



This fact sheet provides Canadian soil quality guidelines for beryllium for the protection of environmental and human health (Table 1). A supporting criteria document is also available (CCME 2015).

Background Information

Beryllium (Be) (CAS 7440-41-7) is the first element of the alkaline earths and has a valency of two. It appears in Group IIA of the periodic table and has two common oxidation states, Be(0) and Be(+2). Beryllium is the lightest of all the solid and chemically stable elements with an atomic number of 4, a molecular weight of 9.01 and a specific gravity of 1.85 at 25°C. It has a melting point of 1278°C and a boiling point of 2471°C. Beryllium also has a high specific heat, high heat of fusion, high strength-to-weight ratio and excellent electrical and thermal conductivities (ATSDR 2002; Haynes 2011; Newland 1982; Reeves 1986; Stonehouse *et al.* 1992).

Table 1. Soil quality guidelines for beryllium (mg·kg⁻¹).

| | Land use | | | |
|--|----------------------|--------------------------|----------------------|---|
| | Agricultural | Residential/ parkland | Commercial | Industrial |
| Guideline | 4^a | 4^a | 8^a | 8^a |
| SQG _{HH} | 75 | 75 | 110 | 1100 ^b |
| Limiting pathway for SQG _{HH} | Direct contact | Direct contact | Direct contact | Offsite migration 550 ^c Direct contact |
| Provisional SQG _{HH} | NC ^d | NC ^d | NC ^d | NC ^d |
| Limiting pathway for provisional SQG _{HH} | ND | ND | ND | ND |
| SQG _E | NC ^e | NC ^e | NC ^e | NC ^e |
| Limiting Pathway for SQG _E | ND | ND | ND | ND |
| Provisional SQG _E | NC ^e | NC ^e | NC ^e | NC ^e |
| Limiting Pathway for provisional SQG _E | ND | ND | ND | ND |
| Interim Soil Quality Criterion (CCME 1991) | 4 | 4 | 8 | 8 |

Notes: SQG_E = soil quality guideline for environmental health; SQG_{HH} = soil quality guideline for human health. NC = not calculated, ND = not determined.

^a Data are sufficient and adequate to calculate only a SQG_{HH}. It is greater than the corresponding interim soil quality criteria (CCME 1991). Therefore the interim soil quality criterion is retained as the soil quality guideline for this land use.

^b ILCR 1×10^{-5}

^c ILCR 1×10^{-6}

^d Because data are sufficient and adequate to calculate an SQG_{HH} for this land use, a provisional SQG_{HH} is not calculated.

^e Data are insufficient/inadequate to calculate a SQG_E or provisional SQG_E for this land use (no attempt was made to derive environmental soil quality guidelines for beryllium).

The guidelines in this fact sheet are for general guidance only. Site-specific conditions should be considered in the application of these values. The values may be applied differently in various jurisdictions. Use of some values listed may not be permitted at the generic level in some jurisdictions. The reader should consult the appropriate jurisdiction before application of the values.

Beryllium alloys are formed with Al, Cu, Ni, Co and/or Fe (ATSDR 2002; Zorn *et al.* 1988). The high oxygen affinity of beryllium is one of the chemical properties it has in common with aluminium and results in the formation of stable surface films of beryllium oxide (BeO) which protect from further oxidation, thus providing high resistance to corrosion, water and cold oxidising acids (Laul and Norman 2008).

Organic substances in soils are known to bind beryllium easily (Kabata-Pendias and Pendias 2000). Beryllium will covalently bond with these organics resulting in organoberyllium compounds, including (CH₃)₂Be and many other complexes (WHO 2001). Be(II) binding to proteins is highly specific and it does not bind indiscriminately to biological macromolecules (Venugopal and Luckey 1978).

⁹Be is the only stable isotope of beryllium and natural beryllium contains 100% of this isotope (Kabata-Pendias and Pendias 2000; Newland 1982; Stonehouse *et al.* 1992). The stable isotope ⁹Be is a trace component in all continental rocks, which is released by weathering and transferred to the ocean predominantly via rivers (Frank *et al.* 2009).

Beryllium is an element that occurs naturally. It is present in a variety of materials including rocks, coal, oil, soil and volcanic dust. Beryllium is found in earth's surface rocks at a concentration of less than 1 to 15 mg/kg. Due to its high reactivity, beryllium is not found as a free metal in nature (ATSDR 2002).

Of the >100 beryllium-containing minerals currently identified only two are of current commercial significance: beryl (3BeO·Al₂O₃·6SiO₂) and bertrandite (4BeO·2SiO₂·H₂O) (ATSDR 2002; Jaskula 2009).

Most of the world's beryllium is found in plagioclase feldspar. However, pyroxenes, micas and clays contain substantial amounts of the element (Griffitts and Skilleter 1990). On average, common rocks and minerals contain from <1 ppm to about 10 ppm beryllium whereas ores can contain several thousand ppm (Fishbein 1981). The beryllium concentration in Canadian feed-coals varies between 0.8 and 1.2 mg/kg (Goodarzi 2002). Fuel oil contains approximately 0.08 ppm beryllium (Fishbein 1981).

Beryllium is found at low levels geologically in Canada, mostly in northern British Columbia and the Northwest Territories (CAREX 2011). Beryllium occurrences in Canada fall into two broad classes of deposits. The main class includes pegmatites in high-temperature and pegmatitic quartz veins and disseminations in granite. The other class is helvite-danalite occurrences in contact-metamorphic or skarn deposits (Mulligan 1960).

A number of beryllium-bearing areas in Canada have been prospected and examined for commercial production (IARC 1993); however, beryllium production levels for Canada were not available at the time of writing this document. There is little documentation regarding mining or commercial extraction of beryllium in Canada (Buffa 1994 pers. com.; EMRC 1990; Holliday *et al.* 1987; Soja and Sabin 1986).

In 2008, Canada imported 58 kg beryllium from the United States and exported 3485 kg in 2010 in the form of unwrought alloys, waste and scrap/powders (UN 2010). The value of exported beryllium has shown a notable decrease (-31.6%) (CMY 2007).

Most beryllium is used in metal alloys which accounts for more than 70% of world consumption. The beneficial properties of beryllium alloys have made them popular in products like computers, mobile telephones, electrical connectors/relays, aircraft engine parts, submarine cable housings, dental applications and noncorroding switch components/connections. Beryllium is also used in products such as golf clubs and jewellery (Henneberger *et al.* 2004; Luttrell 2008). It is also used in the manufacture of springs, gears and other machine components that need a degree of elasticity. Another everyday application is in the manufacture of gasoline pumps using an alloy of copper and beryllium (beryllium bronze) which does not spark when hit against other metals or emit sparks from static electricity (Mineral Information Institute 2010).

In Canada, the metal is used in research and in the manufacture of specialty cameras, thermal coatings, rocket parts, satellite parts, heat shields, gyroscope assemblies for inertial navigation systems, x-ray tubes and reflecting shields in research reactors, optical instruments, aircraft brake parts, high-end audio equipment and fuel rods for CANDU nuclear reactors (Bertolini 1989; Greenstock and Gentner 1990; Hoover 2005; OML 2005).

Virtually every industry (e.g., electric power stations, heating and industrial plants, gasoline combustion, non-ferrous metal smelters, kiln operations in cement plants, and refuse incineration) will emit heavy metals via high temperature processes into the atmospheric, aquatic and terrestrial ecosystems (Wilson *et al.* 1998). In 1970, Canadian beryllium emissions from coal, coke and heavy oil combustion were estimated at 7.1×10^3 kg (EC 1974). Increased emissions from the combustion of fossil fuels have been projected as a result of an expected increase in the use of these fuels for power generation and heating (Fishbein 1981). Beryllium is not included in the National Pollutant Release Inventory (EC 2014). Recent emission data are not available.

The mean beryllium concentration in ambient air is 0.013 ng/m³ (arithmetic mean, SD=0.011, n=3054, range=0-0.087 ng/m³) (HC 2011). This mean is based on National Air Pollutants Surveillance network data (PM_{2.5} fraction analysed by ICP-MS following acid digestion) collected from 2003-2009 from British Columbia, Ontario, Québec and New Brunswick from urban and rural centres. ICP-MS data are not currently available for the remaining provinces and territories. 95% of the data were reported as less than detection limit, but only 53% of these were assumed to be equal to half the detection limit (MDL) for the determination of the beryllium concentration in ambient air (some data were not specifically flagged as below the MDL and therefore were not converted to ½ MDL).

Beryllium concentrations in indoor air samples (n=47) collected in the Windsor Air Quality Study were all less than the detection limit of 0.25 ng/m³ (Bell *et al.* 1994).

A multi-element profile of house dust in relation to exterior dust and soils was conducted in Ottawa, Ontario, an urban centre with a low concentration of heavy industries (Rasmussen *et al.* 2001). Random samples of house dust, street dust and garden soil (within 15 m of each residence) were collected from 10 zones in Ottawa. Metal content was determined by ICP-MS; the beryllium detection limit was 0.02 mg/kg. In house dust (n=48), beryllium concentrations ranged from 0.28-1.00 mg/kg with a mean of 0.56 mg/kg (dry weight) (Rasmussen *et al.* 2001). No values were reported as less than the detection limit.

While beryllium concentrations in soil throughout Canada vary based on geology and anthropogenic inputs, a single background soil concentration is required to develop soil quality guidelines for use throughout Canada. Data from geological surveys conducted by both the Geological Survey of Canada and the New Brunswick Department of Natural Resources were used to develop the concentration distribution of beryllium in Canadian soil (HC 2011). Based on these data, the mean beryllium concentration in soil was determined to be 0.75 mg/kg (arithmetic mean, SD=0.99, n=9876, range=0.25-16 mg/kg) (HC 2011). This value is based on data obtained from till samples (<63µm) analysed by AAS/ICP-ES following aqua-regia digestion (partial digestion by HCl and HNO₃). 66.8% of the data were < MDL and assumed to be equal to ½ MDL in order to calculate the beryllium concentration in soil. The data are representative of till, not the public health layer (surface soil).

Surface water data were available for rivers, streams and lakes in British Columbia, Alberta, Saskatchewan, Manitoba, Ontario and Newfoundland and Labrador. In the majority of collected samples, total beryllium concentrations in surface water were below analytical detection. Reported detection limits (DLs) varied according to province, but may be used to represent environmental beryllium concentrations for surface waters in British Columbia (DL=0.05 µg/L), Alberta (DL=0.2 µg/L), Saskatchewan and Manitoba (DL=1 µg/L) and Ontario (DL=0.1 µg/L) (Anderson 2004 pers. comm.; Boyd 2004 pers. comm.; Cheung 2004 pers. comm.; Regnier and Ryan 1998; Yee 2004 pers. comm.).

The background beryllium concentration in Canadian drinking water is estimated to be 0.04 µg/L (arithmetic mean, SD=0.07, n=3841) based on data obtained from the Ontario Ministry of Environment (1998-2007) and Saskatchewan Ministry of Environment (2000-2009) (HC 2011). 91% of the data were < MDL and assumed to be equal to ½ MDL for the calculation of the beryllium concentration in drinking water. Data from other provinces were not available to include in estimating the national background value.

Health Canada’s Food Directorate provided estimated daily intakes (EDIs) of beryllium from food for Canadians from the Health Canada Total Diet Study (HC TDS) (Dabeka *et al.* 2010). Intake rates were provided for various age groups from 2000 to 2007 (inclusive) as presented below.

| (µg/kg-d) | 0-6m | 7m-4y | 5-11y | 12-19y | 20+ y |
|--------------------|-------|-------|-------|--------|-------|
| | M&F | M&F | M&F | M&F | M&F |
| arithmetic mean | 0.059 | 0.042 | 0.028 | 0.018 | 0.016 |
| standard deviation | 0.077 | 0.052 | 0.035 | 0.021 | 0.019 |

M&F – Male and Female, m – months, y – years

Based on Austrian studies (Krachler *et al.* 1998; 1999) and an Emirati study (Abdulrazzaq *et al.* 2008), the mean beryllium concentration in human breast milk was 0.13 µg/L (arithmetic mean, SD=0.30, n=287) (HC 2011). This concentration includes human breast milk at various stages/maturities. None of the reported data were < MDL.

Environmental Fate and Behaviour in Soil

The majority of beryllium released to the atmosphere is through thermal processes and thus beryllium appears to be present predominantly as BeO (ATSDR 2002; Fishbein 1981; WHO 1990). It is not known whether BeO reacts with sulphur or nitrogen oxides to produce beryllium sulphate and/or nitrate. The conversion of beryllium to these water-soluble compounds would enhance wet deposition and removal from the atmosphere (WHO 2001). Beryllium appears to be predominantly associated with the organic fraction, which suggests it would be discharged in small particles probably as high fired refractory oxides (Skilleter 1987). Stack emission studies showed that beryllium is bound to the small particle fraction of the emissions (Gladney and Owens 1976). Specifically, beryllium binds to particles smaller than 1 µm with a deposition time of 10 days (US EPA 1987). Particulate loadings studies have shown beryllium deposited on particulate matter greater than 0.3 µm throughout the United States (Chambers *et al.* 1955).

Atmospheric deposition of beryllium, per se, has not been measured (US EPA 1987) although Meehan and Smythe (1967) found beryllium concentrations between 0.05 and 0.08 µg/L in Australian rainwater. Assuming that the rate of aerosol deposition is a function of particle size, wind speed and surface roughness, Kwapulinski and Pastuszka (1983) calculated that deposition probably occurs in a similar manner to other metals and on particles of comparable size (US EPA 1987).

With most of the atmospheric beryllium produced from combustion, surface water deposits are most likely as insoluble BeO and would remain in this form in waters in the normal environmental pH range (Callahan *et al.* 1979; US EPA 1987). However, beryllium can be deposited as a soluble salt, which can be hydrolysed to form beryllium hydroxide which possesses limited solubility in the pH range of natural waters (i.e., aquifers, lakes and rivers) or would be complexed with hydroxide ions (Callahan *et al.* 1979; WHO 1990). However, this latter reaction generally occurs at higher pH values than those normally found in natural waters and even when high concentrations of complexing agents are found (i.e., polluted rivers) very little dissolved beryllium is present (Callahan *et al.* 1979).

Beryllium occurs in soils primarily in the oxide forms $(\text{BeO}_2)^{2-}$, $(\text{Be}_2\text{O}_3)^{2-}$, $(\text{BeO}_4)^{6-}$ or $(\text{Be}_2\text{O})^{2+}$ and in calcareous soils as complex anions of $\text{Be}(\text{OH})\text{CO}_3^-$ and $\text{Be}(\text{CO}_3)_2^{2-}$ (Kabata-Pendias and Pendias 2000; Kabata-Pendias 2011). The chemistry of beryllium in soils is believed to be similar to that of aluminium (Fishbein 1981). At low pH, beryllium will most likely be tightly adsorbed onto clay surfaces, displacing divalent cations that share common sorption sites (Fishbein 1981). At high pH values, beryllium may remain precipitated in insoluble complexes or form soluble polynuclear hydroxide complexes (Callahan *et al.* 1979).

Beryllium readily complexes with organic compounds such as humic substances and accumulation in organic soil horizons has been reported (ATSDR 2002; Kabata-Pendias and Pendias 2000; Newland 1982). The majority of beryllium in soil remains bound to soil and does not dissolve in water; therefore, it is unlikely to migrate into the subsurface and groundwater (Irwin 1997). However, distributions in some soil profiles show an accumulation of beryllium in subsoil layers, indicating possible leaching (Anderson *et al.* 1990; Asami and Fukazawa 1985; Kabata-Pendias 2011). Beryllium salts (e.g., BeCl_2 and BeSO_4) are readily soluble and may, therefore, be potentially toxic to plants (Kabata-Pendias 2011).

Behaviour and Effects in Biota

There was no attempt to collect terrestrial ecotoxicity data, or develop environmental soil quality guidelines for beryllium; the current effort for beryllium focused on human health only. Below is a shortened description of ecologically relevant studies.

Terrestrial Plants

Some plant species from the *Leguminosae* and *Cruciferae* families can accumulate large amounts of beryllium (Kabata-Pendias and Pendias 1992). Hickory, an excellent accumulator, can contain as much as 1 µg Be/g dry weight (Newland 1982). Beryllium bioconcentration factors in aquatic plants, animals and fish fall below 1000 (Byrne and DeLeon 1986; Callahan *et al.* 1979,). Beryllium does not bioaccumulate in aquatic plant and animal species (ATSDR 2002).

A plant/soil transfer coefficient range of 0.01 to 0.1 (varies according to plant species and soil properties) has been estimated for beryllium (WHO 2001). There is little evidence of translocation of beryllium from the roots to other sections of the plant (ATSDR 2002; WHO 2001).

There is no evidence of any significant bioaccumulation or biomagnification of beryllium in food chains (ATSDR 2002; Fishbein 1981; WHO 2001).

Livestock and Wildlife

Studies on experimental animals are covered in the next section.

Health Effects in Humans and Experimental Animals

Both cancer and non-cancer endpoints are significant in the toxicological evaluation of beryllium. IARC (1993) has classified beryllium and beryllium compounds as “carcinogenic to humans” (Group 1) based on evidence of carcinogenicity following inhalation exposure in humans and animals. The US EPA (1998) has classified beryllium as a probable human carcinogen (B1) following inhalation exposure, based on sufficient evidence in animals and limited evidence in humans.

Beryllium and beryllium compounds are poorly absorbed after oral exposure. Most data indicate that ingested beryllium compounds pass through the gastrointestinal tract unabsorbed and are eliminated in the faeces. Soluble beryllium compounds may also precipitate as insoluble beryllium phosphate in the higher pH environment of the intestine (Reeves 1965).

The deposition and clearance of inhaled beryllium particles are dependent on dose, particle size and solubility (Henneberger *et al.* 2004; Kolanz 2001; Muller *et al.* 2010; Stefaniak *et al.* 2007). Small amounts of soluble beryllium compounds are absorbed into the bloodstream, while insoluble beryllium compounds can be retained in the lung for long periods of time (Léonard and Lauwerys 1987).

There are few studies that demonstrate dermal absorption of beryllium. Belman (1969) demonstrated that beryllium can bind to alkaline phosphatase and nucleic acids in the skin, resulting in poor dermal absorption. Particle size may be a key factor for dermal absorption. Tinkle *et al.* (2003) demonstrated that relatively insoluble particles <1 µm in diameter may be transported through the skin.

Once beryllium is absorbed into the systemic circulation it is distributed primarily to the skeleton (Finch *et al.* 1990; Morgareidge *et al.* 1977; Reeves 1965) and the liver, tracheobronchial lymph nodes and other soft tissues (ATSDR 2002; Muller *et al.* 2010; NAP 2007). Distribution and absorption of beryllium is also affected by calcination temperature, with more beryllium being translocated to the skeleton and liver, and retained in the lungs after exposure to beryllium oxide prepared at 500°C than at 1000°C (Finch *et al.* 1990). The solubility of beryllium oxide decreases as the temperature at which it is calcined increases (ATSDR 2002).

Krachler *et al.* (1999) studied the transfer of beryllium across the placenta and into breast milk. Beryllium concentrations in umbilical cord serum and colostrum were higher than in maternal serum. Bencko *et al.* (1979) demonstrated the ability of beryllium to cross the placenta following intravenous administration of beryllium chloride in mice although foetal absorption was low.

Beryllium and its compounds are not biotransformed in the body, but soluble beryllium salts may be partially converted to more insoluble forms in the lung or into insoluble beryllium phosphate in the gastrointestinal tract (Reeves 1965). Insoluble beryllium compounds may be ionised by myeloperoxidases when engulfed by phagocytes (ATSDR 2002; US EPA 1998; WHO 2001).

Most beryllium taken in orally and inhaled beryllium that enters the gastrointestinal tract via mucociliary clearance, is excreted in the faeces, unabsorbed (NAP 2007). Beryllium that is absorbed is eliminated primarily in the urine (ATSDR 2002; US EPA 1998; WHO 2001).

Oral LD₅₀ (lethal dose, 50% mortality rate) values vary according to differences in solubility and the potential to form insoluble beryllium phosphate in the gastrointestinal tract. ATSDR (2002) reported oral LD₅₀ values for soluble beryllium compounds including beryllium sulphate (120 mg Be/kg in rats and 140 mg Be/kg in mice), and beryllium chloride (200 mg Be/kg in rats). In a recent study of beryllium metal in rats, an oral gavage dose of 2000 mg Be/kg did not result any signs of toxicity (Strupp 2011). This is thought to be due to the low solubility of beryllium metal.

The gastrointestinal tract appears to be the most sensitive target for oral exposure to beryllium. In a chronic toxicity study by Morgareidge *et al.* (1976 in US EPA 1998; 2008), male and female beagle dogs (5/sex/dose group) were fed a diet containing 1, 5, 50 or 500 ppm beryllium as beryllium sulphate for up to 172 weeks. Dogs exposed to 500 ppm had extensive ulcerative and inflammatory lesions in the small intestine, stomach and large intestine. Bone marrow hypoplasia was also observed in the high dose group. In the 50 ppm dose group two dogs exhibited similar but less severe gastrointestinal lesions.

Most information regarding adverse effects in humans via the inhalation pathway is available from occupational exposure studies. NAP (2007), ATSDR (2002) and US EPA (1998) have comprehensively reviewed effects following beryllium inhalation exposure in humans and animals. There is extensive evidence that the lung is the primary target following inhalation exposure to beryllium. Exposure to beryllium can cause two types of pulmonary disease, acute beryllium disease (ABD) and chronic beryllium disease (CBD).

Acute exposure to high levels of soluble and slightly soluble beryllium compounds can result in ABD (ATSDR 2002; WHO 2001). ABD is a type of pneumonitis generally thought to be due to the direct toxicity of beryllium, although immune and hypersensitivity responses have also been suggested

(Cummings *et al.* 2009; NAP 2007). The severity of ABD is dose-dependent (ATSDR 2002; NAP 2007). Onset of respiratory symptoms usually occurs over several weeks. Symptoms can range from mild nasopharyngitis to tracheobronchitis and severe chemical pneumonitis, which may be fatal. ABD is generally associated with exposure to beryllium concentrations $>0.1 \text{ mg/m}^3$ and has rarely been reported since the implementation of exposure limits in the 1950s and subsequent decreases in respiratory exposure to beryllium (ATSDR 2002; Eisenbud *et al.* 1949; NAP 2007).

While ABD is generally considered to be an irritant response to high exposure levels, CBD is considered a hypersensitivity response to lower exposure levels (at or near $1 \text{ } \mu\text{g/m}^3$) (ATSDR 2002). CBD is a pulmonary granulomatous disease characterised by a beryllium-specific immune response and the formation of noncaseating granulomas (NAP 2007; US EPA 1998). The granulomas interfere with lung function, eventually leading to fibrosis, respiratory failure and cor pulmonale (Sood 2009; Wambach and Laul 2008). While granulomas occur primarily in the lungs, they have also been reported in the skin, liver, spleen, lymph nodes, myocardium, skeletal muscles, kidney, bone and salivary glands (Kriebel *et al.* 1988). Beryllium sensitisation may precede CBD, although not all individuals who are sensitised develop the disease (Newman *et al.* 2005). CBD is known to have a genetic susceptibility component (NAP 2007).

Dermal exposure to beryllium compounds can cause irritant contact dermatitis, allergic contact dermatitis, chemical ulcers, ulcerating granulomas and allergic dermal granulomas (Berlin *et al.* 2003). Dermal exposure appears to play a role in beryllium sensitisation and CBD and may be a significant route of exposure to beryllium (Cummings *et al.* 2007; Curtis 1951; Day *et al.* 2007; Henneberger *et al.* 2001; Kreiss *et al.* 2007).

The US EPA (1998; 1987) and ATSDR (2002) cite the Wagoner *et al.* (1980) cohort study as providing evidence that inhalation exposure to beryllium has resulted in increased lung cancer-related mortality in workers. Wagoner *et al.* (1980) evaluated the carcinogenic potency of inhaled beryllium in a large cohort ($n=3055$) of exposed workers at a major beryllium production facility in Pennsylvania from 1942-1967, with follow-up until 1975. This study revealed a statistically significant increase in lung cancer mortality among workers, in particular among workers with a latency of more 25 years. There was also a statistically significant increase in the number of lung cancer deaths among workers hired before 1950.

The effect of beryllium on reproductive and/or developmental effects has not been adequately assessed. Reviews by the ATSDR (2002) and US EPA (1998) include only one study on the reproductive and developmental toxicity of beryllium following oral exposure (Morgareidge *et al.* 1976) and no studies on the reproductive and developmental toxicity of inhaled beryllium. No multi-generation or male reproductive studies have been carried out. It has also been noted that many of the animal studies may have been conducted at doses that result in maternal toxicity (NAP 2007; US EPA 1998).

Based on the above information, beryllium via the oral and dermal route should be treated as a threshold toxicant. For the inhalation pathway, both threshold and non-threshold scenarios should be considered.

For the oral and dermal route, the most recent and appropriate guidance for an acceptable level of

daily exposure is considered to be provided by US EPA (1998). No specific tolerable daily intake (TDI) has been provided by Health Canada or the World Health Organization. In deriving a reference dose of 2 µg/kg bw/day, US EPA (1998) concluded that the dog dietary study of Morgareidge *et al.* (1976) was the most appropriate study. Based on this study, a benchmark dose level (BMD10) resulting in a 10% increase in small intestinal lesions of 0.46 mg/kg bw/day was estimated by US EPA (1998). US EPA (1998) then applied a 300-fold uncertainty factor to estimate a reference dose (i.e., 10-fold for extrapolation for interspecies differences, 10-fold for consideration of intraspecies variation, and 3-fold for database deficiencies [lack of human oral data and inadequate assessment of reproductive/developmental and immunotoxicologic endpoints in animals]). Thus, US EPA (1998) estimated an oral reference dose of 2 µg/kg bw/day for beryllium. This reference dose was considered to be appropriate as the tolerable daily intake (TDI) for estimating soil quality guidelines for beryllium.

For the inhalation route, both cancer and non-cancer endpoints are considered. The TRVs for beryllium from various agencies (ATSDR, US EPA, WHO) are in agreement. No specific tolerable concentration has been previously provided by Health Canada for the protection of non-cancer effects. For evaluation of inhalation exposures, the reference concentration of 0.02 µg Be/m³, recommended by the US EPA (1998) was used for protection of non-cancer effects. In deriving a reference dose, the US EPA (1998) chose the Kreiss *et al.* (1996) occupational exposure study, which identified a LOAEL_(HEC) (LOAEL-Human Equivalent Concentration) of 0.20 µg/m³, and the Eisenbud *et al.* (1949) community monitoring study, which identified a NOAEL_(HEC) of 0.01-0.1 µg/m³, as co-principal studies. Other occupational studies were examined for the selection of the LOAEL, but lacked exposure monitoring data or were not selected because CBD was not well defined (Cotes *et al.* 1983; Cullen *et al.* 1987; US EPA 1998). The Eisenbud *et al.* (1949) study evaluated the incidence of CBD at different distances from the plant (hence at different estimated exposure levels), and as such, was the only study that was able to identify a NOAEL for CBD. No uncertainty factor was applied to account for human variability since the data were based on the sensitive sub population susceptible to CBD or to adjust for the less than chronic duration of the Kreiss *et al.* (1996) study. The occupational study by Kreiss *et al.* (1996) used more sensitive screening methods to detect CBD than the Eisenbud *et al.* (1949) study, so an uncertainty factor of 3 was applied to account for the sensitive nature of the subclinical endpoint (beryllium sensitisation). A database uncertainty factor of 3 was applied to account for the poor quality of exposure monitoring in the co-principal studies as well as other studies of beryllium sensitisation and CBD. Thus, the US EPA (1998) estimated a reference concentration (RfC) of 0.02 µg/m³. This RfC was also adopted by WHO (2001) and ATSDR (2002) and is considered appropriate as the tolerable concentration for estimating soil quality guidelines for beryllium.

For the cancer endpoint, Health Canada provides no specific tolerable concentration for the protection of cancer effects. For evaluation of inhalation exposures, the inhalation unit risk value of 2.4x10⁻³ (µg/m³)⁻¹, recommended by US EPA (1998; 1987), was used for the protection against cancer effects. US EPA based their unit risk on the Wagoner *et al.* (1980) study. In this subcohort, followed for at least 25 years, the adjusted lung cancer deaths ranged from 13.91-14.67, in comparison with 20 observed, resulting in relative risks of 1.44-1.36. While these risk estimates are not statistically significant (p >0.05), they have been used to calculate an upper limit of lung cancer risk (US EPA 1998). US EPA calculated a range of cancer potency estimates using various assumptions about

relative risk estimates and level of exposures. The geometric mean of the range of potency factors is $2.4 \times 10^{-3} \mu\text{g}/\text{m}^3$. This unit risk value corresponds to risk specific concentrations of $0.004 \mu\text{g}/\text{m}^3$ for an incremental lifetime cancer risk of 1×10^{-5} , and of $0.0004 \mu\text{g}/\text{m}^3$ for an incremental lifetime cancer risk of 1×10^{-6} . Consequently, these values are more stringent than the tolerable concentration of $0.02 \mu\text{g Be}/\text{m}^3$ for protection of non-cancer effects

Guideline Derivation

Canadian soil quality guidelines are derived for different land uses following the process outlined in CCME (2006) using different receptors and exposure scenarios for each land use. Detailed derivations for the soil quality guidelines for beryllium are provided in the supporting document (CCME 2015).

Soil Quality Guidelines for Environmental Health

There are no environmental soil quality guidelines or check values at this time (Table 2).

Soil Quality Guidelines for Human Health

Soil quality guidelines (SQG_{HH}) for beryllium require consideration of both the non-carcinogenic and carcinogenic properties of beryllium. For protection of non-cancer effects, the development of Canadian soil quality guidelines is typically based on 20% of the residual tolerable daily intake (i.e., $20\% \times [\text{TDI} - \text{EDI}]$). The relative absorption factors for inhalation, ingestion are assumed to be 100%, by default (CCME 2006). For dermal exposure the relative absorption factor is assumed to be 10% (HC 2010).

Since beryllium may act as a carcinogen via the inhalation route, the development of SQG_{HH} also considered the protection against cancer risks for respirable soil-based airborne dust particles. Specifically, non-threshold (carcinogenic) substances require the development of SQG_{HH} that employ a critical risk-specific dose (RSD), based on lifetime incremental cancer risks (ILCRs) from exposure to beryllium in soil via inhalation of airborne dust. For all land uses, the adult was chosen as the receptor when considering lifetime cancer risk. Some jurisdictions in Canada have adopted an “essentially negligible” ILCR of 1×10^{-5} (or 1 in 100 000) for managing risks of carcinogenic substances, while other jurisdictions use an ILCR of 1×10^{-6} (or 1 in 1 000 000). In light of this, soil quality guideline calculations were undertaken using both a 1×10^{-5} and 1×10^{-6} ILCR.

The SQG_{HH} that have been derived for beryllium for protection of non-cancer effects are: 75 mg/kg for agricultural and residential/parkland land use, 110 mg/kg for commercial land use, and 1100 mg/kg for industrial land use. For protection of cancer risks (i.e., via inhalation of fugitive dust), the human health-based soil quality guidelines for beryllium are: 5500 mg/kg for all land uses based on an ILCR of 1×10^{-5} . For an ILCR of 1×10^{-6} , the human health-based soil quality guideline for inhalation of fugitive dust is 550 mg/kg for all of the land uses. Consequently, the non-cancer endpoints were the most conservative values and were used as the SQG_{HH} for all land uses except for industrial sites that require protection of cancer risks for an ILCR of 1×10^{-6} .

Various check mechanisms are applied, if relevant, to the human health soil quality guidelines in order to provide them with a broader scope of protection, such as the potential to adversely impact groundwater or food-chain contamination.

No guideline for protection of groundwater used as a source of raw water as drinking was derived for beryllium due to constraints on the mathematical model when applied to inorganic compounds (CCME 2006).

In the derivation of soil quality guidelines for commercial and industrial sites, on-site and off-site exposure scenarios are considered. Transfers of contaminated soil from one property to another are possible by environmental occurrences such as wind and water erosion (CCME 2006). The off-site migration check for commercial and for industrial land uses was determined to be 1100 mg/kg, which is more than the SQG_{HH} for commercial (110 mg/kg) but less than the SQG_{HH} for industrial (1400 mg/kg) land uses. Therefore, only the industrial SQG_{HH} needs to be modified to protect against off-site migration.

A check mechanism for produce, meat and milk was not carried out, since the produce, meat and milk check pertains to substances that are expected to bioconcentrate or biomagnify. It is noted that the SQG_{HH} are considered to be protective at most sites; however, certain exposure pathways have not been evaluated in the development of the SQG_{HH} as discussed above.

Soil Quality Guidelines for Beryllium

The soil quality guidelines are intended to be protective of environmental and human health. Where sufficient and adequate data exist, the interim soil quality criteria (CCME 1991) are superseded.

There are sufficient data to derive the SQG_{HH} . No attempt was made to derive the SQG_E . For beryllium the interim soil quality criteria (CCME 1991) are lower than the SQG_{HH} derived in this report. Therefore, the interim soil quality criteria have been retained as the SQG for beryllium for all land uses (Table 2).

Table 2. Soil quality guidelines and check values for beryllium (mg·kg⁻¹).

| Guideline | Land use | | | |
|---|-----------------|--------------------------|------------------|---|
| | Agricultural | Residential/ parkland | Commercial | Industrial |
| | 4 ^a | 4 ^a | 8 ^a | 8 ^a |
| Human health guidelines/check values | | | | |
| SQG _{HH} | 75 ^b | 75 ^b | 110 ^b | 1100 ^{b,c} /550 ^{b,d} |
| Direct Contact Guideline (Ingestion + Dermal) | 75 | 75 | 110 | 1400 |
| Direct Contact (Inhalation) | | | | |
| 10 ⁻⁶ ILCR | 550 | 550 | 550 | 550 |
| 10 ⁻⁵ ILCR | 5500 | 5500 | 5500 | 5500 |
| Threshold | 5300 | 5300 | 19 000 | 19 000 |
| Inhalation of indoor air check | NC ^e | NC ^e | NC ^e | NC ^e |
| Off-site migration check | - | - | 1100 | 1100 |
| Groundwater check (drinking water) | NC ^f | NC ^f | NC ^f | NC ^f |
| Produce, meat, and milk check | NC ^g | NC ^g | NC | NC |
| Environmental health guidelines/check values | | | | |
| SQG _E | NC ^h | NC ^h | NC ^h | NC ^h |
| Soil contact guideline | NC | NC | NC | NC |
| Soil and food ingestion guideline | NC | - | - | - |
| Nutrient and energy cycling check | NC | NC | NC | NC |
| Off-site migration check | - | - | NC | NC |
| Groundwater check (aquatic life) | NC | NC | NC | NC |
| Interim soil quality criterion (CCME 1991) | 4 | 4 | 8 | 8 |

Notes: NC = not calculated; ND = not determined; SQG_E = soil quality guideline for environmental health; SQG_{HH} = soil quality guideline for human health. The dash indicates a guideline/check value that is not part of the exposure scenario for this land use and therefore is not calculated.

^a Data are sufficient and adequate to calculate only a SQG_{HH}. It is greater than the corresponding interim soil quality criteria (CCME 1991). Therefore the interim soil quality criterion is retained as the soil quality guideline for this land use.

^b The SQG_{HH} is the lowest of the human health guidelines and check values.

^c ILCR 1 x 10⁻⁵

^d ILCR 1 x 10⁻⁶

^e The inhalation of indoor air check applies to volatile organic compounds and is not calculated for metal contaminants.

^f Applies to organic compounds and is not calculated for metal substances. Concerns about metal substances should be addressed on a site specific basis.

^g This check is intended to protect against chemicals that may bioconcentrate in human food. Beryllium is not expected to exhibit this behaviour, and so this pathway was not evaluated.

^h Data are insufficient/inadequate to calculate an SQG_E, or provisional SQG_E for this land use (no attempt was made to derive environmental soil quality guidelines for beryllium).

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