.00. The overall SMR for lung cancer was 1.26 (95% CI, 1.12-1.42; 280 observed deaths, based on US rates). SMRs for cancers of the larynx and of the upper respiratory tract were below 1.00.

Table 13. Years during which major processes were used at the US beryllium plants in the study of Ward *et al.* (1992)

Plant location	Ore refining	Beryllium oxide production	Metal production	Beryllium-copper alloy production	Machining
Lorain, OH	1935-48	1935-48	1935-48	1935-47	-
Reading, PA	1935-66	1935-66	-	1935-present	1938-present
Lucky, OH	1950-58	1950-58	1950-58	-	-
Perkins (Cleveland), OH	1837-55	1937-62	1948-62	-	1941-63
St Clair (Cleveland), OH	-	-	-	-	1963-73
Elmore, OH	1958-77	1958-present	1958-present	1952-present	1958-present
Hazelton, PA	1958-78	1958-78	1958-78	1958-78	1958-78

The dates refer only to the processes and were not used to restrict the cohorts. For example, workers hired at the Lucky plant in 1949 were included in the study, as were a few individuals hired at the Lorain plant in 1949 and early 1950.

The SMRs for lung cancer at individual plants (Table 14) were greater than 1.00 at four of the six locations: two plants near Cleveland, OH—Perkins and St Clair—were combined into one cohort because records of the two plants could not be separately identified. The SMRs were significantly greater than 1.00 only at the Lorain, OH, and Reading, PA, plants [the same facilities studied by Mancuso (1979, 1980) and Wagoner *et al.* (1980)]. It is noteworthy that cohorts in which there was a high SMR for pneumoconiosis and other respiratory diseases, presumably indicating higher exposure to beryllium also consistently had elevated SMRs for lung cancer. When lung cancer SMRs were stratified by latency at each plant, three of the six locations showed higher SMRs for the 15-30-year and > 30-year latency categories compared with the < 15-year latency category (Table15); however, for the total cohort, lung cancer SMRs increased stepwise with increasing latency (bottom row of Table 15). When SMRs were stratified by decade of hire (Table16), values greater than 1.00 were seen for all three locations in which workers were hired before 1950 (the period when exposures to beryllium were also greater than subsequently), but SMRs were also greater than 1.00 in four of the five locations where workers were hired between 1950 and

Table 14. Mortality of workers employed in 1940–69 at the seven US beryllium processing plants in the study of Ward *et al.* (1992)

Plant location	Total no. of workers	Percentage of workers employed for		SMR			No. of lung cancer deaths
		< 1 year	1–5 years	Lung cancer (based on US rates)	Lung cancer (based on county rates)	Pneumoconiosis and other respiratory disease (based on US rates)	
Lorain, OH	1192	84.6	12.8	1.69**	1.60**	1.94**	57
Reading, PA	3569	53.8	22.3	1.24*	1.42**	1.34	120
Cleveland, OH (two plants)	1593	47.3	29.8	1.08	1.05	1.22	44
Lucky, OH	405	62.2	35.8	0.82	0.84	0.87	9
Elmore, OH	1323	29.0	24.9	0.99	1.06	0.69	15
Hazelton, PA	590	19.7	17.8	1.39	1.50	2.00	13
Multiple plants	257	0.8	12.1	1.67	–	2.60	13
Location unknown	296	49.3	41.6	1.33	–	3.47**	9
Total[a]	9225	49.7	23.4	1.26**	1.32*	1.48**	280

*$p < 0.05$; **$p < 0.01$

[a]See also Table 12

1959. As seen in the bottom row of Table 16, decade of hire was one of the strongest correlates of lung cancer mortality risk in the total cohort. Poisson regression analysis, with control for age, race, calendar time and time since first employment, showed an independent effect of decade of hire on lung cancer SMRs in the total cohort. Duration of employment had no effect. [The Working Group noted that, given the much higher exposures to beryllium prior to 1950 and the fact that 73% of the total cohort worked for less than five years, duration of employment does not separate that segment of the cohort which received the highest exposures to beryllium.]

Table 15. Standardized mortality ratios (SMRs) for lung cancer by location of plants and latency since time of first employment in the US beryllium plants in the study of Ward *et al.* (1992)

Location	Latency < 15 years		Latency 15-30 years		Latency > 30 years	
	SMR	Observed deaths	SMR	Observed deaths	SMR	Observed deaths
Lorain, OH	0.38	1	2.09**	21	1.66*	35
Reading, PA	0.78	9	1.17	44	1.40*	67
Cleveland, OH	1.30	9	0.91	20	1.27	15
Lucky, OH	0.96	1	0.85	4	0.76	4
Elmore, OH	0.51	2	1.14	12	1.31	1
Hazelton, PA	1.91	4	1.26	9	-	0
Multiple plants	-	0	1.23	4	2.38*	9
Location unknown	0.64	1	1.28	5	2.30	3
Total	0.89	27	1.20	119	1.46**	134

*$p < 0.05$; **$p < 0.01$

Table16.Standardized mortality ratios (SMRs) for lung cancer by location of plants and decade of hire in the US beryllium plants in the study of Ward *et al.* (1992)

Location	Hired before 1950		Hired 1950-59		Hired 1960-69	
	SMR	Observed deaths	SMR	Observed deaths	SMR	Observed deaths
Lorain, OH	1.69**	57	-	-	-	-
Reading, PA	1.26*	92	1.42	26	0.35	2
Cleveland, OH	1.06	12	1.32	26	0.63	6
Lucky, OH	-	-	0.82	9	-	-
Elmore, OH	-	-	1.42	12	0.45	3
Hazelton, PA	-	-	1.86	9	0.87	4
Multiple plants	2.53**	12	0.36	1	-	-
Location unknown	2.30	4	0.62	2	1.57	3
Total	1.42**	177	1.24	85	0.62	18

*$p < 0.05$; **$p < 0.01$

When lung cancer SMRs for each of the six locations were based on local county mortality rates (Ward *et al.*, 1992; see Table 14), the SMRs differed only slightly from those based on US rates. The largest difference occurred in the Reading, PA, cohort, in which the SMR based on US rates was 1.24 and that based on county rates was 1.42. For all six locations, the lung cancer SMR based on US rates was 1.26 (95%, 1.12-1.42), while that based on local county rates was 1.32 (95% CI, 1.19-1.46). When lung cancer SMRs were adjusted for the distribution of smoking habits at four of the plants in which a smoking survey was conducted in 1968 [covering 1466 (15.9%) of the 9225 members of the cohort], the SMR for the total cohort changed from 1.26 to 1.12, and the SMRs in two of the largest, oldest plants changed from 1.69 to 1.49 (Lorain, OH) and from 1.24 to 1.09 (Reading, PA). The authors noted that the major difficulty in interpreting the smoking-adjusted SMRs is that data on smoking were collected in the late 1960s, while most (94%) of the lung cancer cases occurred among workers hired in the 1940s and 1950s. Thus, the validity of the adjustment for smoking depends on the assumption that differences in smoking habits between the cohort and the US population were the same in the 1940s and 1950s as they were in the late 1960s and that smoking data obtained from 16% of the workers adequately represented the distribution of smoking in the entire cohort. The authors estimated the contribution of smoking to be 13%, i.e., smoking alone could account for a lung cancer SMR of 1.13 versus the 1.26 actually observed.

2.2 Case-control studies

Hinds *et al.* (1985) applied a computerized job-exposure matrix to data from a case-control study of lung cancer among males in Hawaii, USA. Between 1 September 1979 and 31 July 1982, 261 cases of newly diagnosed primary lung cancer among male residents of Oahu, Hawaii, were identified through a population-based tumour registry and a review of pathology records at all major hospitals and interviewed. Controls were identified by random-digit dialling and matched on sex and age. Information on occupation was obtained during the interview and applied to a job-exposure matrix to estimate exposure levels to various agents for each study subject. The job-exposure matrix was constructed from lists of occupational codes by Hoar *et al.* (1980), and these were used to code both the primary and secondary occupations of all subjects according to industry; each code was then linked to various levels of exposure to each agent. Each agent was grouped into three exposure levels (no exposure, low exposure, high exposure). The association of each agent with lung cancer risk was estimated by the odds ratio, which was determined by multiple logistic regression analysis and adjusted for age, ethnicity and smoking status. Excess risk for lung cancer was found to be associated with exposure to beryllium at both low (odds ratio, 1.62; 95% CI, 1.04-2.51) and high levels (1.57; 0.81-3.01). Other exposures considered in the analysis were coal-tar and pitch, petroleum, arsenic, chromium, asbestos and nickel. [The Working Group noted that it is not clear whether the odds ratio for beryllium was simultaneously controlled for the other exposures.]

Carpenter *et al.* (1988) conducted a nested case-control study of cancers of the central nervous system among workers employed at some time between 1973 and 1977 at two nuclear facilities in Oak Ridge, TN (USA); deaths of 72 white males and 17 white females from cancer of the central nervous system were identified from information on death

certificates, and four controls were matched to each case for race, sex, facility at which initially employed, year of birth and year of hire. Each job title and department combination was subjectively evaluated for potential exposure to each of 26 chemicals, including beryllium. The evaluation took into account period of employment, literature on the processes used at each facility, quantities and toxicities of chemicals used in the processes, interviews with workers involved in processes at different time periods, and the results of urine analyses and air monitoring. Each job title/department combination was given a rank for potential exposure to each of the 26 chemicals; rank 0 had probably no exposure, rank 1 had low potential, rank 2 had moderate potential and rank 3 had high potential for exposure to the specified chemical. Matched conditional logistic regression analyses were conducted and included potential confounding factors such as socioeconomic status. On the basis of 26 cases ever exposed to beryllium, the odds ratio for cancers of the central nervous system was 1.5 (95% CI, 0.6-3.9). The matched analysis by highest rank ever held versus rank 0 yielded odds ratios of 1.26, 1.28 and 3.29 for ranks 1, 2 and 3, respectively (all odds ratios had a p value of 0.09 or greater). When risk estimates were calculated for a 10-year latency, the odds ratios were 1.13, 0.85 and 1.77 for ranks 1, 2 and 3, respectively. A further analysis based on time spent in ranks 2 and 3, assuming a 10-year latency, yielded odds ratios of 0.77, 0.90, 1.30 and 1.88 ($p > 0.5$) for workers with < 3 years, 3-10 years, 11-20 years and 21 years or more in ranks 2 and 3 compared with ranks 0 and 1. The authors concluded that their study does not support the hypothesis that occupational exposures to any of the 26 chemicals studied appreciably increase the risk for cancers of the central nervous system; they noted specifically that, although a weak association between exposure to beryllium and cancers of the central nervous system was observed, confidence intervals [not given for analyses by rank or latency] were wide and included the null value.

2.3 Childhood cancer

A case-control study on parental occupation and childhood cancer carried out in Denver, CO, USA (Feingold *et al.*, 1992), included 252 cases of childhood cancer diagnosed during 1976-83 and 222 population controls selected by random-digit dialling. A job-exposure matrix was used to assign parental exposures for six months or longer during the year prior to the child's birth on the basis of job titles. Odds ratios were estimated for all cancers, acute lymphocytic leukaemia and brain cancer, after adjusting for age at diagnosis, year of diagnosis, sex, mother's age at time of birth, maternal smoking during pregnancy, birth weight, birth order and indicators of social class. When all cancers were considered, no association was found between childhood cancer and exposure to beryllium or its compounds for either the mother or the father (odds ratio, 1.0; 95% CI, 0.1-7.1; based on two exposed cases; and 1.6; 0.6-4.4; based on 17 exposed cases, respectively). When the exposures of the fathers were analysed for specific types of cancer, an elevated odds ratio was found for brain cancer (2.1; 0.6-7.6; 5 cases) but not for acute lymphocytic leukaemia (1.3; 0.3-5.9; 5 cases). Most of the subjects considered to have been exposed to beryllium were electrical equipment assemblers and installers (67%), metal processes and welders (20%). [The Working Group noted that other occupational exposures were not considered in the analysis.]

3. Studies of Cancer in Experimental Animals

3.1 Beryllium ores

Inhalation exposure

(*a*) *Rat*

Groups of 60 and 33 male Charles River, caesarian-derived rats and 30 Greenacres Controlled Flora rats (more than four weeks old) were exposed by inhalation to **beryl ore** (geometric mean particle diameter, 0.64 μm) or **bertrandite ore** (geometric mean particle diameter, 0.27 μm) as 15 mg/m^3 dust (the threshold limit value for inert dust in 1968) for 6 h per day on five days a week for up to 17 months. A third group, serving as controls, was housed in an inhalation chamber without exposure. The bertrandite ore atmosphere in the inhalation chamber contained 210 μg/m^3 beryllium, and the beryl ore atmosphere contained 620 μg/m^3 beryllium (for chemical composition, see Table 17). The death rates of the animals exposed to the two ores exceeded that of controls by 13%. Of the animals killed after 12 months of exposure, 5/11 treated with beryl ore had foci of squamous metaplasia or small epidermoid tumours. Of those killed at 17 months, 18/19 had lung tumours (18 bronchiolar alveolar-cell tumours, 7 adenomas, 9 adenocarcinomas and 4 epidermoid tumours). No metastasis was observed. In the group treated with bertrandite ore, granulomatous lesions and some atypical proliferations in the lung were observed, but no bronchiolar alveolar-cell tumour or other lung tumour was found. Controls had no neoplastic or granulomatous pulmonary lesion (Wagner *et al.*, 1969). [The Working Group noted the high crystalline silica content of the bertrandite ore and the incomplete reporting of the study.]

(*b*) *Hamster*

Groups of 48 and 17 male Syrian golden hamsters (more than four weeks old) were exposed by inhalation to **beryl ore** (geometric mean particle diameter, 0.64 μm) or **bertrandite ore** (geometric mean particle diameter, 0.27 μm) as 15 mg/m^3 dust for 6 h per day, five days a week for up to 17 months. A third group, serving as controls, was housed in an inhalation chamber without exposure. The bertrandite ore atmosphere in the inhalation chamber contained 210 μg/m^3 beryllium, and the beryl ore atmosphere contained 620 μg/m^3 (for chemical composition, see Table 17). The mortality of the animals exposed to the two ores exceeded that of controls by 25%. Atypical proliferations, first seen at 12 months in both groups of exposed animals, and lesions considered by the authors to be bronchiolar alveolar-cell tumours, except for their size, occurred. The lesions in the beryl-exposed animals were reported to become larger and more adenomatous after 17 months. The control hamsters had no pulmonary lesion (Wagner *et al.*, 1969). [The Working Group noted the incomplete reporting of the study.]

(*c*) *Monkey*

Groups of 12 and 4 male squirrel monkeys (*Saimiri sciureus*) (more than four weeks old) were exposed by inhalation to **beryl ore** (geometric mean particle diameter, 0.64 mm) or **bertrandite ore** (geometric mean particle diameter, 0.27 μm) as 15 mg/m^3 dust for 6 h per

day, five days a week for up to 23 months. A third group, serving as controls, was housed in an inhalation chamber without exposure. The bertrandite ore atmosphere in the inhalation chamber contained 210 μg/m^3 beryllium, and the beryl ore atmosphere contained 620 μg/m^3 (for chemical composition, see Table 17). The death rates of the animals exposed to the two ores exceeded that of controls by 11%. No tumour was found. Aggregates of dust-laden macrophages, lymphocytes and plasma cells were observed near respiratory bronchioles and small blood vessels in the lungs of exposed animals. Control monkeys had no similar change (Wagner *et al.*, 1969). [The Working Group noted the incomplete reporting and the limited duration of the study.]

Table 17. Chemical composition (of constituents representing > 0.1%) of representative bertrandite and beryl ore samples

Chemical constituent	Analysis by weight (%)	
	Bertrandite	Beryl ore
Be[a]	1.4	4.14
Al_2O_3	9.8	18.1
SiO_2	63.9[b]	
SiO_2 (as silicates)		63.6
SiO_2 (as quartz)		1.9
Fe_2O_3	1.8	1.1
MnO_2	1.8	1.0
CaF_2	8.3	
CaO	0.2	
MgO	2.3	1.1
K_2O	1.2	
Na_2O	1.5	0.5
ZnO	0.7	
CO_2	0.2	
NiO		0.5

Modified from Wagner *et al.* (1969)

[a][Probably as the oxide]

[b]23.5% of the mineral constituents were crystalline quartz and 23.5%, cristobalite (crystalline silica); the remainder was other silicates.

3.2 Beryllium metal and alloys

3.2.1 *Intratracheal instillation*

Rat: Twelve groups of 35 female Wistar rats, three months old, were treated with a single intratracheal instillation of 0.5 or 2.5 mg **beryllium metal** (100% Be), **passivated beryllium metal** (99% Be, 0.26% Cr [as chromate]), **beryllium-aluminium alloy** (62% Be, 38% Al), **beryllium-copper alloy** (4% Be, 96% Cu), **beryllium-copper-cobalt alloy** (2.4%

Be, 0.4% Co, 96% Cu) or **beryllium-nickel alloy** (2.2% Be, 97.8% Ni), with geometric mean particle sizes of 1-2 μm, suspended in 0.4 mL isotonic saline, followed by 0.2 mL saline. Forty control animals were instilled with 0.6 mL saline. The rats were killed when moribund or 18 months after instillation. The first lung neoplasm appeared 8-10 months after instillation. Lung neoplasms, mostly adenocarcinomas and adenomas, were found in 2/21 rats treated with the low dose and in 9/16 rats given the high dose of beryllium metal, in 7/20 animals treated with the low dose and in 9/26 treated with the high dose of passivated beryllium metal, and in 1/21 treated with the low dose and in 4/24 given the high dose of beryllium-aluminium alloy. No lung tumour occurred in 39 controls or in the groups treated with other alloys. The incidence of lung neoplasms was significantly ($p < 0.008$) increased over that in controls (using Fisher's exact test, one-tailed) in the groups that received 2.5 mg beryllium metal or 0.5 mg and 2.5 mg passivated beryllium metal (Groth *et al.*, 1980). [The Working Group noted the low beryllium content of the beryllium-copper alloy, the beryllium-copper-cobalt alloy and the beryllium-nickel alloy.]

3.2.2 *Intravenous injection*

Rabbit: In a study reported as a letter to the Editor, 24 young rabbits [sex and strain unspecified] received a series of intravenous injections of a washed suspension of finely divided **beryllium metal** in water (total dose, 40 mg/animal). Nine animals had died with liver necrosis within seven days, and 10 more died with this condition during the next month. Two of the surviving five rabbits died from pulmonary infections, two developed characteristic bone sarcomata, and a single rabbit survived (Barnes, 1950).

3.3 Beryllium compounds

3.3.1 *Oral administration*

Rat: **Beryllium sulfate** was administered to 52 male and 52 female Long-Evans rats (BLU:LE) in the drinking-water at a concentration of 5 ppm [5 mg/L] from weaning until natural death. The water also contained 5 ppm chromium[III] acetate, 50 ppm zinc acetate and 5 ppm copper acetate; 10 ppm manganese chloride and 1 ppm cobalt chloride; and 1 ppm sodium molybdate. An equal number of animals treated with water served as controls. The life span of the treated rats did not differ significantly from that of controls, but 20-30% of rats in each group died from pneumonia. No significant difference in tumour incidence was observed between treated and control groups (Schroeder & Mitchener, 1975). [The Working Group noted that the dose was too low for an evaluation of carcinogenicity.]

3.3.2 *Inhalation*

(*a*) *Rat*

Twenty-seven male and female albino Wistar rats, weighing 140-210 g, and 109 male and female Sherman rats, weighing 80-110 g, were exposed by inhalation to **beryllium sulfate tetrahydrate** aerosol to give a concentration of 1 μg/ft^3 Be [35.8 μg/m^3], for 8 h per day on 5.5 days a week for 180 days. Control groups of 69 male and female Wistar and 70 male and female Sherman rats were maintained in normal air. The 52 rats that survived the

treatment were transferred to 'normal air' and observed for periods of up to 18 months. Seventy-six lung tumours were found, eight with metastases. The tumours included 18 adenomas, 5 squamous carcinomas, 24 acinous adenocarcinomas, 11 papillary adenocarcinomas and 7 alveolar-cell adenocarcinomas. None of the 139 control rats had lung tumours (Schepers *et al.*, 1957). [The Working Group noted the incomplete reporting of the study.]

A group of 75 male and 75 female Sprague-Dawley CD rats, six weeks of age, were exposed by inhalation to **beryllium sulfate tetrahydrate** aerosol for 7 h per day on five days a week for 72 weeks at a mean atmospheric concentration of 34.25 ± 23.66 μg/m^3 Be (average particle diameter, 0.118 μm). An equal number of control animals was exposed to an aerosol of distilled water. Subgroups of animals were killed each month up to the 56th week of exposure; 87% of all animals survived to their scheduled sacrifices. The first lung tumour was observed after nine months of exposure. All of the 43 rats that survived 13 months or more after the beginning of treatment had tumours, and all of the 56 tumours studied histologically were reported to be alveolar adenocarcinomas. No lung tumour was found in the control group (Reeves *et al.*, 1967). [The Working Group noted the incomplete reporting of the study.]

Groups of 30-50 female albino rats, weighing 155-160 g, received **beryllium oxide** or **beryllium chloride** by inhalation at concentrations of 0.8, 4, 30 or 400 μg/m^3 for 1 h per day on five days a week for four months. A group of 160 females served as controls. Only malignant epithelial lung tumours were considered: these occurred in 3/44, 4/39, 6/26 and 8/21 rats treated with beryllium oxide and in 1/44, 2/42, 8/24 and 11/19 treated with beryllium chloride, but in none of the controls (Litvinov *et al.* 1984) [The Working Group noted the incomplete reporting of the study.]

(*b*) *Rabbit*

Three groups of rabbits [sex, strain and age unspecified] were exposed by inhalation to aerosols of **beryllium oxide** (average particle diameter, 0.285 μm; range, 0.11-1.25) at doses of 1 (five rabbits), 6 (six rabbits) or 30 (eight rabbits) μg/L Be for 5 h per day on five days a week for 9-13 months. No control group was available. An osteogenic sarcoma in the left pubis with widespread visceral metastases was observed in one rabbit that had been exposed to 6 μg/L Be for 235 days over 11 months (Dutra *et al.*, 1951). The Working Group noted the small number of animals and the short duration of exposure.]

(*c*) *Monkey*

In a study reported as an abstract, 16 rhesus monkeys (*Macaca mulatta*) were exposed daily by inhalation 'for a long period of time' to **beryllium sulfate** aerosol at a concentration of 35 μg/m^3 Be. Primary anaplastic pulmonary tumours with adenomatous and epidermoid patterns were observed in three monkeys between six months and eight years after the beginning of exposure (Vorwald, 1967).

3.3.3 *Intratracheal instillation*

(*a*) *Rat*

A group of 35 female Wistar-derived rats, three months old, received single intratracheal instillations of 50 mg Be as **beryllium hydroxide** suspended in distilled water,

followed 10 months later by a second instillation of 25 mg. A group of 35 controls received a single intratracheal instillation of 2.5 mg chrysotile asbestos. Both materials were suspended in 0.4 mL distilled water, and the instillation was followed by 0.2 mL distilled water. Of the beryllium hydroxide-treated rats sacrificed at 19 months of age, 13/25 had pulmonary tumours (six adenomas and seven adenocarcinomas); one rat had both an epidermoid carcinoma and an adenocarcinoma. The lungs of all of the animals instilled with chrysotile had small and occasionally larger scars; adenomas occurred in two rats and an adenocarcinoma in a third. Metaplastic foci were found in the lungs of 5% of the chrysotile-treated group, whereas in 90% of the animals instilled with beryllium most of the normal lung tissue was replaced by metaplastic foci and tumours (Groth *et al.*, 1980). [The Working Group noted the lack of an appropriate control group.]

Two groups of 30 male Wistar rats, 10 weeks of age, were instilled intratracheally with **beryllium oxide** (low-temperature fired, 900 °C; 1 mg as Be) or arsenic trioxide (1 mg as As) once a week for 15 weeks. A group of 16 rats served as untreated controls. All rats in the beryllium-treated group, 19 in the arsenic-treated group and all of the controls survived the treatment period and were observed for life. Two malignant (one squamous-cell carcinoma and one adenocarcinoma) and four benign lung adenomas (three suspected of malignancy) were found in rats treated with beryllium, and one malignant lung tumour (a squamous-cell carcinoma) was found in those treated with arsenic; no lung tumour was observed in the control group (Ishinishi *et al.*, 1980).

Eight groups of inbred albino rats [initial number and sex unspecified], weighing 140-150 g, received single intratracheal instillations of **high-temperature fired beryllium oxide** (2000 °C) or **low-temperature fired beryllium oxide** (600 °C) at doses of 0.036, 0.36, 3.6 and 18 mg/kg bw. A group of 300 untreated rats served as controls. All animals were observed for life. Malignant epithelial lung tumours occurred in 0/76, 0/84, 2/77 and 2/103 rats treated with the high-temperature fired beryllium oxide and in 3/69, 7/81, 18/79 and 8/26 rats treated with the low-temperature fired compound. None were found in 104 controls (Litvinov *et al.*, 1983).

(*b*) *Monkey*

In a study reported as an abstract, a group of 20 rhesus monkeys (*Macaca mulatta*) received an intrabronchial intubation and/or a bronchomural injection [unspecified] of **beryllium oxide** particulates suspended in sterile physiological saline. The first bronchogenic tumour was detected about 4.5 years after first treatment. In the course of the following year, two additional monkeys developed tumours, which were highly anaplastic, with adenomatous and epidermoid patterns (Vorwald, 1967).

3.3.4 *Intravenous injection*

(*a*) *Mouse*

In a study reported as an abstract, three groups of mice received 20-22 intravenous injections(two/week)of either **zinc beryllium silicate** (8.36 mg Zn, 0.264 mg Be), zinc silicate (2.8 mg Zn) or **beryllium oxide** (1.54 mg Be). A fourth group was untreated. ‘Some’ mice given zinc beryllium silicate were reported to have developed malignant bone tumours (Cloudman *et al.*, 1949).

(*b*) *Rabbit*

In a study reported as an abstract, rabbits received synthetic **zinc beryllium silicate** and its ingredients, **beryllium oxide**, zinc oxide, silicic acid and zinc silicate, intravenously in 20 doses totalling 1 g of particles 3 μm or smaller, over a six-week period. All of the seven rabbits given zinc beryllium silicate which survived the injections for seven months or more developed malignant osteosarcomas, four with visceral metastases. One rabbit killed one year after injection of beryllium oxide had a malignant osteosarcoma. Such tumours were not induced by administration of 65 other minerals in the same way (Gardner & Heslington, 1946).

In a study reported as an abstract, three groups of rabbits received 20-22 intravenous injections (two/week) of either **zinc beryllium silicate** (550 mg Zn, 17 mg Be), zinc silicate (390 mg Zn) or **beryllium oxide** (390 mg Be). A fourth group was untreated. Four of five rabbits given zinc beryllium silicate which survived over one year from the start of injections had bone tumours, three with metastases (Cloudman *et al.*, 1949).

Six groups comprising 67 rabbits of different breeds and sexes were injected intravenously twice a week with various samples of **zinc beryllium silicate** (67% ZnO, 28% SiO_2, 2% BeO and 3% MnO; or 67% ZnO, 31% SiO_2 and 2% BeO), **beryllium silicate** or zinc silicate, with particle sizes of 5 μm or less as a 1 mL suspension in water at the dose schedule indicated in Table 18. Bone sarcomas developed in 7/21 rabbits injected with beryllium silicates that survived for 30 weeks or more. The earliest evidence of malignant change was observed at 32 weeks, and the latest tumour occurred 83 weeks after the last injection. No tumour was found in any of the animals injected with zinc silicate only (Barnes *et al.*, 1950). [The Working Group noted the poor survival.]

Table 18. Results of experiments in rabbits with beryllium silicates

Material injected	Conc. of suspension (%)	No. of injections	Total amount injected (g)	Initial no./group	No. of survivors	No. with osteosarcomas
Zinc beryllium silicate	10	10	1.0	10	3	0
Zinc beryllium silicate	30	6	2.1	12	3	2
Zinc beryllium silicate	10	10	1.0	12	11	4
Beryllium silicate	20	6	1.2	11	3	1
Beryllium silicate	10	10	1.0	12	8	0
Zinc silicate	20	6	1.2	10	8	0

From Barnes *et al.* (1950)

Young, adult, male and female white rabbits [number unspecified] were given intravenous injections of either a highly purified **beryllium oxide** or a **calcined phosphor** containing beryllium oxide, zinc oxide and silica mixed in a molar ratio of 1:1:1, as 1% suspensions in physiological saline.The particles of the powders were smaller than 1μm.The beryllium oxide-treated group received a total of 360-700 mg Be/rabbit in 20-26 injections, and the phosphor group received 64-90 mg Be/rabbit in 17-25 injections. The compounds were given three times a week over approximately six to nine weeks. One year or more after the first injection, six animals given beryllium oxide and three given calcined phosphor were

still alive. The first tumour was found 11.5 months after the start of the experiment. Osteosarcomas were found in all six beryllium oxide-treated rabbits (two were reported after the paper had been submitted for publication); some were metastases and some were multiple primary tumours. Osteosarcomas were found in 2/3 rabbits given the phosphor. About 50 untreated rabbits kept for similar or longer periods developed no malignant tumour (Dutra & Largent, 1950). [The Working Group noted the small group sizes, the limited reporting and the incomplete observations.]

A group of 13 female and 11 male rabbits of unselected strains, with an average initial body weight of 5.5 lbs [2.5 kg], received intravenous injections of insoluble beryllium compounds under sterile conditions at a dose of 5 mL at one-day or four-day intervals, in an attempt to administer a total of 1 g of the powder. Five animals received **beryllium phosphate**; six rabbits received a **zinc beryllium silicate** containing 60% ZnO, 30% SiO_2, 2% MnO and 2.3% BeO; four received another zinc beryllium silicate containing 14% **beryllium oxide** and 48% zinc oxide; and nine rabbits received **beryllium oxide** from different sources. Except for the beryllium phosphate, which was administered in a 0.1% suspension in saline, all substances were injected as 1% suspensions in saline. Eight animals died of various causes within three months of the start of treatment, and eight more rabbits died at 14-28 months from infectious diseases. Seven of the eight surviving rabbits developed osteogenic sarcomas: three in the group treated with zinc beryllium silicate containing 2.3% BeO, three in the group treated with zinc beryllium silicate containing 14% BeO and one treated with beryllium oxide. One animal that received 100 mg beryllium phosphate was still alive 2.5 years after injection (Hoagland *et al.*, 1950). [The Working Group noted the small group size and the lack of appropriate controls.]

Osteosarcomas were found in 2/4 rabbits within 18 months after a single intravenous injection of 1g **beryllium phosphate**; no tumour was found in three rabbits that received 1 g **beryllium oxide**. Of animals injected with beryllium oxide mixed with zinc oxide, manganese oxide and/or silicon oxide, 9/31 developed osteosarcomas (Araki *et al.*, 1954). [The Working Group noted the small number of animals, the lack of an appropriate control group and the incomplete reporting.]

Ten adult, male rabbits received two intravenous injections per week for 10 weeks of 5 mL of a 1% suspension of **zinc beryllium silicate** containing 3.36% **beryllium oxide** (total dose, 1 g zinc beryllium silicate or 33.6 mg beryllium oxide). Five rabbits developed osteogenic sarcomas 9-11 months after the injection period (Janes *et al.*, 1954). [The Working Group noted the lack of an appropriate control group and the small group size.]

Fourteen rabbits were injected intravenously with 5 mL of a 1% suspension of **zinc beryllium silicate** (size of particles, 1-3 μm) in physiological saline twice a week for 10 weeks (total dose, 1 g zinc beryllium silicate). The animals died or were killed 28-57 weeks after the last injection. Osteogenic sarcomas appeared in 10/14 rabbits 30-52 weeks after the last injection (Kelly *et al.*, 1961). [The Working Group noted the lack of an appropriate control group and the small group size.]

Osteosarcomas were induced in 3/20 rabbits 15-18 months after single intravenous injections of **beryllium oxide** (total dose, 1 g/rabbit) as a 1% suspension in saline (Komitowski, 1968). [The Working Group noted the lack of an appropriate control group.]

Sixty rabbits, six months of age on average, were treated intravenously with a 1% **beryllium oxide** suspension in 5 mL physiological saline, once a week for 25 weeks. Of the 29 animals that survived until the end of the experiment, 21 developed sarcomas (Fodor, 1977). [The Working Group noted the lack of an appropriate control group and the incomplete reporting.]

3.3.5 *Intraperitoneal injection*

Mouse: In a screening assay based on the accelerated induction of lung adenomas in a strain highly susceptible to development of this neoplasm, three groups of 20 male A/J mice, five to six weeks old, were injected intraperitoneally three times a week for eight weeks with **beryllium sulfate tetrahydrate** (purity ≥ 99%) suspended in distilled water at doses of 0.02, 0.05 or 0.1 (maximum tolerated dose) mg/mouse per injection. An equal number of animals were treated with the vehicle only and served as controls. The authors stated that beryllium sulfate produced a significant (χ^2 analysis) increase in lung tumour incidence at total doses of 1.2 and 2.4 mg/mouse with no significant increase in lung tumour multiplicity (Ashby *et al.*, 1990). [The Working Group noted that the increases were not significant using Fisher's exact test.]

3.3.6 *Implantation and/or injection into bone*

Rabbit: Of 55 rabbits that received 1-43 injections of 10 mg **beryllium oxide** as a 1% suspension in isotonic saline into the marrow of the right femur twice weekly (20 mg/week), one developed a chondroma, three developed osteomas, 15 developed chondrosarcomas and seven developed osteochondrosarcomas. The average time between the last injection and the appearance of a tumour was 85 days. The period of observation was one to two years (Yamaguchi, 1963).

A group of 12 rabbits of mixed breeds and sexes, six weeks old, received 20 mg zinc **beryllium silicate powder** (particle diameter, ≤ 5 μm), suspended in 0.5 mL of water, as a single intramedullary injection into the upper end of the right tibia. A similar suspension of **zinc oxide** was injected into the left tibia as a control. All rabbits survived the injections for at least 12 months; four animals died of intercurrent infections. Osteogenic sarcomas were found in four rabbits at 12-15 months; three metastasized. The remaining four animals were killed at 15-20 months with no clinical or radiological evidence of tumours. No effect was seen with zinc oxide (Tapp, 1966).

Three groups of six rabbits of mixed breeds and sexes, six to eight weeks old, received implants of 10 mg zinc **beryllium silicate, beryllium oxide** or **beryllium silicate** under the periosteum of the upper end of the right tibia. Three animals from each group also received implants of zinc oxide or zinc silicate in a similar procedure into the left tibia and served as controls. Nine animals were killed between 2 and 18 months; the remaining animals lived for 25 months. Four of the animals developed central osteogenic sarcomas between 10 and 25 months after implantation; two occurred in animals treated with beryllium and metastasized, one occurred in an animal given zinc beryllium silicate and metastasized, and one occurred in an animal given beryllium silicate. No tumour occurred in the left tibia of the animals implanted with zinc oxide or zinc silicate (Tapp, 1969).

After intramedullary administration of **beryllium oxide** [purity, dose and dose schedule unspecified] (particle size, ~4 μm) in gelatin into the femur, 5/20 rabbits developed osteogenic sarcomas with lung metastases during an observation period of 24 months. The first tumour was observed 13 months after injection (Komitowski, 1974). [The Working Group noted the lack of an appropriate control group and the incomplete reporting.]

Rabbits were given intramedullary implantations of **beryllium carbonate** (173 rabbits), **beryllium acetate** (18 rabbits), **beryllium acetylacetonate** (10 rabbits), **beryllium laurate** (3 rabbits) or **beryllium stearate** (3 rabbits). Thirty animals given beryllium carbonate developed osteosarcomas 10-17 months after the first treatment; the tumours were detected radiologically between 10 and 21 months and confirmed histologically. One rabbit given beryllium acetylacetonate that survived 13 months developed an osteosarcoma (Matsuura, 1974). [The Working Group noted the incomplete reporting and the small numbers of animals in groups other than the group treated with beryllium carbonate.]

A group of 65 Fauve de Bourgogne rabbits [sex unspecified], 15-20 weeks old, received single intraosseous injections of 0.5 mL of a suspension prepared from 1 g **zinc beryllium silicate** in 15 mL distilled water and gelatin (33 mg Be) into the tibial or femoral metaphysis. Of the 65 rabbits that survived more than four months after the injection, 45 developed osteogenic sarcomas. Radiographic examination indicated that the first sarcomatous changes occurred after three months (Mazabraud, 1975). [The Working Group noted the lack of an appropriate control group.]

Three groups of 10 male rabbits [strain unspecified], six weeks of age, received implants of pellets of hydroxypropylcellulose mixed with **beryllium oxide** into the distal metaphysis of the right femur as follows: Group 1, into the internal callus one week after production of an artificial fracture at a dose of 300 mg; Group 2, into the bone-marrow cavity at a dose of 300 mg; and Group 3, into the bone-marrow cavity at a dose of 50 mg. A further group of 10 rabbits served as untreated controls. At 56 weeks, osteosarcomas had developed in 10/10 rabbits in Group 1, in 7/10 rabbits in Group 2 and in 1/10 rabbits in Group 3. Tumours appeared significantly earlier in Group 1 than in the other groups, and 80% of animals with osteosarcomas had lung metastases (Hiruma, 1991).

3.3.7 *Administration with known carcinogens*

Mouse: Five groups of 40 female and 40 male SENCAR mice, seven to nine weeks old, received a single intraperitoneal injection of 0, 0.01, 0.1, 1.0, 5.0 or 10.0 μg/mouse **beryllium sulfate** [purity unspecified]) in saline. One week after treatment, each animal received dermal applications of 2 μg 12-*O*-tetradecanoylphorbol 13-acetate (TPA) twice a week for 26 weeks. A positive control group received 50.5 μg/mouse benzo[*a*]pyrene followed by the TPA treatment. About 95% of the animals survived the treatment. Beryllium sulfate did not induce a significant number of mouse skin papillomas (Nesnow *et al.* 1985).

4. Other Relevant Data

4.1 Absorption, distribution, metabolism and excretion

The kinetics and effects of beryllium in humans and animals have been reviewed (Eisenbud, 1984; Skilleter, 1984; Cullen *et al.*, 1986; Reeves, 1986; Skilleter, 1986; Kriebel *et al.*, 1988b; Reeves, 1989; WHO, 1990; Deodhar & Barna, 1991; Haley, 1991).

4.1.1 *Humans*

After accidental exposure of 25 people to beryllium dust, the mean serum concentration of beryllium one day later was 3.5 ppb (μg/L); six days later, it had decreased to 2.4 ppb (Zorn *et al.*, 1986). In unexposed humans who had a mean blood beryllium concentration of 0.9 ng/g (mL), 33.2% of the beryllium in blood was associated with cellular constituents, 7.3% with low-molecular-weight compounds, 8.0% with prealbumin and 51.5% with γ-globulin (Stiefel *et al.*, 1980).

Subjects in the Beryllium Case Registry had elevated concentrations of beryllium in lung tissue (e.g. 0.32 μg/g in a metastinal node) more than 20 years after termination of short-term occupational exposure to beryllium (Sprince *et al.*, 1976).

4.1.2 *Experimental systems*

Retention of carrier-free ^{7}Be as chloride after oral dosage of RF mice, Sprague-Dawley rats, beagle dogs and *Macaca speciosa* monkeys was followed in urine excreted during the first two days. The authors estimated from counts in urine that the gastrointestinal absorption was about 0.6%; however, the urinary excretion of the three monkeys studied was reported to be 3.71% (Furchner *et al.*, 1973).

An early study on the kinetics of continuously inhaled beryllium sulfate in rats showed that the pulmonary burden of beryllium reached a plateau after about 36 weeks. After cessation of exposure, clearance was faster in males than in females. Beryllium was accumulated in tracheobronchial lymph nodes, where the concentration reached a peak at 52 weeks (Reeves & Vorwald, 1967). When rats were exposed to ^{7}Be as chloride and ^{4}Be as sulfate in aqueous aerosols by inhalation using nose-only exposure, 60% of the amount of beryllium deposited initially (the sum of the total body burden and the excreted amount) was found in the lungs and 13.5% in the skeleton (Zorn *et al.*, 1977).

When dogs inhaled aerosols of ^{7}Be as oxide calcined at 500 °C (low-fired) or 1000 °C (high-fired) through the nose, disappearance from the lungs followed first-order kinetics. The clearance half-time was 240 days for high-fired beryllium oxide and 64 days for the low-fired compound. Most of the beryllium in the body was located in the skeleton, tracheobronchial lymph nodes, liver and blood. During the first 32 days after exposure, 59% of the low-fired and 68% of the high-fired beryllium oxide was excreted through the gastrointestinal tract; by 180 days, 47% of the low-fired and 54% of the high-fired was excreted by that route and the balance *via* the kidneys (Finch *et al.*, 1990).

In rats, the clearance of inhaled beryllium oxide calcined at 1000 °C through the lungs showed two successive half-times: the first, comprising 30% of the initial lung burden, was

2.5 days, and the second (70%), 833 days. One to 63 days after exposure, a small fraction (0.58-1.73%) of the initial lung burden was observed in thoracic lymph nodes. About 15% was excreted in the faeces and 1.4% in the urine (Rhoads & Sanders, 1985). The clearance from the alveoli of inhaled beryllium oxide calcined at 1000 °C was faster in hamsters than in rats (Sanders *et al.*, 1975).

The disappearance of beryllium from the lungs of rats 3-171 days after exposure to 800 mg/m^3 metallic beryllium aerosol (mass median aerodynamic diameter, 1.4 μm; geometric mean standard deviation, 1.9) by nose-only inhalation once for 50 min was reported to fit best a first-order kinetic model with a half-time of 240 days (Haley *et al.*, 1990). In a carcinogenicity study (Wagner *et al.*, 1969), described in detail in section 3.1, rats, hamsters and squirrel monkeys were exposed by inhalation to ore dusts containing beryllium, beryl (containing 4.14% beryllium) and bertrandite (containing 1.4% beryllium). Increased concentrations of beryllium were detected in the skeleton, liver and lung after 6-12 months of exposure to beryl or bertrandite; exposure to beryl led to higher tissue concentrations than did exposure to bertrandite.

The highest concentrations of beryllium after an intramuscular injection of carrier-free ^{7}Be as chloride to rats were observed initially in the skeleton, liver, kidney, lungs and spleen; 56.3% of the dose injected was still at the site of injection after one day. During a 64-day follow-up, the skeleton and, to a lesser degree, spleen showed a constant increase, while there was a gradual decrease in the other organs; 20.5% of the dose injected was still at the site of injection (Crowley *et al.*, 1949). Accumulation in the liver, kidney, spleen and, especially, the skeleton was also observed seven days after an intravenous administration of ^{7}Be to rats and rabbits. In rats receiving ^{7}Be as sulfate, the liver and spleen contained appreciable amounts of beryllium; in animals receiving carrier-free ^{7}Be, a higher percentage was found in the skeleton. These differences were less marked in rabbits (Scott *et al.*, 1950).

Accumulation of beryllium in compact bone, liver and kidney was observed in dairy cows given carrier-free ^{7}Be as chloride orally or intravenously (Mullen *et al.*, 1972).

After intravenous injection of carrier-free ^{7}Be as chloride into rats in a solution at pH 2, 47% of the dose was excreted predominantly in the urine and 43% was detected in bone and bone marrow after 24 h; only 4% was detected in liver and 0.1% in spleen. When 1 μmol unlabelled beryllium chloride was added as carrier to the solution to be injected, the proportion found in the liver increased to 25% and that in spleen to 1%. At pH 6, 59% was found in the liver after administration of carrier-free ^{7}Be and 44% after addition of unlabelled beryllium chloride. Administration of labelled plus 0.15 μmol unlabelled beryllium chloride in citrate at pH 6 elicited similar responses to carrier-free ^{7}Be at pH 2, while labelled plus 0.3 μmol unlabelled beryllium hydroxide was accumulated strongly in the liver and spleen (Klemperer *et al.*, 1952).

The uptake of intravenously administered (20-800 μg/kg bw) beryllium phosphate was much more extensive in the liver and spleen (approximately 55% of the dose) than that of beryllium sulfate or citrate in mouse; the same phenomenon was observed in rats given a single dose (200 μg/kg bw). The uptake of the two soluble compounds was practically nil at dose levels up to 50 μg/kg, while uptake of the phosphate was independent of dose (Vacher *et al.*, 1974).

Beryllium phosphate and beryllium sulfate accumulated in both nonparenchymal and parenchymal cells of the liver after intravenous administration (Skilleter & Price, 1978). Beryllium oxide granules accumulated intracellularly in marrow throughout the skeletal system after intravenous administration to rabbits of beryllium oxide [method of preparation not given] (Fodor, 1977).

After an intraperitoneal or intravenous dose of carrier-free ^{7}Be as chloride, the disappearance of beryllium was best characterized by three consecutive half-times of 0.2-0.5, 6.3-21.7 and 50.9-52.4 days in mice, rats, dogs and *Macaca speciosa* monkeys (Furchner *et al.*, 1973).

Transplacental transfer of beryllium was demonstrated in mice after intravenous injection of beryllium chloride (Bencko *et al.*,1979).Transport of ^{7}Be [chemical unspecified] across the rat placenta after intravenous injection was also reported (Schulert *et al.*, 1969).

An estimated 1% of a single oral dose of carrier-free ^{7}Be as chloride to a dairy cow was excreted in the milk within 91 h (Mullen *et al.*, 1972).

After an intravenous injection of beryllium sulfate to rats, most of the beryllium in plasma coeluted in Sephadex chromatography with phosphate and was attached to plasma globulins. A small part of the dose remained in a low-molecular-weight form (Vacher & Stoner, 1968). One-fourth to one- third of blood-borne beryllium in unexposed guinea-pigs and rats was bound to cellular constituents; this proportion was unchanged in animals exposed to beryllium by inhalation. In both exposed and unexposed guinea-pigs, the proportion bound to prealbumin was approximately 70%; in rats, it was 65% (Stiefel *et al.*, 1980). When beryllium chloride (10^{-4} mol/L) was dissolved in different plasma constituents at their normal plasma concentrations, only a very small proportion (generally less than 2.5%) remained dialysable; only citrate (62%), maleate (30%) and bicarbonate (10%) were significantly dialysable. Phosphate decreased the dialysable part of beryllium to 0.2%, and 4% of the added beryllium remained dialysable. It was concluded that at beryllium concentrations in excess of about 10^{-7} mol/L, most of the beryllium in plasma is nondialysable phosphate, and the small dialysable part is mainly citrate (Feldman *et al.*, 1953). In line with this finding, only 3% of beryllium sulfate added to serum *in vitro* traversed a dialysis membrane within 24 h (Reeves & Vorwald, 1961). A low-affinity binding site for beryllium was observed on the outer cell surface of human and guinea-pig lymphocytes; a binding site with a higher affinity was detected in the cell nucleus (Skilleter & Price, 1984).

After repeated intraperitoneal administrations to rats of beryllum sulfate, beryllium was concentrated in nuclei in the cells of the proximal convoluted tubuli (Berry *et al.*, 1987, 1989). In hepatocytes, beryllium was accumulated in lysosomes and nuclei (Levi-Setti *et al.*, 1988). After intravenous administration, the highest concentrations were observed in lysosomes; only at doses approaching the LD_{50} (corresponding to 2-83 μmol/kg bw beryllium sulfate) was there also accumulation in the nuclei in the liver (Witschi & Aldridge, 1968).

Beryllium showed affinity to nuclei isolated from rat liver *in vitro* (Witschi & Aldridge, 1968); it was not bound to DNA or histones (Witschi & Aldridge, 1968; Parker & Stevens, 1979) but to a highly phosphorylated non-histone protein fraction (Parker & Stevens, 1979).

4.2. Toxic effects

4.2.1 *Humans*

Exposure to beryllium compounds may cause an acute chemical pneumonitis, tracheobronchitis, conjunctivitis, dermatitis and chronic granulomatous pulmonary disease with systemic manifestations (Hardy & Tepper, 1959; Freiman & Hardy, 1970). The acute pulmonary disease was first described in Germany in 1933 (Weber & Engelhardt, 1933) and the chronic form in the USA in 1946 (Hardy & Tabershaw, 1946).

Acute beryllium disease, most frequently related to intense but brief exposure, consists of respiratory tract irritation and dermatitis, sometimes with conjunctivitis. The respiratory tract symptoms range from mild nasopharyngitis to a severe chemical pulmonitis, which may be fatal (Hardy & Tepper, 1959; Kriebel *et al.*, 1988b). In fatal cases, histopathological findings in the lungs have included interstitial oedema, cellular infiltration, elevated numbers of plasma cells, alveolar cell proliferation or desquamation and, sometimes, inter-alveolar oedema, hyaline membranes and organizing pneumonia (Freiman & Hardy, 1970).

Chronic beryllium disease is a systemic disorder with primary manifestations in the lung, characterized by a decrease in transfer factor with restrictive and obstructive ventilatory function. Histopathologically, the disease is characterized by non-caseating granuloma formation with giant cells, as in sarcoidosis, primarily seen in the lungs but also in other tissues. Chest radiography usually shows diffuse infiltrates and hilar adenopathy (Hardy & Tepper, 1959; Freiman & Hardy, 1970; Jones Williams, 1977; Kriebel *et al.*, 1988b). An improvement in lung function and even in lung radiographic findings was reported after a significant decrease in the air concentration of beryllium due to improved engineering and ventilation in plants (Sprince *et al.*, 1978).

Beryllium compounds known to cause beryllium-induced diseases include metallic beryllium (Jones Williams, 1977), beryllium alloys (Lieben *et al.*, 1964) and beryllium oxide fumes (Cullen *et al.*, 1987). The first cases of beryllium disease were identified in the fluorescent light-bulb industry (Hardy & Tabershaw, 1946), in which beryllium-containing phosphors (zinc beryllium manganese silicate), prepared by firing the individual oxides with silica, were used (Eisenbud & Lisson, 1983).

Although chronic beryllium disease has become rare since the adoption of stringent industrial hygiene measures, sporadic cases are still reported (Karkinen-Jääskeläinen *et al.*, 1982; Cullen *et al.*, 1987; Rossman *et al.*, 1988; Kreiss *et al.*, 1989; Newman *et al.*, 1989), e.g., among workers in a precious metal refinery, where exposure to beryllium did not exceed 2 $\mu g/m^3$ (Cullen *et al.*, 1987). A conspicuous feature of chronic beryllium disease is its occasional occurrence outside facilities in which beryllium compounds are used: Sterner and Eisenbud (1951) reported 10 cases among people who had never worked in a beryllium plant but who lived within 1 km of one; the best estimate of beryllium concentrations in the air in the area was 0.01-0.1 $\mu g/m^3$. In 1983, when the US registry for beryllium diseases contained 622 cases of chronic beryllium disease, 65 had had no occupational exposure to beryllium, 42 could be attributed to air pollution (41 occurred in the vicinity of two large production plants and one in a woman living near a fluorescent-lamp plant) and 23 to household exposure to dust brought home on work clothes (Eisenbud & Lisson, 1983).

In the cohort study based on the Beryllium Case Registry, reported in detail in section 2 (p. 68), the SMR for non-neoplastic respiratory diseases was 16.4 ($p < 0.001$) and that for non-neoplastic respiratory diseases (other than influenza and pneumonia), 32.1 ($p < 0.001$) (Infante *et al.*, 1980). In an updating of the cohort (Steenland & Ward, 1991), described in detail in section 2, the SMR for nonmalignant lung disease was 26.3 (95% CI, 20.6-33.1) for workers with less than four years of exposure and 45.8 (95% CI, 36.6-56.5) for workers with longer exposure.

In a cohort study of 9225 male workers employed in seven beryllium processing facilities in the USA (Ward *et al.*, 1992; described in section 2, p. 69), the SMR for pneumoconiosis and other respiratory diseases was 1.48 (95% CI, 1.21-1.80), that for diseases of the heart was 1.06 (1.00-1.12) and that for chronic and unspecified nephritis, renal failure and other renal sclerosis, 1.49 (1.00-2.12).

A nonsymptomatic form of chronic beryllium disease─typical granulomatous changes in transbronchial biopsy specimens with positive lymphocyte transformation tests─has been reported (Newman *et al.*, 1989).

Beryllium dermatitis may be a typical contact dermatitis, localized dermal ulceration or a subcutaneous granuloma. Ulceration of granulomas develops after a particle of a beryllium-containing substance is introduced into an abrasion, laceration or cut (Hardy & Tepper, 1959). People with beryllium-induced contact dermatitis react to patch testing (Curtis, 1951; DeNardi *et al.*, 1952). Patch testing may cause a flare of the dermatitis in sensitized people; it may also induce beryllium sensitivity (Curtis, 1951)

A role of immunological mechanisms in beryllium-induced chronic disease was originally proposed by Sterner and Eisenbud (1951). The condition has the features of a type IV cell-mediated hypersensitivity disorder, the beryllium acting as a hapten (Dayan *et al.*, 1990). Cell-free extracts of blood lymphocytes from people with experimentally induced, localized, dermal granulomatous beryllium lesions cultured in the presence of beryllium oxide contained migration inhibition factor, which inhibits the migration of guinea-pig peritoneal exudate cells (Henderson *et al.*, 1972). The factor was also produced by cell cultures originating from the blood of patients with chronic beryllium disease (Jones Williams *et al.*, 1972; Marx & Burrell, 1973). Lymphocytes from such patients responded to a beryllium oxide or beryllium sulfate challenge by blast transformation and increased thymidine incorporation (Hanifin *et al.*, 1970; Deodhar *et al.*, 1973). Proliferation of lymphocytes from patients with chronic beryllium disease in response to a challenge with beryllium sulfate or fluoride was more marked in lymphocytes obtained by bronchoalveolar lavage than in those harvested from circulating blood (Epstein *et al.*, 1982; Cullen *et al.*, 1987; Saltini *et al.*, 1989). The only lymphocytes obtained from bronchoalveolar lavage which proliferated were CD4+ (helper/inducer) T cells (Saltini *et al.*, 1989).

4.2.2 *Experimental systems*

When beryllium (as lactate or sulfate) was given intravenously to rats or rabbits at a dose of 0.5 or 0.75 mg/kg Be, death invariably followed within four days; the primary cause of death was liver damage and ensuing hypoglycaemia. In rabbits, but not in rats, convulsions were observed before death (Aldridge *et al.*, 1950).

A granulomatous lung disease, morphologically and immunologically similar to chronic beryllium disease in humans, was induced in beagle dogs by inhalation of beryllium oxide calcined at 500 °C, but not with beryllium oxide calcined at 1000 °C (Haley *et al.*, 1989).

Intratracheal instillation of 10 mg beryllium oxide (calcined at 560 °C) into male Hartley guinea-pigs of an inbred strain caused focal interstitial lymphomononuclear infiltrates in the lungs, which progressed to granulomatous lung lesions with fibrosis. Lymphocytes from the blood of these animals responded to beryllium sulfate *in vitro* by increased incorporation of tritiated thymidine (lymphocyte transformation test). The animals exhibited a positive reaction to intradermal beryllium sulfate. Intravenous or oral administration of beryllium sulfate before intratracheal instillation of beryllium oxide decreased the intensity of the pulmonary reaction; a similar effect was observed when the animals were treated with prednisone, L-asparaginase or cyclophosphamide. Splenic cells from animals with beryllium-induced lung disease given intraperitoneally to another group of animals of the same strain caused a similar disease and skin reactivity to beryllium sulfate. No lung disease, skin reactivity or reaction in the lymphocyte transformation test was induced by similar treatment of another inbred strain of guinea-pigs (Barna *et al.*, 1981).

In another study using the same responsive guinea-pig strain, lymphokine production by isolated lymph node cells from animals treated with beryllium oxide endotracheally and challenged with beryllium sulfate was demonstrated *in vitro*. The cells also secreted a factor that inhibited the migration of macrophages (Barna *et al.*, 1984).

Strain A (H-2^a haplotype) mice given an intratracheal instillation challenge of beryllium sulfate or beryllium oxide (calcined at 550 and 1100 °C) after immunization with beryllium sulfate had increased numbers of lymphocytes in bronchoalveolar lavage fluids two, four and eight weeks (months for the oxide) after the challenge. The cells were mainly CD4 + T lymphocytes. By four weeks, microgranulomas were observed in the lungs, which had developed into granulomatous lesions by eight weeks in the case of the sulfate. Such changes were not observed in mice not immunized with beryllium sulfate or in pretreated mice that were not challenged, nor in two strains of mice with different H-2 haplotypes [C57BL/6(H-2^b) and BALB/c(H-2^d)] (Huang *et al.*, 1992).

In a descriptive toxicity study (see p. 86), male Fischer 344/N rats were exposed by nose only to 800 mg/m^3 metallic beryllium dust (mass median aerodynamic diameter, 1.4 μm) for 50 min, to give an initial lung burden of 625 μg. The animals were then followed for 171 days with timed terminations at 3, 7, 10, 14, 31, 59 and 115 days. Necrotizing, haemorrhagic pulmonitis and intra-alveolar fibrosis, followed by chronic inflammatory changes, were observed. The prevailing cell type obtained by bronchoalveolar lavage was neutrophils; few lymphocytes and no granulomas were observed (Haley *et al.*, 1990). Similarly, after a 1-h exposure of rats to 4.05 mg/m^3 Be as beryllium sulfate (mass median aerodynamic diameter, 1.9 μm), progressive focal interstitial pneumonitis, but no granulomatous disease, was observed; the gross histological picture was similar three weeks and 3, 6 and 12 months after the exposure (Sendelbach *et al.*, 1989).

Intratracheal instillation of beryllium sulfate after immunization with a subcutaneous injection of beryllium sulfate fortified with ovalbumin and Freund's adjuvant resulted in

granulomatous pulmonary disease in Fischer 344 rats within six weeks, accompanied by accumulation of both T and B lymphocytes in the lung tissue (Votto *et al.*, 1987).

In a carcinogenicity study (Wagner *et al.*, 1969; see section 3.1, p. 76), granulomatous lung lesions were observed in hamsters and rats exposed to bertrandite but not in those exposed to beryl ore. [It is not clear if the granulomas were morphologically similar to those observed in humans with chronic beryllium disease or to those in dogs and guinea-pigs after short-term exposure to beryllium oxide.]

The effect of beryllium sulfate (1-h exposure by inhalation; 13 mg/m^3 Be; particle mass median aerodynamic diameter, 1.9 μm) on cell kinetics was studied in rats and mice by autoradiographic determination of the proportion of tritium-labelled cells 90 min after intraperitoneal administration of tritiated thymidine (Sendelbach *et al.*, 1986). In rats, a strong proliferative response was seen, involving type II alveolar epithelial cells and interstitial and capillary endothelial cells. In mice, the proliferative response was weaker and was limited to alveolar macrophages and interstitial and endothelial cells.

Dietary administration of beryllium carbonate at 0.125-1% caused changes typical of rachitis in the skeleton of rats (Guyatt *et al.*, 1933).

Exposure of female rats by nose-only inhalation to beryllium oxide aerosol (mass median aerodynamic diameter, 1.10 μm; calcined at approximately 1000 °C [dust concentration and length of exposure not given]), to give an initial alveolar deposition of 30 μg beryllium, decreased alveolar clearance of subsequently administered plutonium oxide by up to 40% (Sanders *et al.*, 1975).

The concentration of beryllium sulfate required to decrease the viability of canine pulmonary alveolar macrophages in vitro by 50% was 0.11 mmol/L; the corresponding concentration for beryllium oxide calcined at 500 °C was 1.4 mmol/L, and that for beryllium oxide calcined at 1000 °C was 3.3 mmol/L. [Because of the limited solubility of beryllium sulfate in tissue culture media, it is not clear what proportion was truly in solution.] The solubility of the high-fired beryllium oxide in 100 mL 0.1 N hydrochloric acid was considerably lower than that of the low-fired compound. There was a similar tendency for differential solubility in simulated serum ultrafiltrate, which was not, however, significant (Finch *et al.*, 1988). Similar results were obtained in a study of cultured rat tracheal epithelial cells (Steele *et al.*, 1989).

Intravenous administration of beryllium sulfate at 30 μmol/kg bw to rats decreased thestimulation of thymidine incorporation into liver DNA after partial hepatectomy (Witschi, 1968); the decrease was accompanied by decreased activities of thymidine kinase, thymidylate kinase, thymidylate synthetase, deoxycytidylate deaminase and DNA polymerase (Witschi, 1970). No effect was observed on the incorporation of 14C-orotic acid into RNA, the activity of RNA polymerase, incorporation of 14C-leucine into histones or acetylation of histones (Marcotte & Witschi, 1972).

Addition of beryllium sulfate at 1-5 μmol/L increased 3H-thymidine incorporation into splenic lymphocyte DNA by two to three fold (Price & Skilleter, 1985). This weak mitogenic effect was limited to B lymphocytes (Newman & Campbell, 1987). Beryllium sulfate, brought into solution as a sulfosalicylic acid complex, inhibited the growth of mouse fibroblasts in culture at concentrations higher than 10-5 mol/L (Rössner & Bencko, 1980).

Be^{2+} at a concentration of 0.1 mmol/L inhibited the proliferation of rat hepatocytes in culture induced by epidermal growth factor by 72%, but it did not affect the binding of growth factor to its receptors on the hepatocytes (Skilleter & Legg, 1989).

Beryllium fluoride complexes were bound to microtubules polymerized in the presence of glycerol from tubulin isolated from pig brain and stabilized the polymer formed (Carlier *et al.*, 1988, 1989). Divalent beryllium ($BeSO_4$), but not beryllium fluoride, stimulated microtubule-associated protein-dependent polymerization of tubulin purified from bovine brain and stabilized the polymer formed (Hamel *et al.*, 1991, 1992).

4.3 Reproductive and developmental effects

4.3.1 *Humans*

Kline *et al.* (1951) described the pregnancy of a 25-year-old woman who worked in a fluorescent-tube factory in 1942-44. She displayed signs of radiographic changes in lungs, cyanosis and dyspnoea in the seventh month of her second pregnancy in 1950. No beryllium was detected in a lung biopsy. The woman was treated with adrenocorticotrophic hormone and steroids and delivered a 2.75-kg child seven weeks later. Twenty-four-hour specimens of the urine of the infant collected on the second and third day after birth contained 0.4 and 0.015 μg Be. The child became severely hypoglycaemic after 48 h but was subsequently released from hospital.

Savitz *et al.* (1989) examined a subset of people covered by the 1980 US National Natality and Fetal Mortality Surveys for indications of adverse effects related to maternal or paternal occupational exposures to beryllium, as assessed from a job-exposure matrix. Paternal occupational exposure was associated with 3170 stillbirths, 552 preterm deliveries and 371 babies small for gestational age; the corresponding odds ratios (with 95% CI) were: 1.0 (0.7-1.3), 1.0 (0.5-2.0) and 0.9 (0.5-1.7), respectively. Maternal exposure to beryllium was not associated with these end-points.

4.3.2 *Experimental systems*

The effects of beryllium compounds on reproduction and prenatal development have been reviewed (Barlow & Sullivan, 1982). After oral exposure of male and female rats to a single intratracheal dose of 0.2 mg beryllium oxide (fired at 960 °C in one study and 500 °C in a second), no effect was noted in repeated breeding trials on fertility, postnatal viability or growth over 15 months. In fact, beryllium-treated rats tended to produce more litters over time than did controls (Clary *et al.*, 1975).

All offspring of Sprague-Dawley rats exposed intravenously to 0.316 mg/kg bw beryllium nitrate (one-tenth of the reported LD_{50}) on gestation day 1 died within two to three days after birth. Exposure to beryllium on day 11, but not on day 12, 13, 15 or 17 of gestation, resulted in death *in utero*; all pups in the other groups died within two to three days of delivery (Mathur *et al.*, 1987). [The Working Group noted the potential confounding effect of anaesthesia and surgery in the experimental design.]

4.4 Genetic and related effects

4.4.1 *Humans*

No data were available to the Working Group.

4.4.2 *Experimental systems* (see also Table 19 and Appendices 1 and 2)

(*a*) *Beryllium salts*

Beryllium sulfate was mutagenic to *Bacillus subtilis* in the *rec* assay, but no effect was seen using a higher dose of beryllium chloride. [The latter was actually a null effect, as no zone of inhibition was seen.] Both beryllium chloride and beryllium nitrate were mutagenic in a *rec* assay using spores of *B. subtilis*.

A null effect was also seen with beryllium sulfate in *Escherichia coli* in the *pol*$^+$/*pol*$^-$ assay for DNA modifying effects. In a spot test using four strains of *E. coli* with different repair capacities, beryllium sulfate caused zones of inhibition of growth only in repair-deficient strains. The inhibition decreased with increasing pH, with little effect above pH 5-6. The authors suggested that beryllium interferes with use of exogenous orthophosphate rather than with DNA repair.

Beryllium chloride did not induce SOS repair, measured as λ prophage induction; no inhibition of growth was seen with continuous exposure to up to 5 mM, however, suggesting lack of uptake.

Beryllium sulfate was inactive in most bacterial mutagenesis assays. It did not induce point mutations in *Salmonella typhimurium* in the absence of metabolic activation in four laboratories. Negative results were found in the presence of various metabolizing systems, except in strain TA1535, in which equivocal results were obtained in the presence of some Aroclor-induced liver enzymes; however, no toxicity was seen, even at doses up to 5 mg/plate. Beryllium chloride and beryllium nitrate at similarly high doses were not mutagenic to *S. typhimurium*. Beryllium sulfate was not mutagenic to *S. typhimurium* in a plate incorporation assay, but it gave positive results in single fluctuation tests with *E. coli* and with one strain of *S. typhimurium*. Beryllium chloride induced a modest increase in the number of mutations in the *lac*I gene when grown with *E. coli*, but no clear dose-response relationship. It did not enhance the mutagenicity of ultraviolet radiation to *E. coli*, but it enhanced the mutagenicity of 9-aminoacridine to *S. typhimurium*.

Beryllium sulfate was not mutagenic when injected intraperitoneally to adult male Swiss-Webster mice in a host-mediated assay using *S. typhimurium* strains. It did not induce mitotic recombination in *Saccharomyces cerevisiae* D3 in the presence or absence of metabolic activation, and did not induce mutation in a host-mediated assay using the same strain.

Beryllium sulfate tetrahydrate did not induce unscheduled DNA synthesis in primary hepatocytes, as measured by autoradiographic light nuclear labelling; however, a dose of 10 mg/mL was reported to be toxic.

In the only study available, beryllium chloride was reported to increase the frequency of 8-azaguanine-resistant mutants in Chinese hamster V79 cells by a factor of about 6.

Beryllium chloride and beryllium nitrate induced sister chromatid exchange in the same cells. Beryllium sulfate also increased the frequency of sister chromatid exchange in cultured human lymphocytes and in Syrian hamster embryo cells. Studies on the ability of beryllium salts to induce chromosomal aberrations *in vitro* have had mixed results. Beryllium sulfate increased the frequency of chromatid aberrations in human lymphocytes in one of two studies, and a 21-fold increase was seen in the same study with Syrian hamster embryo cells. Higher doses of beryllium sulfate were nonclastogenic to Chinese hamster lung cells; however, toxicity was seen only at 2.5 mg/mL. It had little effect on chromosomes in Chinese hamster ovary cells, but fairly high concentrations enhanced the frequency of X-ray-induced chromatid-type exchanges. Extremely high concentrations of beryllium chloride caused chromosomal 'stickiness' in cultured peripheral lymphocytes of domestic pigs; chromosomal breakage was rare, whereas chromatid breaks were frequent.

Beryllium sulfate induced morphological transformation of Syrian hamster embryo cells and enhanced the transformation of the cells by simian adenovirus SA7 [no dose-response given]. In a comparative evaluation of in-vitro transformation systems, beryllium sulfate induced morphological transformation in BALB/3T3 cells, in Syrian hamster embryo cells and in Rauscher murine leukaemia virus-infected Fischer 344 rat embryo cells. [In none of the studies were transformed cells injected into suitable hosts to verify the occurrence of malignant transformation.]

In the only report of exposure *in vivo*, beryllium sulfate given by gavage at 50 and 80% of the four-day maximal tolerated dose did not induce micronuclei in the bone marrow of mice. A marked depression of bone-marrow erythropoiesis was observed, suggesting a toxic effect to the marrow.

(*b*) *Beryllium oxide*

This sparingly soluble compound did not induce differential toxicity in *B. subtilis*, mutation in two strains of *S. typhimurium* or sister chromatid exchange in Chinese hamster V79 cells.

Both single-strand breaks and morphological cell transformation were reported to be induced by low-fired beryllium oxide, but conflicting results were obtained for both end-points with high-fired beryllium oxide. [The data were not particularly convincing.]

Considerations with regard to genotoxic mechanisms

As pointed out in a review, beryllium is uniquely amphoteric among the alkaline earth elements. It can form positive and negative ions in acidic and basic media but not at neutrality, at which it forms poorly soluble particulates. Beryllium salts are readily precipitated in the tissues and are transported in blood predominantly as colloidal phosphate-hydroxide complexes weakly associated with plasma globulins; these may be taken up by macrophages. Cultured cells essentially accumulate only colloidal or particulate beryllium, by a temperature-dependent process deduced to be endocytosis. Macrophages, the cells most active in the endocytosis of particulate materials, appear to be those most sensitive to the cytotoxicity of beryllium (reviewed by Skilleter, 1984). Beryllium was toxic to mammalian cells only at concentrations at which a precipitate was seen in the culture

Table 19. Genetic and related effects of beryllium compounds

Test system	Result		Dose[a] (LED/HID)	Reference
	Without exogenous metabolic system	With exogenous metabolic system		
Beryllium chloride				
PRB, λ Prophage induction, *Escherichia coli*	–[b]	0	45	Rossman *et al.* (1984)
BSD, *Bacillus subtilis rec* assay, differential toxicity	–	0	22.5	Nishioka (1975)
BSD, *Bacillus subtilis* (spores) *rec* assay, differential toxicity	+	0	84	Kuroda *et al.* (1991)
SA0, *Salmonella typhimurium* TA100, reverse mutation	–	0	NR	Ogawa *et al.* (1987)
SA0, *Salmonella typhimurium* TA100, reverse mutation	–	–	280	Kuroda *et al.* (1991)
SA2, *Salmonella typhimurium* TA102, reverse mutation	–	0	NR	Ogawa *et al.* (1987)
SA7, *Salmonella typhimurium* TA1537, reverse mutation	–	0	NR	Ogawa *et al.* (1987)
SA7, *Salmonella typhimurium* TA1537, reverse mutation	+[c]	0	450	Ogawa *et al.* (1987)
SA9, *Salmonella typhimurium* TA98, reverse mutation	–	0	NR	Ogawa *et al.* (1987)
SA9, *Salmonella typhimurium* TA98, reverse mutation	–	–	280	Kuroda *et al.* (1991)
SA5, *Salmonella typhimurium* TA2637, reverse mutation	–	0	NR	Ogawa *et al.* (1987)
SA5, *Salmonella typhimurium* TA2637, reverse mutation	+[c]	0	450	Ogawa *et al.* (1987)
ECK, *Escherichia coli* KMBL 3835 (*lac*I gene), forward mutation	+	0	0.09	Zakour & Glickman (1984)
EC2, *Escherichia coli* WP2, reverse mutation	–[d]	0	18	Rossman & Molina (1986)
G9H, Gene mutation, Chinese hamster lung V79 cells, *hprt* locus, *in vitro*	+	0	18	Miyaki *et al.* (1979)
SIC, Sister chromatid exchange, Chinese hamster lung V79 cells, *in vitro*	+	0	3.5	Kuroda *et al.* (1991)
CIA, Chromosomal aberrations, swine lymphocytes, *in vitro*	+	0	1.8	Vegni Talluri & Guiggiani (1967)
Beryllium nitrate				
BSD, *Bacillus subtilis* (spores) *rec* assay, differential toxicity	+	0	51	Kuroda *et al.* (1991)
SA0, *Salmonella typhimurium* TA100, reverse mutation (spot test)	–	0	900	Tso & Fung (1981)
SA0, *Salmonella typhimurium* TA100, reverse mutation	–	–	170	Kuroda *et al.* (1991)

Table 19 (contd)

Test system	Result		Dose[a] (LED/HID)	Reference
	Without exogenous metabolic system	With exogenous metabolic system		
Beryllium nitrate (contd)				
SA9, *Salmonella typhimurium* TA98, reverse mutation	?	0	NR	Arlauskas *et al.* (1985)
SA9, *Salmonella typhimurium* TA98, reverse mutation	–	–	170	Kuroda *et al.* (1991)
SIC, Sister chromatid exchange, Chinese hamster lung V79 cells, *in vitro*	+	0	2.0	Kuroda *et al.* (1991)
Beryllium sulfate				
ECD, *Escherichia coli pol* A, differential toxicity (spot test)	–	0	28	Rosenkranz & Poirier (1979)
BSD, *Bacillus subtilis rec* assay, differential toxicity	+	0	90	Kada *et al.* (1980); Kanematsu *et al.* (1980)
ERD, *Escherichia coli rec* strains, differential toxicity	+	0	2.25	Dylevoi (1990)
SA0, *Salmonella typhimurium* TA100, reverse mutation	–	–	6	Simmon (1979a)
SA0, *Salmonella typhimurium* TA100, reverse mutation	–	–	14	Dunkel *et al.* (1984)[e]
SA0, *Salmonella typhimurium* TA100, reverse mutation	–	0	NR	Arlauskas *et al.* (1985)
***Salmonella typhimurium* TA100, reverse mutation (fluctuation)	+	0	4.5	Arlauskas *et al.* (1985)
SA0, *Salmonella typhimurium* TA100, reverse mutation	–	–	127	Ashby *et al.* (1990)
SA5, *Salmonella typhimurium* TA1535, reverse mutation	–	–	10	Rosenkranz & Poirier (1979)
SA5, *Salmonella typhimurium* TA1535, reverse mutation	–	–	6	Simmon (1979a)
SA5, *Salmonella typhimurium* TA1535, reverse mutation	–	?[f]	0.9	Dunkel *et al.* (1984)[e]
SA5, *Salmonella typhimurium* TA1535, reverse mutation	–	0	NR	Arlauskas *et al.* (1985)
SA5, *Salmonella typhimurium* TA1535, reverse mutation	–	–	127	Ashby *et al.* (1990)
SA7, *Salmonella typhimurium* TA1537, reverse mutation	–	–	6	Simmon (1979a)
SA7, *Salmonella typhimurium* TA1537, reverse mutation	–	–	14	Dunkel *et al.* (1984)[e]
SA7, *Salmonella typhimurium* TA1537, reverse mutation	–	0	NR	Arlauskas *et al.* (1985)
SA7, *Salmonella typhimurium* TA1537, reverse mutation	–	–	127	Ashby *et al.* (1990)
SA8, *Salmonella typhimurium* TA1538, reverse mutation	–	–	10	Rosenkranz & Poirier (1979)
SA8, *Salmonella typhimurium* TA1538, reverse mutation	–	–	6	Simmon (1979a)

Table 19 (contd)

Test system	Result		Dose[a] (LED/HID)	Reference
	Without exogenous metabolic system	With exogenous metabolic system		
Beryllium sulfate (contd)				
SA8, *Salmonella typhimurium* TA1538, reverse mutation	-	-	14	Dunkel *et al.* (1984)[e]
SA8, *Salmonella typhimurium* TA1538, reverse mutation	-	0	NR	Arlauskas *et al.* (1985)
SA8, *Salmonella typhimurium* TA1538, reverse mutation	-	-	127	Ashby *et al.* (1990)
SA9, *Salmonella typhimurium* TA98, reverse mutation	-	-	6	Simmon (1979a)
SA9, *Salmonella typhimurium* TA98, reverse mutation	-	-	14	Dunkel *et al.* (1984)[e]
SA9, *Salmonella typhimurium* TA98, reverse mutation	-	0	NR	Arlauskas *et al.* (1985)
SA9, *Salmonella typhimurium* TA98, reverse mutation	-	-	127	Ashby *et al.* (1990)
SA5, *Salmonella typhimurium* TA1535, reverse mutation	-	-	6	Simmon (1979a)
ECW, *Escherichia coli* WP2 *uvr*A, reverse mutation	-	-	14	Dunkel *et al.* (1984)[e]
***, *Escherichia coli* WP2 *uvr*A, reverse mutation (fluctuation test)	?	0	NR	Arlauskas *et al.* (1985)
SCH, *Saccharomyces cerevisiae* D3, mitotic recombination	-	-	430	Simmon (1979b)
URP, Unscheduled DNA synthesis, primary rat hepatocytes	-	0	86	Williams *et al.* (1982)
SIS, Sister chromatid exchange, Syrian hamster embryo cells *in vitro*	+	0	0.05	Larramendy *et al.* (1981)
CIC, Chromosomal aberrations, Chinese golden hamster ovary cells *in vitro*	-	0	9	Brooks *et al.* (1989)
CIC, Chromosomal aberrations, Chinese hamster ovary cells *in vitro*	+[g]	0	9	Brooks *et al.* (1989)
CIC, Chromosomal aberrations, Chinese hamster lung cells *in vitro*	-	-	64	Ashby *et al.* (1990)
CIS, Chromosomal aberrations, Syrian hamster embryo cells *in vitro*	+	0	0.25	Larramendy *et al.* (1981)
TBM, Cell transformation, BALB/c 3T3 mouse cells *in vitro*	+	0	0.05	Dunkel *et al.* (1981)
TCS, Cell transformation, Syrian golden hamster embryo cells *in vitro*	+	0	0.016	Pienta *et al.* (1977)
TCS, Cell transformation, Syrian hamster embryo cells *in vitro*	+	0	0.13	DiPaolo & Casto (1979)

Table 19 (contd)

Test system	Result		Dose[a] (LED/HID)	Reference
	Without exogenous metabolic system	With exogenous metabolic system		
Beryllium sulfate (contd)				
TRR, Cell transformation, RLV/Fischer rat embryo cells *in vitro*	+	0	0.005	Dunkel *et al.* (1981)
T7S, Cell transformation SA7/Syrian hamster embryo cells *in vitro*	+	0	5	Casto *et al.* (1979)
SHL, Sister chromatid exchange, human lymphocytes *in vitro*	+	0	0.05	Larramendy *et al.* (1981)
CHF, Chromosomal aberrations, human MRC5 fibroblasts *in vitro*	-	0	0.005	Paton & Allison (1972)
CHL, Chromosomal aberrations, human lymphocytes *in vitro*	+	0	0.25	Larramendy *et al.* (1981)
CHL, Chromosomal aberrations, human WI38 lymphocytes *in vitro*	-	0	0.009	Paton & Allison (1972)
HMM, Host-mediated assay, *Salmonella typhimurium* TA1530 in male Swiss–Webster mice	-		1.25, im or po	Simmon *et al.* (1979)
HMM, Host-mediated assay, *Salmonella typhimurium* TA1535 in male Swiss–Webster mice	-		103, im or po	Simmon *et al.* (1979)
HMM, Host-mediated assay, *Salmonella typhimurium* TA1538 in male Swiss–Webster mice	-		1.25, im or po	Simmon *et al.* (1979)
HMM, Host-mediated assay, *Saccharomyces cerevisiae* in mice	-		103, im or po	Simmon *et al.* (1979)
MVM, Micronucleus test, mouse bone marrow *in vivo*	-		116, po × 1	Ashby *et al.* (1990)
Beryllium oxide				
BSD, *Bacillus subtilis* (spores) *rec* assay, differential toxicity	-[h]	0	0.1	Kuroda *et al.* (1991)
SA0, *Salmonella typhimurium* TA100, reverse mutation	-[h]	-	0.08	Kuroda *et al.* (1991)
SA9, *Salmonella typhimurium* TA98, reverse mutation	-[h]	-	0.08	Kuroda *et al.* (1991)
DIA, DNA strand breaks, rat tracheal epithelial cells	+[i]	0	0.36	Steele *et al.* (1989)
DIA, DNA strand breaks, rat tracheal epithelial cells	?[j]	0	10	Steele *et al.* (1989)

Table 19 (contd)

Test system	Result		Dose[a] (LED/HID)	Reference
	Without exogenous metabolic system	With exogenous metabolic system		
Beryllium oxide (contd)				
SIC, Sister chromatid exchange, Chinese hamster V79 lung cells *in vitro*	-[g]	0	0.03	Kuroda *et al.* (1991)
TCL, Cell transformation, rat tracheal epithelial cells *in vitro*	+[i]	0	0.1	Steele *et al.* (1989)
TCL, Cell transformation, rat tracheal epithelial cells *in vitro*	?[j]	0	10	Steele *et al.* (1989)

+, considered to be positive; (+), considered to be weakly positive in an inadequate study; –, considered to be negative; ?, considered to be inconclusive (variable responses in several experiments within an adequate study); 0, not tested

[a]LED, lowest effective dose; HID, highest ineffective dose. In-vitro tests, μg/ml; in-vivo tests, mg/kg bw. Doses given as concentration of element, not concentration of compound; im, intramuscularly; po, orally; NR, not reported

[b]Precipitate

[c]Comutation with 9-aminoacridine (100 μmol/plate) (not on profile)

[d]Comutation with ultraviolet radiation (not on profile)

[e]Results from four independent laboratories

[f]Negative in two laboratories, inconsistently positive in two laboratories

[g]Enhancement of effect of X irradiation (not on profile)

[h]BeO unspecified

[i]Low-fired oxide

[j]High-fired oxide

***Not displayed on profiles

medium (Rossman *et al.*, 1987). [The Working Group noted that the lack of toxicity of beryllium compounds in many studies of bacteria suggests lack of uptake.] In mammalian cells, intracellular transfer is from lysozyme to nucleus (reviewed by Skilleter, 1984).

Beryllium chloride (1-10 mM) increased misincorporation of nucleoside triphosphates during polymerization of poly-d(A-T) by *Micrococcus luteus* DNA polymerase (Luke *et al.*, 1975). In a similar system, beryllium chloride reduced the fidelity of DNA synthesis *in vitro* in the presence of avian myeloblastosis virus DNA polymerase, a synthetic prime template and complementary and noncomplementary nucleoside triphosphates. This effect was observed at concentrations at which even incorporation of complementary triphosphates was inhibited and was ascribed to the noncovalent binding of ionic divalent beryllium to DNA polymerase rather than to DNA (Sirover & Loeb, 1976). [It is not clear that such effects can occur within the cell, where the concentrations of Be^{2+} would probably be much lower; e.g. chromosomal aberrations have been reported at an extracellular concentration of < 5 μM.] The binding of beryllium by purified DNA is very weak ($K_a = 7 \times 10^3$/mol) (Truhaut *et al.*, 1968). It was reported in an abstract that beryllium can induce DNA-protein complexes (Kubinski *et al.*, 1977). [The Working Group considered that any 'genotoxic' effects of Be^{2+} are probably not caused by direct damage to DNA.]

5. Summary of Data Reported and Evaluation

5.1 Exposure data

Beryllium is found at low concentrations in the Earth's crust. Since the early twentieth century, it has been produced and used in a variety of applications as the metal, in alloys and as its oxide.

Although only a relatively small number of workers worldwide are potentially exposed to high levels of beryllium, mainly in the refining and machining of the metal and in production of beryllium-containing products, a growing number of workers are potentially exposed to lower levels of beryllium in the aircraft, aerospace, electronics and nuclear industries. Although the range of industrial processes with potential occupational exposure to beryllium has expanded over the past two decades, exposures have generally decreased over the same period.

The most important source of exposure to beryllium in the general environment is the burning of coal.

5.2 Human carcinogenicity data

In an early series of cohort mortality studies of workers at two beryllium extraction, production and fabrication facilities in the USA, a consistent, marginally significant excess of deaths from lung cancer was observed. The excess increased with time since first exposure. In a more recent mortality analysis of some 9000 workers at seven beryllium plants in the USA, including the two plants studied previously, a small but significant excess in mortality from lung cancer was found in the total cohort. The risks for lung cancer were

consistently higher in those plants in which there was also excess mortality from nonmalignant respiratory disease. Also, the risk for lung cancer increased with time since first exposure and was greater in workers first hired in the period when exposures to beryllium in the work place were relatively uncontrolled. Mortality from cancers at other sites was not increased. The association between lung cancer risk and exposure to beryllium was judged not to be confounded by smoking.

Follow-up of deaths among workers entered into the US Beryllium Case Registry (which registered cases of acute beryllium-related pneumonitis and chronic beryllium-related nonmalignant lung disease, including cases from the plants mentioned above) revealed excess mortality from lung cancer; the excess was greater in those who were entered into the Registry with acute beryllium pneumonitis. Potential confounding by smoking was addressed in several ways and did not appear to explain the increased risk for lung cancer. The results of the follow-p of the Case Registry subjects yielded a higher risk for lung cancer than had been found in the previous cohort mortality study of the seven production facilities.

In a nested case-control study of cancers of the central nervous system among workers at two nuclear facilities in the USA, an increasing risk of cancer of the central nervous system was suggested with longer duration of employment in jobs with more highly ranked exposure to beryllium.

Several aspects of the two most recent cohort studies support the conclusion that the work environment of workers involved in refining, machining and producing beryllium metal and alloys was causally associated with an increased risk of lung cancer: the large number of lung cancer cases, providing a stable estimate of the mortality ratio; the consistency of the lung cancer excess in most of the locations; the greater excess in workers hired before 1950, when exposures to beryllium in the work place were relatively uncontrolled and much higher than in subsequent decades; the highest risk for lung cancer being found in the plant from which the greatest proportion of cases of acute beryllium pneumonitis was provided to the Beryllium Case Registry; the increasing risks with increasing latency; the greater lung cancer risk observed in the Beryllium Case Registry cohort, the highest risk for lung cancer being observed among individuals diagnosed with acute beryllium-induced pneumonitis, who represent a group that had the most intense exposure to beryllium; and the highest risks for lung cancer occurring in the plants where the risk for pneumoconiosis and other respiratory diseases was highest. Aspects of the studies which limit their interpretation are: the absence of any individual measurements of exposures to beryllium, the relatively low excess risk for lung cancer and the absence of any mention of exposure of workers to other lung carcinogens in the work place, although there is no evidence that other lung carcinogens were present.

5.3 Animal carcinogenicity data

Beryl ore and bertrandite ore were tested for carcinogenicity in rats, hamsters and monkeys by inhalation exposure in three experiments in one study. Beryl ore was shown to produce malignant and benign lung tumours in rats. The experiments in hamsters and monkeys were inadequate for evaluation, as were all experiments with bertrandite ore.

In one study in rats by single intratracheal instillation, beryllium metal, passivated beryllium metal (99% beryllium, 0.26% chromium as chromate) and beryllium-aluminium

alloy (62% beryllium) produced dose-related increases in the incidence of lung tumours, which were mostly adenocarcinomas and adenomas.

Various beryllium compounds were tested by inhalation in five studies in rats, rabbits and monkeys. In two studies in rats, beryllium sulfate tetrahydrate produced lung tumours, which were mostly adenocarcinomas. In one study, both beryllium oxide and beryllium chloride produced dose-related increases in the incidence of malignant epithelial lung tumours in rats. The studies in rabbits and monkeys were considered to be inadequate for evaluation. Beryllium hydroxide and low- and high-temperature-fired beryllium oxide were tested in rats by intratracheal instillation; beryllium hydroxide produced lung adenocarcinomas and adenomas in one study, and low-temperature-fired (below 900 °C) beryllium oxide produced malignant lung tumours in two studies.

Rabbits given intravenous injections of beryllium metal and various compounds of beryllium (zinc beryllium silicate, beryllium silicate, beryllium oxide and beryllium phosphate) developed osteosarcomas. Similar findings were obtained in rabbits treated by implantation or injection into the bone of beryllium oxide, zinc beryllium silicate and beryllium carbonate.

5.4 Other relevant data

Increased levels of beryllium have been found in the lungs of people exposed up to 20 years previously. In dogs and rats, the lung clearance of beryllium oxide calcined at high temperatures is slower than for that calcined at low temperatures. After inhalation, beryllium also accumulates in tracheobronchial lymph nodes. Gastrointestinal absorption of beryllium and beryllium compounds is very limited. Beryllium accumulates in bone and, to a lesser extent, in the liver. Absorbed beryllium is excreted mostly in the urine.

Beryllium may cause a fatal acute pneumonitis and, after long-term exposure, a chronic, non-caseating granulomatous pulmonary disease with a high rate of fatality; the pathogenesis of the latter disease involves cell-mediated immunological reactions. Susceptibility to chronic beryllium disease varies between individuals, and the disease may develop after low environmental exposures in some people. A similar disease is seen in exposed dogs, guinea-pigs and sensitized rats. Beryllium causes contact dermatitis, which is also associated with cell-mediated immunological reactions.

Beryllium sulfate did not induce micronuclei in the bone marrow of mice treated *in vivo*. Beryllium salts induced sister chromatid exchange and possibly chromosomal aberrations in mammalian cells *in vitro*. Beryllium sulfate induced morphological transformation in a number of different systems. In one report, beryllium chloride induced gene mutation in mammalian cells. In bacteria, beryllium chloride was comutagenic with 9-aminoacridine but not with ultraviolet radiation. Beryllium compounds are not mutagenic in most bacterial systems. In assays of differential toxicity, beryllium salts gave mixed results.

In cultured mammalian cells, low-temperature-fired beryllium oxide induced single-strand breaks in DNA and morphological transformation; an unspecified beryllium oxide did not induce sister chromatid exchange in mammalian cells or differential toxicity or mutation in bacteria.

5.5 Evaluation[1]

There is *sufficient evidence* in humans for the carcinogenicity of beryllium and beryllium compounds.

There is *sufficient evidence* in experimental animals for the carcinogenicity of beryllium and beryllium compounds.

Overall evaluation

Beryllium and beryllium compounds *are carcinogenic to humans (Group 1).*

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[1]For definintion of the italicized terms, see Preamble.

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Appendix B: Finch *et al.* (1996). Animal Models of Beryllium-induced Lung Disease. Environ Health Perspect 104(Suppl 5):B-1 – B-14.

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Animal Models of Beryllium-induced Lung Disease

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Abstract

The Inhalation Toxicology Research Institute (ITRI) is conducting research to improve the understanding of chronic beryllium disease (CBD) and beryllium-induced lung cancer. Initial animal studies examined beagle dogs that inhaled BeO calcined at either 500 or 1000°C. At similar lung burdens, the 500°C BeO induced more severe and extensive granulomatous pneumonia, lymphocytic infiltration into the lung, and positive Be-specific lymphocyte proliferative responses *in vitro* than the 1000°C BeO. However, the progressive nature of human CBD was not duplicated. More recently, Strains A/J and C3H/HeJ mice were exposed to Be metal by inhalation. This produced a marked granulomatous pneumonia, diffuse infiltrates, and multifocal aggregates of interstitial lymphocytes with a pronounced T helper component and pulmonary *in situ* lymphocyte proliferation. With respect to lung cancer, at a mean lung burden as low as 17 μg Be/g lung, inhaled Be metal induced benign and/or malignant lung tumors in over 50% of male and female F344 rats surviving ≥ 1 year on study. Substantial tumor multiplicity was found, but K-*ras* and p53 gene mutations were virtually absent. In mice, however, a lung burden of approximately 60 μg (~300 μg Be/g lung) caused only a slight increase in crude lung tumor incidence and multiplicity over controls in strain A/J mice and no elevated incidence in strain C3H mice. Taken together, this research program constitutes a coordinated effort to understand beryllium-induced lung disease in experimental animal models. -- **Environ Health Perspect** 104(Suppl 5):973-979 (1996)

Key words: beryllium, inhalation, beagle dogs, monkeys, rats, mice, granuloma, lymphocyte proliferation, cancer

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Abbreviations used: Be, beryllium; BeO, beryllium oxide; $BeSo_4$, beryllium sulfate; BrdU, 5-bromo-2-deoxyuridien; CBD, chronic beryllium disease; ITRI, Inhalation Toxicology Research Institute; LPA, lymphocyte proliferation assays; $^{239}PuO_2$, plutonium dioxide.

Introduction

The toxicity of beryllium (Be) and its compounds has been a topic of concern for some 60 years, even though earlier reports dealt with this issue (1). Concerns were largely driven by reports of Be-induced toxicity in humans in Europe in the 1930s and in the United States in the 1940s (2). After approximately 1950, the acute form of Be-induced lung disease was largely eliminated due to the establishment of workplace exposure limits, but the chronic form of the disease is still of concern. Chronic beryllium disease (CBD) is characterized by progressive, noncaseating granulomatous infiammation of the lung that may be fatal. CBD occurs in only approximately 3% of exposed individuals and it has been suggested that a genetic predisposition is involved (3).

Numerous animal models of Be-induced toxicity were investigated in the 1940s, despite a 1943 report by the U.S. Public Health Service (4) that erroneously exonerated Be as the causative toxic agent. The early work was brought together in 1947 with the Sixth Saranac Symposium (5), a galvanizing meeting for investigators dealing with industrial hygienic and toxicologic concerns for Be.

Over the subsequent decades, numerous reports were published from animal experiments involving Be exposures. These include the production of pneumonitis in animals inhaling Be compounds comparable to that seen in humans, the induction of osteosarcomas in rabbits injected with beryllium oxide (BeO) and zinc Be silicate (6), the production of lung tumors in rats inhaling beryllium sulfate ($BeSO_4$) (7), and the characterization of differing immune responses in two strains of guinea pigs (8). A full review of this work is beyond the scope of this article; other recent reviews and summaries of the literature describing the health effects (9-11) and biokinetics (12) are available.

This article provides an overview of studies of the inhalation toxicity of Be conducted at the Inhalation Toxicology Research Institute (ITRI). These studies, which began in 1982, are described below.

Studies at the Inhalation Toxicology Research Institute

The ITRI is conducting research to improve the understanding of CBD and to examine Be-induced lung cancer. Central to these efforts have been field studies of Be-containing aerosols likely to be found in the workplace, development of laboratory model aerosols mimicking workplace aerosols, detailed physicochemical characterization of these materials, and use of these aerosols in laboratory animal models. The following sections describe aerosol and physicochemical studies, efforts to develop an animal model having the key features of human CBD, and studies of Be-induced carcinogenesis.

Aerosol and Physicochemical Studies

Initial ITRI studies focused on proposed uses of Be as a plasma limiter in fusion devices and soon expanded to include the potential uses of Be in structural, navigational, and nuclear reactor systems for space. Beryllium aerosols formed under industrial and applied research conditions were collected and

examined (13); materials included machining-generated Be metal and BeO aerosols, stock Be metal and BeO powders, and aerosols derived from electron or laser beam impaction on Be blocks, and Be particles from a research fusion device. Particles of respirable size were found in all cases; particle morphology ranged from branched-chain aggregates in the case of laser vaporization to irregular shapes produced by the other operations. Additional efforts were made to characterize aerosols produced by the machining of Be metal, BeCu, or BeNi alloys; for a given machining operation, a greater percentage of the Be metal aerosol was found in the respirable size fraction than in either alloy (14). During this period of extensive aerosol development, an overview for practicing engineers was also prepared on the history of Be dispersion, regulations and industrial hygiene practices related to Be, and perspectives on the health risks of using Be (15).

Efforts were begun to mimic these workplace and research aerosols with appropriate surrogate aerosols produced under well-controlled laboratory conditions. Model aerosols for a radioisotope-labeled ^{7}BeO generated from the nebulization of a $^{7}Be(OH)_2$ suspension and calcined at either 500 or 1000°C were developed (16). A laboratory laser vaporization technique capable of generating branched-chain aggregate aerosols of either Be metal (when operated under an argon atmosphere) or BeO (when operated under air) was also developed (17). Finally, a method employing dry-powder aerosolization with size fractionation using an aerosol cyclone was developed for an industrial preparation of Be metal powder (18).

An extensive quality control program was begun to certify and compare the chemical and physical properties of the laboratory aerosols. This program involved determination of particle morphology and geometric size, aerodynamic size, specific surface area, density, dissolution characteristics, chemical form, crystallinity, and composition (19-21). The work was complemented with *in vitro* toxicity studies in cell cultures in which for a given Be compound, short-term toxicity appeared to be governed by the amount of specific surface area of the preparation, and thus presumably the surface available for dissolution of Be ions (22).

Important features of these laboratory model aerosols include the production of particle sizes ranging from several tenths to 2 μm in mass median aerodynamic size, thus making the aerosols of optimal size for deposition in the alveolar compartment of the lung; thorough physical and chemical characterization, as described above; and ability to generate exposure atmospheres over a wide range of concentrations, thus permitting a wide range of lung burdens to be delivered in relatively short times. This latter point is particularly true for Be metal; the aerosolization system for this material can provide mass concentrations ranging from several tenths of mg/m^3 up to over 1 g/m^3 in a nose-only inhalation chamber (18).

Studies of Be-induced Granulomatous Lung Disease

Studies in Dogs. Studies of Be-induced granulomatous lung disease began with an examination of the toxicokinetics of 500 and 1000°C BeO in the beagle dog. An associated goal was the possible development of a CBD model. Justification for this approach included the clear indication from the literature of the importance of BeO preparation temperature on Be disposition and toxicity following inhalation (23), and the need for biokinetic data describing the disposition of these two BeO preparations. The beagle dog was selected because it represents a good biokinetic model for the disposition of other important elements (24), is amenable for the collection of toxicokinetic data and monitoring of pulmonary responses (using periodic radiographs and intrapulmonary lavage), and has immunological responses similar to those of humans (25).

Table 1. Experimental design for study of beagle dogs exposed to BeO calcined at 500 or 1000°C.[a]

Sacrifice time (days after exposure)[b]	Controls[c]	Mean lung burden achieved and BeO calcination temperature			
		17 µg BeO/kg[d]		50 µg BeO/kg[d]	
		500°C	1000°C	500°C	1000°C
8	–	2[e]	2	–	–
32	–	2	2	–	–
64	–	2	2	–	–
180	–	2	2	2	2
360	–	2	2	2	2
~1100	4	4	4	4	4

[a]Dogs sacrificed from 8 to 360 days after exposure to examine biokinetics and histopathologic effects of BeO. Dogs sacrificed at approximately 1100 days after exposure were reexposed to 500°C BeO (mean initial lung burden of 74 µg BeO/kg) at approximately 900 days after first exposure and were used to examine the immunopathologic effects of BeO. Additional details have been published (*25,26,28*). [b]Single, acute, nose-only inhalation exposure. [c]Control dogs were sham-exposed to filtered air only. [d]For each BeO preparation temperature, mean lung burden (after completion of rapid clearance phase of BeO deposited on conducting airways) normalized by body weight at time of exposure for each dog. [e]Number of dogs per group; equal numbers of males and females. A dash (–) indicates no dogs exposed at the indicated conditions.

A dose-response pilot study in dogs using BeO treated during generation at 500°C indicated that granulomatous lung lesions were present 1 month after exposure (26). Additional dogs were subsequently exposed by inhalation to ^{7}BeO that had been treated at 500°C during generation and subsequently calcined at either 500 or 1000°C. Dogs received mean lung burdens of either 17 or 50 µg/kg body weight; control dogs received a sham exposure (experimental design given in Table 1). Groups of dogs (2 dogs per time point per calcination temperature per lung burden level) were sacrificed at various times through 1 year after exposure (a total of 28 dogs) to measure ^{7}Be content in various tissues (27), and to evaluate lung and lung-associated lymph node lesions (28). Another group of dogs was held for periodic assessment as described below. As expected, the BeO prepared at 500°C was cleared from the lung more rapidly than the 1000°C material (clearance half-times of 72 and 210 days, respectively). Beryllium cleared from the lung was either excreted (principally in feces at early times after exposure, later in urine) or translocated primarily to bone and liver. Through 1 year after exposure, lung lesions observed included macrophage hyperplasia, granulomas, fibrosis, alveolar epithelial cell hyperplasia, and lymphocytic infiltrates. These lesions were generally more extensive or severe in dogs exposed to the 500°C BeO, and peaked in relative severity at 2 months after exposure.

Twenty dogs (4 controls and 4 each per calcination temperature per lung burden) were not sacrificed, but were followed by periodic radiography and collection of blood and intrapulmonary lavage fluids for assessment of cell types and performance of standard *in vitro* lymphocyte proliferation assays (LPA) to detect Be-specific immune responses (28). In blood, positive LPA results were observed only sporadically in all exposure groups. Lymphocytes constituted over 50% of lung lavage cells 3 months after exposure in a group of four dogs inhaling 500°C BeO, then percentages declined to less than 30% by 7 months after exposure. The positive LPA results observed were most prominent in dogs that inhaled the 500°C BeO to achieve the 50 µg/kg lung burden. These results generally peaked 6 to 8 months after exposure, then declined. There was substantial variability among individual dogs, and an apparent shift toward more T-helper lymphocytes when lymphocyte numbers were elevated relative to controls. Additional work using cloned lung lymphocyte T-cell lines suggested a Be-specific, major histocompatibility complex Class-II-mediated nature of the response (29).

Continued monitoring of the dogs through 2 years after exposure, however, coupled with the Be lung clearance data and the decrease in the relative severity of lung toxicity from 2 months to 1 year in the sacrificed dogs, suggested that toxic reactions to Be had largely resolved. Thus, although these results were promising, a model of the progressive nature of CBD was not developed. To determine if potential immune memory of Be might result in responses greater in either magnitude or duration than seen after the first exposure, the dogs were reexposed by inhalation to 500°C BeO approximately 2.5 years after

their first exposure to result in a mean lung burden of 74 µg/kg (30). The influx of lymphocytes, reactivity of the lymphocytes as revealed by the LPA, and lung lesions upon sacrifice 6 months after exposure were similar to those seen after the first exposure, indicating that these responses did not appear to be cumulative using this exposure regime.

Studies in Cynomolgus Monkeys. To refine and extend these observations in dogs, the immunopathologic responses to Be were examined in cynomolgus monkeys (*Macaca fascicularis*). One important reason to extend these studies to nonhuman primates was the lack at that time of appropriate antibodies against the various T-lymphocyte subpopulations in the dog. The monkeys were exposed by bronchoscopic, intrabronchiolar instillation to either BeO calcined at 500°C or to Be metal (31). A separate lung lobe received an instillation of the saline vehicle alone. The masses of Be used ranged from 0.4 to 38 µg for the BeO, and 1.0 to 148 µg for the Be metal; the differing amounts were used because they were estimated to provide roughly equimolar amounts of the Be^{++} ion dissolved from the particles over the 6-month study.

The monkeys underwent bronchoalveolar lavage at various times after instillation. The animals were sacrificed at either 80 or 180 days after exposure for evaluation of lung histopathology. Compared to control lung lobes, the numbers of lymphocytes obtained from exposed lobes were elevated at 14, 30, and 90 days postexposure (dpe) in the Be metal-exposed animals, and at 60 dpe in the BeO-exposed monkeys. Be-specific *in vitro* lymphocyte proliferation occurred at 14, 60, and 90 dpe in lymphocytes from Be-exposed lung lobes only; no Be-specific lymphocyte proliferation was observed in BeO-exposed animals. Lung lesions in Be metal-exposed monkeys included focally intense, interstitial fibrosis, marked hyperplasia of the alveolar epithelium, and variable lymphocytic infiltrates. Some Be metal-exposed animals had discrete immune granulomas characterized by tightly organized lymphocytic cuffs surrounding epithelioid macrophage aggregates. When present, lesions in BeO-exposed monkeys were rare and much less severe.

Thus, lung lesions having certain features of CBD were successfully produced in the cynomolgus monkey and were accompanied by Be-specific immune responses. Furthermore, the results suggested that Be metal produced more severe lesions than the BeO prepared at 500°C. However, the experimental design precluded an examination of whether the pulmonary responses increased over time or resolved, as was observed in the dogs. Largely because of the expense of working with the nonhuman primates and the related inability to study more than a few individuals, this line of investigation was not pursued.

Studies in Rodents. To determine if mice that inhaled Be develop responses that mimic human CBD, female strains A/J and C3H/HeJ mice were exposed to a Be-metal aerosol to achieve mean initial lung burdens of 47 µg or 64 µg, respectively (32). The mice were sacrificed 28 weeks after exposure. Cells were harvested from peripheral blood, spleen, and bronchial lymph nodes of both exposed and control mice. Be-specific *in vitro* lymphocyte proliferation was assayed, but responses were seen only in the positive control samples in which the lymphocytes were exposed to phytohemagglutinin.

The right cardiac lung lobes from selected mice were inflated with a cryopreservative agent, frozen, then sections were cut and reacted with antibodies to detect mouse B, helper T, and suppressor T lymphocytes. Remaining lung lobes were fixed and sectioned for standard histopathology; this examination revealed a marked, multifocal, granulomatous pneumonia with mild interstitial fibrosis, perivascular and interstitial mononuclear (lymphocytes, plasma cells, monocytes, and macrophages) cell infiltrates, and multifocal interstitial mononuclear cell aggregates. Multinucleated giant cells were common; most were of the foreign-body type, but Langhans giant cells were also found. Immunohistochemical examination showed that these interstitial mononuclear cell aggregates were of two types: some consisted primarily of helper T cells and Be-containing macrophages (microgranulomas), while others consisted of a central zone of B cells and a peripheral zone of helper T

cells. Helper T cells, which were the majority of lymphocytes in the lungs of Be-exposed mice, were located in the aggregates described above, in the interstitium within foci of granulomatous inflammation, and in perivascular cuffs. Suppressor ($CD8^+$) T cells were infrequent and scattered within the lesions.

A subgroup of the mice received injections of a 5-bromo-2-deoxyuridine (BrdU) solution 2 days to 1 hr before sacrifice to label the nuclei of replicating cells. This treatment revealed lymphocyte proliferation within microgranulomas, perivascular cuffs, and the lymphoid aggregates. Unfortunately, because different groups of mice received lung cryosection immunohistochemistry and the BrdU labeling, the BrdU technique could not permit the identification of either the proliferating lymphocyte subtype or Be specificity of the response.

No substantive differences in response between the two murine strains were observed; other strains have not been examined. The observed chronic lung lesions parallel those seen in human CBD cases in several important respects: morphologically, with the helper T cells constituting the primary lymphocytic component, and proliferatively, with the pronounced *in situ* lymphocyte replication (Table 2). However, the Be specificity of these responses must be demonstrated before the disease in mice can be considered an animal model of human CBD. Efforts in this area continue.

Table 2. Comparison of responses between human chronic beryllium disease cases and strains A/J and C3H/HeJ mice inhaling beryllium metal.[a]

Response[b]	Humans	Mice
Microgranulomas/mononuclear infiltrates	+	+
Significant lymphocytic component	+	+
Accumulation of helper T cells	+	+
Lymphocyte proliferation		
In vivo	+/?	+
Be-specific *in vitro*	+	–/?
Delayed hypersensitivity	+	?

[a]Two strains of mice received a single, acute, nose-only inhalation exposure to result in mean initial lung burdens of 47 µg (for strain A/J) or 64 µg (for strain C3H) Be metal; experiment described in text. [b]Key to responses: + = response observed; +/? = response probably occurs but has not been definitively proven; –/? = response not observed but a systematic examination of the response was not performed; ? = existence of response not known.

Studies of Be-induced Cancer

Studies in Rats. Studies of Be metal-induced cancer began at ITRI as part of a larger program to study the cancer risks from exposures to combinations of radiation and other agents. Pertinent to this article, a study is being conducted in rats exposed to Be metal and/or plutonium dioxide ($^{239}PuO_2$) (33,34). The following discussion relates primarily to rats exposed only to Be metal within the larger study; the Be portion of the design of this study is given in Table 3.

Table 3. Experimental design for study of Be metal carcinogenicity in F344 rats.[a]

Planned initial lung burden of Be metal (μg)[b]	Rats exposed (no.)		Total rats (no.)
	Study Phase I	Study Phase II	
0	208[c]	270	478
0.3	–	288	288
1.0	–	288	288
3.0	–	288	288
10	–	288	288
50	240	156	396
150	240	–	240
450	240	–	240
Total	928	1578	2506

[a]As described in the text, this is a part of a larger study of the carcinogenicity of combined exposures of rats to Be metal and $^{239}PuO_2$; this table describes the portion of the study in which rats receive no radiation treatment; [b]Planned level of initial lung burden resulting from a single, acute, nose-only inhalation exposure to Be metal; [c]Number of animals per group; equal numbers of male and female rats. A dash (–) indicates no rats exposed at the indicated conditions.

Groups of F344/N rats (raised in the ITRI barrier facility) were designated for single, nose-only exposure to Be metal to result in lung burdens of approximately 50, 150, or 450 μg. This involved exposures of 10 to 41 min to Be metal mass concentrations of 470 to 960 mg/m^3. Control rats received filtered air alone. Following exposure, groups of rats were designated for serial sacrifice at times ranging from 8 to 450 dpe for determination of the quantity of Be within the lungs and for assessment of presence or progression of lung lesions.

Exposure to the highest level of Be metal (target lung burden of 450 μg) proved acutely lethal to a substantial fraction of the rats (35). Thirty-seven percent of male and 49% of female rats died approximately 2 weeks after exposure. The lungs of these rats were characterized by a severe hemorrhagic pneumonia (36). This acute mortality was not observed in rats exposed to lower lung burdens of Be metal. Inhaled Be metal also decreased long-term survival in a dose-dependent manner (37). For both genders, median survival times of Be metal-exposed rats were similar to those of controls in groups receiving the lowest target lung burdens, and were approximately 80% those of controls at the highest lung burdens.

Another effect observed in this combined exposure study was a striking reduction in the lung's ability to clear Be and other materials (33,37). Clearance of ^{239}Pu from the lung in rats also inhaling Be metal was best modeled by a single-component, negative exponential function having a half-time of some 500 days. This effect was independent of the level of Be metal examined. In contrast, ^{239}Pu clearance in rats not also exposed to Be was best modeled by a two-component, negative exponential, and the clearance half-time for the first component (which accounted for approximately 80% of the ^{239}Pu lung burden) was about 35 days. For a given level of $^{239}PuO_2$ exposure, the coexposure to Be metal with the associated reduction in lung ^{239}Pu clearance served to increase the total potential life-span radiation dose to the lung by a factor of approximately three, compared to controls. This phenomenon has subsequently been examined in more detail (below).

The most notable result from this study was the carcinogenicity of Be metal to the lungs of the F344/N rats; these data have been reported in abstract form (38,39). The most prevalent neoplasm observed was the bronchiolar/alveolar adenocarcinoma having alveolar, papillary, or tubular patterns. Other tumors observed included adenosquamous carcinomas and squamous cell carcinomas. In addition, substantial multiplicity of lung tumors within the same animal was observed.

In four groups of 30 male and 30 female rats each receiving mean Be metal initial lung burdens of 40,

110, 360, and 430 µg Be, tumors became apparent by 14 months after exposure, and a crude incidence of 64% of the rats developed lung tumors over their lifetimes (40). An analysis in the Be-induced rat lung adenocarcinomas of genes frequently mutated in human lung cancers (the oncogenes K-*ras* and c-*raf*-1, and the tumor suppressor gene p53) revealed few alterations. Direct sequencing of exons 1 and 2 in 24 tumors did not reveal any mutations in K-*ras* codons 12, 13, or 61. A more sensitive technique revealed codon 12 base pair transversions in 2 of 12 tumors examined, suggesting K-*ras* oncogene activation was a rare, late event in the carcinogenic process. No p53 gene mutations were observed through either immunohistochemical techniques or direct sequencing of exons 5 through 8, nor were c-*raf*-1 mutations evident by Southern blot analysis. Thus, the mechanisms underlying the production of pulmonary adenocarcinomas from inhaled beryllium in the rat do not involve gene dysfunctions common with human non-small-cell lung cancer.

As a result of the level of carcinogenicity observed in this study, additional rats (CDF(F344)/CrlBR, Charles River Laboratories, Raleigh, NC) have been exposed to lower lung burdens of Be metal (Table 3) and are being observed. Target initial lung burdens for this portion of the study range from 0.3 to 50 µg. The goal of this work is to define dose-response relationships between lower lung burdens of Be metal and lung cancer and to reproduce in F344/Crl rats the findings described above in F344/N rats.

Studies in Mice. The carcinogenicity of inhaled Be metal is being examined in two strains of mice: A/J mice, which are susceptible to either spontaneous or chemically induced lung cancer, and C3H/HeJ mice, a strain that is relatively resistant to lung cancer induction (41). Groups of mice were exposed to Be metal to result in group mean initial lung burdens of 47 µg Be (A/J) or 64 µg Be (C3H). Serial sacrifices were conducted to yield lung tissue for histologic examination, molecular analysis of gene changes in the carcinogenic process, and analysis of Be for dosimetry and lung clearance data.

Histopathological analyses of the lungs have been completed (42). Compared to control mice, the crude incidence of lung tumors in Be metal-exposed A/J mice is slightly elevated (46% in exposed vs 37% in controls) and in C3H/HeJ is slightly decreased (5% in exposed mice vs 10% in controls). In addition, tumor multiplicity is slightly increased in the exposed A/J mice compared to that in controls. The potential statistical significance of these data and the multiplicity and time-to-tumor data are being analyzed. Be exposure reduced survival for both strains. In a log-rank test (Breslow test; SAS P1L, SAS Institute, Cary, NC), this reduction in survival was statistically significant for strain C3H mice (p=0.042) but only marginally significant for strain A/J mice (p=0.077). Both exposed and control strain A/J mice appeared to have slightly greater survival times than C3H mice; however, neither of these differences were statistically significant (p>0.05).

An additional topic of ongoing analysis in this study is the potential for mutations in the K-*ras* oncogene (43). Preliminary data suggest that K-*ras* gene mutations are more common in the mouse lung tumors than in the rat lung tumors, but mutational hotspots are lacking within the gene, which suggests that Be is not acting as a genotoxic carcinogen.

Studies of Acute and Chronic Inflammatory Lung Disease in Rats and Mice. In concert with the cancer studies in rats and mice described above, the nature of acute and chronic responses to inhaled Be metal have been examined through 1 year after exposure in both species. Male F344/N rats were exposed to Be metal to result in lung burdens ranging from 0.32 to 100 µg (about 0.2-85 µg Be/g lung tissue), then sacrificed at 8, 16, 40, 90, 210, and 365 dpe (44). The Be metal aerosol was mixed with an aerosol of ^{85}Sr-labeled fused aluminosilicate particles (^{85}Sr-FAPs), a relatively insoluble particle used as a tracer particle to study clearance from the lungs. Control rats received the ^{85}Sr-FAPs alone. Be exposure significantly retarded ^{85}Sr-FAP lung clearance in all exposure groups, except for the lowest lung burden (0.32 µg) where clearance was slightly retarded but not statistically different from that in controls. In

addition, lung burdens of 10 or 100 μg Be induced minimal to mild acute and chronic inflammation, hyperplasia of the alveolar epithelium, and early-occurring fibrosis, whereas a lung burden of 1.8 μg caused only late-occurring, minimal chronic inflammation and alveolar epithelial hyperplasia. The histological changes were generally accompanied by alterations in the enzyme, protein, and cellular components of bronchoalveolar lavage fluids.

A virtually identical study was also performed in female C3H/HeJ mice (45). Mice received both ^{85}Sr-FAP tracer particles and Be metal lung burdens of 1.7 to 34 μg (about 14-280 μg Be/g lung). A lung burden of 1.7 μg Be had some measurable but minimal effect on lung clearance, the 2.6-μg Be lung burden was intermediate in effect, and lung burdens of 12 or 34 μg Be induced a substantial reduction in pulmonary clearance of the ^{85}Sr-FAP. Histological evaluation of the lungs revealed granulomatous pneumonia at later times, an increased number and size of interstitial lymphocytic aggregates, and interstitial infiltration of mononuclear cells. Findings were most pronounced in the two highest lung burden groups, although a minimal granulomatous pneumonia was observed in many of the mice in the 2.6-μg lung burden group. As with the rats, indications of lung damage revealed by bronchoalveolar lavage generally mirrored the lung histology results.

These studies in rats and mice provide dose-response data describing the effects of inhaled Be metal on lung toxicity. The most striking difference in lung pathology between the two species is the marked component of interstitial lymphocytic aggregates in the mouse; lymphocytes are not a substantial component of the response in rats. A comparison between the two species is shown in Figure 1, in which Be metal lung burdens are divided by control animal lung weight in an attempt to normalize the data for comparison. Another important difference between the species appears to be the levels of Be lung burdens required to induce a toxic reaction in the lung; the rats are affected by the various changes described above at weight-normalized lung burdens substantially lower than those in mice.

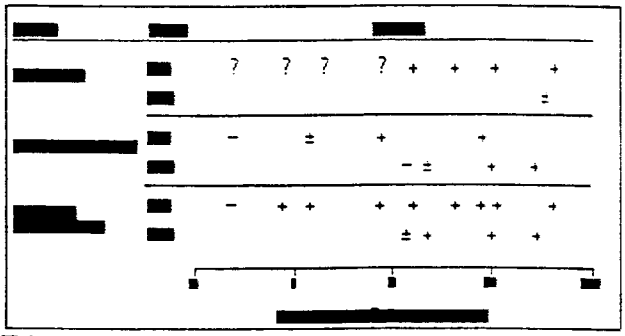

Figure 1. Comparative responses of rats and mice following single, acute, nose-only inhalation exposure to beryllium metal to result in a range of initial lung burdens. Symbols: (+), response observed; (±), response minor or equivocal; (-), response not observed; (?), potential response currently being studied.

Discussion

As noted in the introduction, a substantial body of toxicity studies of Be in animals exists (9-11). It can be difficult, however, to comprehend the effects of Be in animals from this work. Many of the studies, particularly the early ones, are plagued by problems such as confounding diseases within the animal colonies; use of inappropriate modes of exposure; failure to quantitate dose or disposition; or use of exposure materials that were poorly characterized, poorly described, or irrelevant to workplace exposures (9).

Our studies of granulomatous lung disease indicate that dogs and monkeys respond to Be with many of the responses seen in human CBD patients. These responses include granulomatous lung lesions having a significant lymphocytic component, and the presence of *in vitro*, Be-specific lymphocyte proliferative capability (46,47). However, the finding in dogs that both of these responses resolve indicates that a true, progressive model of CBD has not been achieved following the acute exposure modes used. In addition,

further work with dogs and monkeys is not promising because of the substantial expense associated with working with these large-animal models and the related inability to examine the large numbers of subjects necessary with these outbred species. The potential for developing useful models of beryllium disease in rodents appears much more promising.

Work with F344 rats indicates that the lack of significant lymphocytic response to inhaled Be metal in this species renders it unsuitable for detailed immunopathogenic study (46). In mice, however, several parallels between murine and human responses were observed, most notably including the development of granulomas and/or mononuclear infiltrates having a pronounced helper T cell component (Table 2). Efforts continue to demonstrate Be-specific lymphoproliferative and delayed hypersensitivity responses in the mouse. This work is based on the premise that the development of a laboratory animal model having the significant features of human CBD will afford opportunities to study not only the cellular and molecular mechanisms of responses involved in the progression of CBD but also to examine both the influence of the physicochemical form of Be and the exposure mode (single, chronic, multiple) on disease outcome and the potential for therapeutic intervention.

Studies of the carcinogenicity of inhaled Be metal are being conducted in both rats and mice. A striking difference in response between these species is being observed. The F344 rat develops a relatively high crude incidence and multiplicity of lung tumors. These tumors, however, essentially lack mutations in genes commonly found to be mutated in various types of human cancers, including lung cancers. On the other hand, at doses that induce substantial carcinogenicity in rats, the carcinogenic response is weak in strain A mice and absent in strain C3H mice. Clearly, continued efforts are required to understand the similarities/differences in responses of rats versus those in mice, the molecular events surrounding Be-induced carcinogenesis, and the responses of these species to Be-containing compounds other than Be metal before these findings can be extrapolated to humans.

In conclusion, ITRI studies are oriented toward understanding events involved in the development of beryllium-induced, immune-mediated, chronic granulomatous lung diseases, and lung cancer. This research program constitutes an ongoing, coordinated effort to understand beryllium-induced lung disease in experimental animal models. Use of multiple species in this program increases the scientific basis for eventual extrapolation of the results from laboratory animal models to humans.

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Appendix C: Carcinogen Profile for Beryllium and Beryllium Compounds (NTP 8th Report on Carcinogens 1998) pp. C-1 – C-4.

Beryllium and Certain Beryllium Compounds

First Listed in the *Second Annual Report on Carcinogens*

Carcinogenicity

There is sufficient evidence for the carcinogenicity of beryllium (CAS No. 7440-41-7) and the following beryllium compounds in experimental animals: beryllium-aluminum alloy (12770-50-2), beryllium chloride (7787-47-5), beryllium fluoride (7787-49-7), beryllium hydroxide (13327-32-7), beryllium oxide (1304-56-9), beryllium phosphate (13598-15-7), beryllium sulfate (13510-49-1), beryllium sulfate tetrahydrate (7787-56-6), beryllium zinc silicate (39413-47-3), and beryl ore (1302-52-9) (IARC V.1, 1972; IARC V.23, 1980; IARC S.4, 1982). Beryllium metal, beryllium-aluminum alloy, beryl ore, beryllium chloride, beryllium fluoride, beryllium hydroxide, beryllium sulfate (and its tetrahydrate) and beryllium oxide, all produced lung tumors in rats exposed by inhalation or intratracheally. Single intratracheal instillations or 1-hour inhalation exposures were effective. Beryllium oxide and beryllium sulfate produced lung anaplastic carcinomas in monkeys after intrabronchial implantation or inhalation. Beryllium metal, beryllium carbonate, beryllium oxide, beryllium phosphate, beryllium silicate, and zinc beryllium silicate all produced osteosarcomas in rabbits after intravenous and/or intramedullary administration.

An IARC Working Group reported that there is limited evidence for the carcinogenicity of beryllium in humans (IARC V.23, 1980; IARC S.4, 1982; IARC S.7, 1987). There were no data available to evaluate the carcinogenicity of beryllium compounds in humans. Four early epidemiological studies and three recent studies of occupational exposure to beryllium were considered to provide limited evidence that exposure to beryllium may lead to human lung cancer. The data for most of the studies were derived from two beryllium plants and from the Beryllium Case Registry. Although 55 new cases of beryllium disease were registered between 1973 and 1977, no further data were available on the incidence of lung cancer. An analysis of the pathology of the 47 lung cancers noted in one study confirmed the post-mortem diagnoses of lung cancer in 32 of the 37 cases available for review. Of the 47 cases, 21 were reported smokers, but the smoking histories of individuals in the other cases were not given (IARC S.4, 1982).

Properties

Beryllium is a grey metal with a close-packed hexagonal crystal structure. It is insoluble in cold water and mercury, slightly soluble in hot water, in which it decomposes, and soluble in dilute acids and alkalies. Beryllium chloride occurs as white-to-colorless deliquescent crystals. It is very soluble in cold and hot water; soluble in alcohol, benzene, ether, chloroform, and carbon disulfide; and insoluble in ammonia and acetone. Beryllium fluoride occurs as a colorless amorphous mass that is readily soluble in water but only slightly soluble in alcohol. Beryllium hydroxide exists in three forms: as a metastable tetragonal crystalline solid; as a stable orthorhombic crystalline solid; and in a slightly basic pH, it appears as a slimy, gelatinous substance. It is soluble in acids and alkalies but insoluble in water. Beryllium oxide (BeO) occurs as a white amorphous powder or gel which is insoluble in both cold and hot water but is soluble in acids, alkalies, and ammonium carbonate. Beryllium metaphosphate is a white porous powder or granular material that is insoluble in water. Beryllium orthophosphate is soluble in both cold and hot water and acetic acid. Beryllium sulfate occurs as colorless crystals which are insoluble in cold water and alcohol but decompose in hot water. Beryllium sulfate tetrahydrate occurs as crystals that are soluble in water, practically insoluble in ethanol, and slightly soluble in concentrated sulfuric acid. Beryl ore is a colorless, blue-green, yellow, or white, transparent, hexagonal crystal that is insoluble in acid. When heated to decomposition, beryllium, beryllium-aluminum alloy, beryllium chloride, beryllium fluoride, beryllium hydroxide, beryllium oxide, beryllium sulfate, and beryllium sulfate tetrahydrate emit toxic fumes of BeO. In addition, beryllium chloride emits toxic fumes of hydrochloric acid and other chlorinated compounds, beryllium fluoride emits toxic fumes of hydrofluoric acid and other fluorinated compounds, beryllium phosphate emits toxic fumes of phosphorus oxides (PO_x), and beryllium sulfate and beryllium sulfate tetrahydrate emit toxic fumes of sulfur oxides (SO_x).

Beryllium metal is available in the United States as a technical grade with over 99.5% purity, as a commercial grade with 97% minimum purity, and as an electro-refined metal in various grades, i.e., vacuum hot pressed S-200, S-65, and I-40. Beryllium chloride and beryllium fluoride are available with 11.2% and 19.0% beryllium content, respectively. Both contain various metallic impurities. Beryllium-aluminum alloy is available as a grade containing 62% beryllium and 38% aluminum. Beryllium hydroxide is either beryl-derived or bertrandite-derived. Depending upon the source of ore, beryllium hydroxide is available with a varying percentage of beryllium content and metallic impurities. Beryllium oxide is available as technical grade, C.P., pure, ceramic grade, and as single crystals. Commercial-grade beryllium oxide, available in the United States, has an approximate purity of 99.5%. Beryllium sulfate crystals are available with a minimum of 20% beryllium. Beryllium sulfate tetrahydrate is produced commercially in a highly purified state. Beryl ore is available in commercial grades containing 70%-90% beryl, including 10%-13% BeO.

Use

Beryl ore is processed to make beryllium and its compounds. Industry is increasing the use of beryllium for fiber optics and cellular network communication systems (USDOI, 1990). Because it is expensive, applications will be limited to those that require light-weight, high-strength, and high-thermal conductivity. The use pattern for beryllium in 1989 was estimated to be 23% as alloy and metal for aerospace and defense; 17% as alloy and oxide for electrical components; 35% as alloy and oxide in electronic components; and 25% as alloy, metal and oxide in other applications (USDOI, 1990). In 1987, 22% of the beryllium produced was used as an alloy and metal in aerospace applications and defense application; 36% was used as an alloy and oxide in electrical equipment; 20% was used as an alloy and oxide in electronic components; and 22% was used as compounds, alloys, and metal in other applications (USDOI, 1988). Beryllium is used as a window material for X-ray tubes, as a moderator material for nuclear weapons, and as a neutron reflector in high-flux reactors. It is also used in high-performance aircraft brakes, in inertial guidance systems in space optics, as an

additive in solid propellant rocket fuels, and in alloys (Sax, 1987; Kirk-Othmer V.3, 1978). Beryllium-aluminum alloy is not known to be produced for commercial use (IARC V.23, 1980). It has been used in light aircraft construction (Merian, 1984). It also has potential use in casting alloys, where it refines the grain size resulting in better surface polishing, reduces melt losses, and improves casting fluidity (Kirk-Othmer V.3, 1978; IARC V.23, 1980). Beryllium chloride's primary use is in the laboratory manufacture of beryllium metal by electrolysis. It also finds use as an acid catalyst in organic reactions. Beryllium fluoride and beryllium hydroxide find commercial use as intermediates in the production of beryllium metal and beryllium alloys. Beryllium fluoride is also used in the manufacture of glass and nuclear reactors (Sax, 1987). Beryllium oxide is the most important high-purity commercial beryllium chemical produced (Kirk-Othmer V.3, 1978). Its primary use is in the manufacture of ceramics. It is often used in electronic and microelectronic application, such as semiconductor devices and integrated circuits requiring thermal dissipation (IARC V.23, 1980; Kirk-Othmer V.3, 1978). Beryllium oxide is also used in the preparation of beryllium compounds, as an additive to glass and plastics, and as a catalyst for organic reactions and in high temperature reactor systems. Beryllium oxide was used in the past for the manufacture of phosphors for fluorescent lamps. Beryllium metaphosphate has limited use as a raw material for special ceramic compositions and as a catalyst carrier. The primary use of beryllium sulfate tetrahydrate is as a chemical intermediate in the processing of beryl and bertrandite ores (Sax, 1978). A former use of beryllium zinc sulfate is as an oxygen-dominated phosphor in luminescent materials (IARC V.23, 1980; Sax, 1987).

Production

In 1989, mine production of beryllium was estimated to be 450,000 lb, imports were 110,000 lb, and exports were 44,000 lb (USDOI, 1990). In 1988, 466,000 lb were mined, 103,000 lb were imported, and 81,000 lb were exported. Import and export data for 1988 and 1989 may not be comparable to earlier years due to different reporting methods. In 1987, mine production of beryllium was estimated to be 560,000 lb. It was estimated that 280,000 lb were imported, and 200,000 lb were exported in 1987. In 1986, two companies produced 522,000 lb of beryllium, of which 80,000 lb were exported. The United States imported 162,000 lb of beryllium in 1986. In 1985, 460,000 lb of beryllium were produced, 244,000 lb were imported, and 120,000 lb were exported. In 1984, 40,000 lb of the 482,000 lb of beryllium produced were exported, and 176,000 lb were imported. United States production in 1983 was reported to be 534,000 lb, imports were 194,000 lb, and exports were 38,000 lb (USDOI, 1988; USDOI, 1987). In 1982, beryllium production was reported to be 436,000 lb, imports were 230,000 lb, and exports were 134,000 lb (USDOI, 1987). Imports of beryllium were 174,000 lb in 1981, and exports were 78,000 lb. In 1980, imports of beryllium were 148,000 lb and exports were 58,000 lb (USDOI, 1985). The 1979 TSCA Inventory reported that in 1977, three companies produced 110,000 lb of beryllium and two companies imported 500 lb, with some site limitations (TSCA, 1979).

In 1987, two U.S. companies produced beryllium alloys and beryllium oxide (USDOI, 1988). In 1985, about 3.3 million lb of beryllium ore, less than 2,532 lb of beryllium oxide, and 7,332 lb of unspecified beryllium compounds were imported (USDOC Imports, 1986). In 1984, the United States imported 2.7 million lb of beryllium ore, less than 179 lb of beryllium oxide, and 43,059 lb of unspecified beryllium compounds (USDOC Imports, 1985). The 1979 TSCA Inventory reported that in 1977, three companies produced 605,000 lb of beryllium oxide and one company imported 500 lb; two companies produced 550,000 lb of beryllium sulfate, with some site limitations; and one company produced 5.5 million lb of beryl ore. No data were reported for beryllium phosphate and beryllium zinc sulfate (TSCA, 1979). U.S. companies have produced beryllium and some beryllium compounds commercially since the 1940s and beryllium oxide since 1958 (IARC V.1, 1972).

Exposure

The primary routes of potential human exposure to beryllium and certain beryllium compounds are inhalation and dermal contact. In 1970, NIOSH estimated that the number of workers potentially exposed to the dust or fumes of beryllium in the workplace was about 30,000, of which 2,500 were employed in its production (IARC V.23, 1980). The National Occupational Hazard Survey, conducted by NIOSH from 1972 to 1974, estimated that 19,867 U.S. workers may have been exposed to beryllium in the workplace (NIOSH, 1976). The National Occupational Exposure Survey (1980-1983) estimated that 19,012 total workers, including 1,778 women, may be exposed (NIOSH, 1984). The workers potentially exposed to beryllium include beryllium ore miners, beryllium alloy makers and fabricators, phosphor manufacturers, ceramic workers, missile technicians, nuclear reactor workers, electric and electronic equipment workers, and jewelers. In addition, workers involved in fluorescent powder manufacture and in the manufacture and salvage of fluorescent lamp works were previously exposed to beryllium oxide and beryllium zinc silicate. The industry abandoned the use of these compounds because of the incidence of beryllium disease (IARC V.1, 1972). The ACGIH has adopted a threshold limit value (TLV) of 0.002 mg/m^3 as an 8-hr time-weighted average (TWA) (ACGIH, 1986).

The general population is potentially exposed to beryllium by inhaling air and consuming food contaminated with beryllium residues. Exposure occurs mainly through the release of beryllium into the atmosphere from the burning of coal. From 10 to 20 million lb/yr of beryllium may be emitted from coal burning and refuse incineration globally. Beryllium concentrations in U.S. coal ranges from 1.46 to 1.52 mg/kg (IARC V.23, 1980). In the United States, more than 80% of the beryllium emissions originate from coal-fired vessels (Merian, 1984). The EPA estimated the total release of beryllium to the atmosphere from point sources to be 5,500 lb/yr, with the principal emissions from beryllium-copper alloy production. The Toxic Chemical Release Inventory (EPA) listed 11 industrial facilities that produced, processed, or otherwise used beryllium in 1988 (TRI, 1990). In compliance with the Community Right-to-Know Program, the facilities reported releases of beryllium to the environment which were estimated to total 41,000 lb. Approximately 721,000 persons living within 12.5 miles of point sources are possibly exposed to small amounts of beryllium (median concentration, 0.005 $\mu g/m^3$). In the eastern United States, urban atmospheric concentrations were measured at 0.3-3.0 ng beryllium/m^3. In rural areas concentrations were 12 times lower (Merian, 1984). Beryllium occurs naturally in rocks and minerals with concentrations ranging from 0.038 to 11.4

mg/kg. The beryllium content of mineral oils has been estimated to be less than 100 µg/l. Small concentrations of beryllium have been reported in drinking water supplies and in food. Beryllium has also been found in tobacco (Merian, 1984). Concentrations of beryllium in cigarettes ranged from 0.47 to 0.74 mg/cigarette; 4.5%-10% of the beryllium content escaped into the smoke during smoking (IARC V.23, 1980). Additional exposure information may be found in the ATSDR Toxicological Profile for Beryllium (ATSDR, 1993c).

Regulations

In 1980 CPSC preliminarily determined that beryllium, beryllium oxide, and beryllium sulfate was not present in consumer products under its jurisdiction. Subsequently, public comment was solicited to verify the accuracy of this information; no comments were received. Pending receipt of new information, CPSC plans no action on this chemical. In 1973, EPA promulgated a National Emissions Standard for Hazardous Air Pollutants (NESHAP) for extraction and production sites for beryllium and beryllium oxide and for beryllium rocket-motor firing. In 1980, EPA published a water quality criteria document on beryllium for the protection of human health under the Clean Water Act (CWA) and established regulations under the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) for releases of beryllium and beryllium compounds. These regulations were based on the inclusion of beryllium and its compounds on the EPA Carcinogen Assessment Group's list of potential carcinogens. The CERCLA final reportable quantity (RQ) is 10 lb for beryllium and beryllium dust and 1 lb for beryllium chloride and beryllium fluoride. RCRA subjects wastes known to contain beryllium or beryllium compounds to handling and report/recordkeeping requirements. EPA does not plan to regulate beryllium in drinking water under the Safe Drinking Water Act. Beryllium and its compounds are also regulated under the Superfund Amendments and Reauthorization Act (SARA), which subjects them to reporting requirements. FDA regulates beryllium in bottled water under the Federal Food, Drug and Cosmetics Act (FD&CA). NIOSH recommended that exposure to beryllium and beryllium compounds should not exceed 0.5 µg/m^3. Current OSHA standards for workers exposed to Beryllium are a 2 µg/m^3 8-hr TWA, 5 µg/m^3 ceiling, and 25 µg/m^3 maximum peak in 30 minutes. These standards were adopted by OSHA for toxic effects other than cancer. OSHA has proposed regulating occupational exposure to beryllium, based on its carcinogenicity as well as other toxic effects. OSHA regulates beryllium and certain beryllium compounds under the Hazard Communication Standard and as chemical hazards in laboratories.