Lead in Soil
Part II: Relative Absorption Factors and Source Allocation Factors for Use with Selected Toxicity Reference Values

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Executive Summary

This is Part II of the ministry’s two-part *Lead in Soil* document and should be considered in conjunction with *Lead in Soil – Part I: Toxicity Reference Values Selected for Children and Adults*. The following table presents relative absorption factors (RAFs) and source allocation factors (SAFs) recommended for use with the child- and adult-specific risk-specific doses (RSDs) selected by the ministry for lead (Pb) in soil. Details about the selections of these RAFs and SAFs are presented in this document.

Receptor Category	**Relevant RSD**	**Estimated RAF_{ORAL} for Soil Pb**	**Estimated $\text{RAF}_{\text{DERMAL}}$ for Soil Pb**	**SAF**
infant	5.0×10^{-4} mg/kg/d EFSA (2013) child-specific RSD	60%	0.4%	20%
toddler		60%		50%*
child (4 to <12 y)		35%		20%
teen (12 to <20 y)		45%		80%
adult	6.3×10^{-4} mg/kg/d EFSA (2013) adult-specific RSD	60%	1%	80%
pregnant woman		100%		

* For the toddler, the SAF of 50% is contingent on the soil ingestion rate of 200 mg/d considered representative of an upper estimate of ingestion of soil and house dust combined. The use of an alternative soil ingestion rate for only soil (no house dust) would require a revision of the SAF to 20%.

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1.0 Introduction

Please note that although this two-part *Lead in Soil* document with toxicity reference values (TRVs), relative absorption factors (RAFs), and source allocation factors (SAFs) for Pb in soil is considerably more detailed than the ministry's TRV selection documents for other contaminants, it is beyond the scope of the ministry's TRV program to provide extensive details. The goal of this document was not to report on the entire database of relevant data, but rather, to provide a reasonable snapshot of relevant data sufficient to inform science-based decisions.

For sites contaminated with lead (Pb) in soil, risk-specific doses (RSDs) for Pb may be used to develop soil Pb criteria and to conduct human health risk assessments (HHRAs). To refine these calculations, a relative absorption factor (RAF) and source allocation factor (SAF) may be applied in conjunction with a Pb RSD. This is Part II of the ministry's *Lead in Soil* document which estimates and provides generic RAFs and SAFs for use with the child- and adult-specific Pb RSDs selected in Part I.

Oral and dermal RAFs (RAF_O and RAF_D, respectively) are discussed in Section 2.0. SAFs are discussed in Section 3.0.

2.0 Relative Absorption Factors

The absorption of a contaminant is dependent on the receptor, the medium containing the contaminant, and the exposure route. The following are the key parameters generally affecting Pb absorption in the context of human exposures on contaminated sites, though other factors may affect absorption as well:

- absorption of Pb by infants or adults vs. absorption by other receptor categories
- absorption of Pb from diet or drinking water vs. absorption from soil
- absorption of Pb via the oral route vs. the dermal route of exposure

Relative absorption in the context of human exposure to soil Pb on contaminated sites can be defined as the route-specific absorption of soil Pb by the human receptor in the exposure scenario of interest *relative to* the oral absorption of Pb in the RSD's key study scenario (the human receptor category and medium forming the basis of the key study/studies used in the derivation of the RSD).

Sections 2.1 and 2.2 present recommended oral and dermal RAF values, respectively.

2.1 Oral Relative Absorption Factor Values

An oral relative absorption factor (RAF_O) may be applied with a TRV in HHRAs and in the development of soil criteria to assist in the quantification of exposures via the oral route. The following discussion shows the method for estimating RAF_O values for use with the Pb RSDs selected in Part I of the ministry's *Lead in Soil* document for each receptor category of interest: infant, toddler, child, teen, adult, and pregnant woman.

RAF_O values for the infant/toddler and the average adult are calculated using Equation 1 as shown below. However, for the child, teen, and pregnant woman, data on absolute oral Pb absorption *from soil* are lacking; the ratio of relative absorption of dietary calcium (Ca) between receptor categories can help determine oral soil Pb absorption for these receptor categories. Pb competes and interferes with Ca throughout the body, including absorption in the gastrointestinal tract via passive transport through epithelial cell tight junctions and via active transport for which the Ca transport protein exhibits high affinity for both Pb and Ca (Kordas, 2017; Rădulescu and Lundgren, 2019).

Equation 2a assumes that the ratio of soil Pb absorption among two receptor categories is similar to the ratio of dietary Ca absorption among those same receptor categories. Therefore, if "*oral soil Pb absorption for receptor of interest*" (the numerator of Equation 1) is not available, this parameter may be estimated using dietary Ca absorption data (and Equation 2b). In other words, Equation 2a uses Ca absorption data and can be rearranged into Equation 2b to solve for "*oral soil Pb absorption for receptor of interest*". Equations 1 and 2b can then be combined to obtain Equation 3 in order to calculate RAF_O. **Since absolute oral soil Pb absorption values are not available for the child, teen, and pregnant woman, Equation 3 is used to calculate RAF_O for these receptor categories.** Sample calculations for estimating RAF_O values for the child (4 to <12 years old) and for the pregnant woman are shown below the initial presentation of the equations.

For each receptor category, Table 2-1 presents each estimated RAF_O value and a rationale for its estimation. Sources of all *absolute* absorption values used are as follows:

- For the key study scenario of EFSA's (2013) child-specific RSD, absolute absorption of soil Pb for the infant and toddler is assumed to be 30%, which is based on professional judgement from US EPA (1994) in the Integrated Exposure Uptake Biokinetic (IUEBK) model.
- Absolute absorption of dietary Pb for the infant is estimated to be 50% based on the studies by Alexander *et al*. (1974) and Ziegler *et al*. (1978); this is also the value used in US EPA's (1994) IEUBK model for absolute absorption from Pb in the diet for ages 1 to 6.
- For the key study scenario of EFSA's (2013) adult-specific RSD, absolute absorption of soil Pb for the average adult is assumed to be 12%, which is US EPA's (2003) default estimate used for assessing risks associated with adult exposures to soil Pb.
- Absolute absorption of Pb in drinking water for adults is assumed to be 20%. This is US EPA's default estimate based on a weight-of-evidence determination and applies to soluble forms of Pb in drinking water and food (US EPA, 2003).
- Estimates of absolute dietary Ca absorption for various receptor categories are shown in Table A-1 in Appendix A.

$$\mathrm{RAF_O} = \frac{\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for receptor of interest}\end{pmatrix}}{\begin{pmatrix}\text{oral Pb absorption}\\ \text{in RSD's key study scenario}\end{pmatrix}}$$

(Equation 1)

$$\frac{\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for receptor of interest}\end{pmatrix}}{\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for receptor in RSD's key study scenario}\end{pmatrix}} = \frac{\begin{pmatrix}\text{dietary Ca absorption}\\ \text{for receptor of interest}\end{pmatrix}}{\begin{pmatrix}\text{dietary Ca absorption}\\ \text{for receptor of RSD's key study scenario}\end{pmatrix}}$$

(Equation 2a)

$$\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for receptor of interest}\end{pmatrix} = \frac{\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for receptor in RSD's key study scenario}\end{pmatrix} \times \begin{pmatrix}\text{dietary Ca absorption}\\ \text{for receptor of interest}\end{pmatrix}}{\begin{pmatrix}\text{dietary Ca absorption}\\ \text{for receptor of RSD's key study scenario}\end{pmatrix}}$$

(Equation 2b)

$$\mathrm{RAF_O} = \frac{\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for receptor of RSD's key study scenario}\end{pmatrix} \times \begin{pmatrix}\text{dietary Ca absorption}\\ \text{for receptor of interest}\end{pmatrix}}{\begin{pmatrix}\text{oral Pb absorption}\\ \text{in RSD's key study scenario}\end{pmatrix} \times \begin{pmatrix}\text{dietary Ca absorption}\\ \text{for receptor of RSD's key study scenario}\end{pmatrix}}$$

(Equation 3; from Equations 1 and 2b combined)

Sample calculation - Estimation of $\mathrm{RAF_O}$ for the child (4 to <12 years old):

From equation 1:

$$\mathrm{RAF_O} = \frac{\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for receptor of interest}\end{pmatrix}}{\begin{pmatrix}\text{oral Pb absorption}\\ \text{in RSD's key study scenario}\end{pmatrix}} = \frac{\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for child}\end{pmatrix}}{\begin{pmatrix}\text{dietary Pb absorption}\\ \text{for infant/toddler}\end{pmatrix}}$$

From equation 3:

$$\mathrm{RAF_O} = \frac{\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for receptor of RSD's key study scenario}\end{pmatrix} \times \begin{pmatrix}\text{dietary Ca absorption}\\ \text{for receptor of interest}\end{pmatrix}}{\begin{pmatrix}\text{oral Pb absorption}\\ \text{in RSD's key study scenario}\end{pmatrix} \times \begin{pmatrix}\text{dietary Ca absorption}\\ \text{for receptor of RSD's key study scenario}\end{pmatrix}}$$

$$= \frac{\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for infant/toddler}\end{pmatrix} \times \begin{pmatrix}\text{dietary Ca absorption}\\ \text{for child}\end{pmatrix}}{\begin{pmatrix}\text{dietary Pb absorption}\\ \text{for infant/toddler}\end{pmatrix} \times \begin{pmatrix}\text{dietary Ca absorption}\\ \text{for infant/toddler}\end{pmatrix}}$$

$$= \frac{(30\%) \times (35\%)}{(50\%) \times (60\%)}$$

$$\mathrm{RAF_O}\ \text{for child} = 35\%$$

Sample calculation - Estimation of $\mathrm{RAF_O}$ for pregnant woman:

From equation 1:

$$\mathrm{RAF_O} = \frac{\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for receptor of interest}\end{pmatrix}}{\begin{pmatrix}\text{oral Pb absorption}\\ \text{in RSD's key study scenario}\end{pmatrix}} = \frac{\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for pregnant woman}\end{pmatrix}}{\begin{pmatrix}\text{dietary Pb absorption}\\ \text{for average adult}\end{pmatrix}}$$

From equation 3:

$$\mathrm{RAF_O} = \frac{\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for receptor of RSD's key study scenario}\end{pmatrix} \times \begin{pmatrix}\text{dietary Ca absorption}\\ \text{for receptor of interest}\end{pmatrix}}{\begin{pmatrix}\text{oral Pb absorption}\\ \text{in RSD's key study scenario}\end{pmatrix} \times \begin{pmatrix}\text{dietary Ca absorption}\\ \text{for receptor of RSD's key study scenario}\end{pmatrix}}$$

$$= \frac{\begin{pmatrix}\text{oral soil Pb absorption}\\ \text{for average adult}\end{pmatrix} \times \begin{pmatrix}\text{dietary Ca absorption}\\ \text{for pregnant woman}\end{pmatrix}}{\begin{pmatrix}\text{dietary Pb absorption}\\ \text{for average adult}\end{pmatrix} \times \begin{pmatrix}\text{dietary Ca absorption}\\ \text{for average adult}\end{pmatrix}}$$

$$= \frac{(12\%) \times (60\%)}{(20\%) \times (20 \text{ to } 36\%)}$$

$$\mathrm{RAF_O} \text{ for pregnant woman} = 100 \text{ to } 180\%$$

Table 2-1: Recommended Oral Relative Absorption Factor (RAF_O) Values by Receptor Category

Receptor Category	Relevant RSD	Estimated RAF_O for Soil Pb	Rationale
infant & toddler	EFSA (2013) child-specific RSD	60%	• Based on US EPA’s (1994) IEUBK model: Absolute absorption of soil Pb for infant/toddler (exposure scenario) is 30% (based on US EPA professional judgement) & absolute absorption of dietary Pb for infant / toddler (RSD’s key study scenario) is 50% (Alexander *et al*., 1974; Ziegler *et al*., 1978). [30% ÷ 50% = 60%]
child (4–11 y)		35%	• Cannot be estimated directly because data on absolute absorption of soil Pb for the child (soil Pb absorption for receptor of exposure scenario) are not available. • RAF_O of 35% can be estimated using Equation 3: ○ 30% absolute oral soil Pb absorption for receptor of RSD’s key study (soil Pb, infant); US EPA, 1994 ○ 35% absolute dietary Ca absorption for receptor of exposure scenario (dietary Ca, child); Appendix A ○ 50% absolute oral Pb absorption in RSD’s key study scenario (dietary Pb, infant); US EPA, 1994 ○ 60% absolute dietary Ca absorption for receptor of RSD’s key study (dietary Ca, infant); Appendix A • (30% x 35%) ÷ (50% x 60%) = 35%
Teen (12–19 y)		45%	• Cannot be estimated directly because data on absolute absorption of soil Pb for the teen (soil Pb absorption for receptor of exposure scenario) are not available. • RAF_O of 25–45% can be estimated using Equation 3: ○ 30% absolute oral soil Pb absorption for receptor of RSD’s key study (soil Pb, infant); US EPA, 1994 ○ 25–45% absolute dietary Ca absorption for receptor of exposure scenario (dietary Ca, teen); Appendix A ○ 50% Pb absolute absorption in RSD’s key study scenario (dietary Pb, infant); US EPA, 1994 ○ 60% absolute dietary Ca absorption for receptor of RSD’s key study (dietary Ca, infant); Appendix A • (30% x 25–45%) ÷ (50% x 60%) = 25–45% • 45% RAF_O selected to account for highest Ca absorption of teen years being during puberty (EC-SCF, 2003)
adult	EFSA (2013) adult-specific RSD	60%	• US EPA (2003) provides 12% for absolute absorption of soil Pb for average adult (exposure scenario), 20% for absolute absorption of soluble Pb for adult (which can be used here as absolute absorption of drinking water Pb for adult (adult RSD’s key study scenario)), and 60% for RAF_O. [12% ÷ 20% = 60%]
pregnant woman		100%	• Cannot be estimated directly because data on absolute absorption of soil Pb for the pregnant woman (soil Pb absorption for receptor of exposure scenario) are not available. • RAF_O of 100–180% may be estimated using Equation 3: ○ 12% absolute oral soil Pb absorption for receptor of RSD’s key study (soil Pb, average adult); US EPA, 2003 ○ 60% absolute dietary Ca absorption for receptor of exposure scenario (dietary Ca, pregnant woman); App. A ○ 20% Pb absolute absorption in RSD’s key study scenario (drinking water Pb, average adult); US EPA, 2003 ○ 20–36% absolute dietary Ca absorption for receptor of RSD’s key study (dietary Ca, average adult); App. A • (12% x 60%) ÷ (20% x 20–36%) = 100–180% • Assumption of 100% RAF_O is selected under the assumption that the *pregnant* woman absorbs Pb from soil to same degree that the average adult absorbs Pb from drinking water.

The RAF_O values shown in Table 2-1 are recommended as generic or default values for the ministry's selected Pb RSDs for use in HHRAs and in the development of soil criteria. Note that the RAF_O values for the adult and pregnant woman should not be directly compared to the RAF_O values for other receptor categories as they are for use with different RSDs and are based on different key study scenarios.

2.2 Dermal Relative Absorption Factor Values

A dermal relative absorption factor (RAF_D) is applied with an RSD in HHRAs and in the development of soil criteria to assist in the quantification of exposures via the dermal route. Table 2-2 shows values for absolute dermal Pb absorption reported in the scientific literature.

Table 2-2: Absolute Dermal Absorption of Lead in the Scientific Literature

Reported Dermal Absorption	Species	Dermal Absorption Measured as Into or Through the Skin?	Occluded or Unoccluded Skin?	Notes	Reference
up to 0.4%	human, *in vivo*	through skin (whole body measurements)	unoccluded	lead acetate, for 24 h	Moore *et al*., 1980
0.2%	human, *in vivo*	into blood	occluded	lead acetate, for 24 h	Stauber *et al*., 1994
0.4% (in 21 h)	mouse, *in vivo*	through skin (into circulatory system)	occluded	lead acetate	Florence *et al*., 1998
up to 0.001%	rat, *in vivo*	through skin (into circulatory system)	occluded	various forms of Pb, for 48 h	Sun *et al*., 2002
up to 0.003%	human, *in vitro*	migrated through skin	unoccluded	lead oxide powder for 24 h	Filon *et al*., 2006
0.001–0.004% (in 24 h)	pig fetus, *in vitro*	through skin into receptor medium	unoccluded	Pb in metal cutting fluids	Julander *et al*., 2020

The absolute dermal absorption rates obtained from the literature range across several orders of magnitude. Some reported dermal absorption rates were excluded from consideration based on aspects of study methodology or reporting:

- *Excessive exposure duration*: Dermal absorption rates reported in Pounds (1979) were excluded as they were based on exposure durations of 14 days or 4 weeks rather than a duration more relevant to the use of dermal absorption data in HHRAs (*i.e*., closer to 24 hours).
- *Inclusion of Pb retained in skin in measurement of dermal absorption*: Dermal absorption implies the passage of the contaminant *through* the skin and into the systemic circulation. The portion of the contaminant which enters the skin but is retained there (rather than passing through the dermal layers) might not enter the systemic circulation. Indeed, exfoliation could be an important pathway of elimination of metals from the skin (Hursh *et al*., 1989). Dermal absorption rates reported by Bress and Bidanset (1991) and the absorption rate of ≤29% from Stauber *et al*. (1994) were excluded as those values include Pb retained within the skin.

Skin occlusion generally refers to applying a patch over the test area of skin. It may increase percutaneous absorption of applied chemicals; however, among the studies shown in Table 2-2 above, there does not appear to be an evident relationship between occlusion and reported dermal absorption. Therefore, skin occlusion was not considered as a factor in selecting a dermal absorption rate.

Based on the range of relevant values identified, an absolute dermal absorption rate of 0.2% is selected as it represents a midpoint of the range. Since data specific to age or pregnancy status is lacking, the value of **0.2% for absolute dermal absorption of soil Pb is applied to all receptor categories**.

Determining a RAF_D requires both an estimate of *absolute* dermal absorption in the exposure scenario (determined above to be 0.2%) and an estimate of absolute absorption in the RSD's key study scenario. As discussed in Table 2-1, an estimate of absolute oral absorption of dietary Pb for the infant/toddler (the key study scenario for EFSA's (2013) child-specific Pb RSD) is 50% (Alexander *et al*., 1974; Ziegler *et al*., 1978; US EPA, 1994). **Therefore, the proposed RAF_D for use with EFSA's (2013) child-specific Pb RSD (for the infant, toddler, child, and teen) is 0.4%** (0.2% ÷ 50% = 0.4%).

Also discussed in Table 2-1, an estimate of absolute oral absorption of soluble Pb for adults (used as an estimate of absolute absorption of drinking water Pb for adults in the key study scenario of EFSA's (2013) adult-specific Pb RSD) is 20% (US EPA, 2003). **Thus, the proposed RAF_D for use with EFSA's (2013) adult-specific Pb RSD of (for the adult and the pregnant woman) is 1%** (0.2% ÷ 20% = 1%).

3.0 Source Allocation Factors

3.1 Methodology for Determining Source Allocation Factors for Pb

A source allocation factor (SAF) is generally applied in conjunction with a threshold TRV (*e.g.*, a tolerable daily intake; TDI) to calculate a medium-based criterion or concentration (*e.g.*, a soil criterion). The purpose of applying a SAF with a threshold TRV is to prevent total exposures (background exposure plus exposure from implementation of the criterion) from exceeding the threshold TRV. An SAF is determined by estimating exposures from various sources. To ensure that estimated total exposures (including exposure from the medium regulated through the criterion) are not excessive requires also considering the TRV's value. *This means an SAF is specific to the contaminant and specific to the TRV*.

To determine an appropriate SAF value, recent data are used to determine an *upper estimate* of background exposure (rather than a central tendency estimate), thereby taking the majority of the population into consideration. To avoid an overconservative estimate of background exposure, the ministry's approach is to **combine an upper estimate from the most significant background exposure medium with central tendency estimates from other media**.

The ministry's default SAF value is 20%. However, in cased where sufficient information is available, the ministry has begun a system of determining SAFs which could be considered a modification of the subtraction method used by other agencies.

In general, background exposure data are imprecise and commonly vary between data sources; therefore, rather than estimating falsely precise SAF values, the ministry's approach results in one of three default SAF values:

- **80%:** ceiling value used when background exposures are relatively low compared to the TRV
- **50%**: middle value used when background exposures are roughly half of the TRV
- **20%**: floor value used when background exposures are close to or exceeding the TRV

Soil criteria are often developed using TDIs. However, the TRVs selected for Pb are RSDs based on a target increase in risk or change in effect (a 1 IQ point decrement for infants, toddlers, children, and teens; a 10% increased prevalence of chronic kidney disease for adults) rather than a threshold. **For Pb RSDs, the ministry has decided to allocate the target change in effect to *total* Pb exposures, not to Pb exposures from soil alone. Thus, only a part of the Pb RSD is allocated to soil based on the proportion of the RSD remaining after accounting for other exposures.**

3.2 Sources of Background Exposure to Pb

3.2.1 Lead in House Dust

Pb has been identified in house dust at significant concentrations. A study of urban homes across Canada reported a **median house dust Pb concentration of 100 ppm**, a mean of 210 ± 446 ppm, and **90th percentile of 357 ppm** (Rasmussen *et al*., 2013). A study of homes in Ottawa reported median and 90th percentile house dust Pb concentrations of 222 and 969 ppm, respectively (Rasmussen *et al*., 2001). Hejami *et al*. (2020) reported a median of 36 ± 169 ppm for the Greater Toronto Area homes, and for downtown Toronto homes the mean was 190 ppm; upper percentiles were not reported. To estimate background Pb exposure from house dust in this document, the Rasmussen *et al*. (2013) study was selected because of its broad span of homes surveyed in several cities.

Pb intakes from the incidental ingestion of house dust were calculated using house dust Pb concentrations reported in Rasmussen *et al*. (2013) in conjunction with estimates of body weight and incidental house dust ingestion rate. Richardson (2013) reports mean body weights of 8.1, 15.3, 35.2, 65.2, and 76.5 kg (Richardson, 2013) respectively for the infant, toddler, child, teen, and adult. US EPA (2017) recommends central tendency indoor dust ingestion rates of 20 mg/d for <6 months and 40 mg/d for 6 months to <1 year (an average of 30 mg/d, suitable for the infant category), 50 mg/d for 1 to <2 years (suitable for the toddler category), 30 mg/d for 6 to <12 years (suitable for the child category), and 20 mg/d for 12 years through adult (suitable for the teen, adult, and pregnant woman categories).

For the infant, toddler, child, teen, and adult, respective estimated house dust Pb intakes were central tendencies of 0.37, 0.33, 0.085, 0.031, and 0.026 µg/kg/d and upper estimates of 1.3, 1.2, 0.30, 0.11, and 0.093 µg/kg/d.

3.2.2 Lead in the Diet

As Pb in the diet has been decreasing over time, recent studies are the most relevant. The most recent studies relevant to dietary Pb intakes in Ontario are from two publications out of the U.S. Food and Drug Administration. For a variety of age categories, Spungen (2019) and Gavalek *et al*. (2020) report mean and 90th percentile dietary Pb intakes. According to these studies, the “hybrid” means and 90th percentiles reported were calculated by setting values below the limit of detection (LOD) to zero if there were no detections from 2009 to 2016, and otherwise set to ½ the LOD. These estimates are summarized below.

For toddlers 1–3 years old, Spungen (2019) reported a mean dietary Pb intake of 0.12 µg/kg/d and 90th percentile of 0.20 µg/kg/d. These values are suitable for the toddler category in this document.

For children 4–6 years old, the mean was 0.10 µg/kg/d and the 90th percentile was 0.15 µg/kg/d (Spungen, 2019). For people 7–17 years old, Gavalek *et al*. (2020) reports a mean dietary Pb intake of 2.2 µg/d and 90th percentile of 3.4 µg/d. Using a body weight of 35.2 kg for children 4 to <12 years old (Richardson, 2013), the corresponding dietary Pb intakes are roughly a mean and 90th percentile of 0.063 and 0.097 µg/kg/d, respectively. For the child category (4 to <12 years old) in this document, a range of 0.063 to 0.10 µg/kg/d was selected as central tendency estimates.

The above-mentioned mean and 90th percentile dietary Pb intakes for people 7–17 years old (2.2 and 3.4 µg/d; Gavalek *et al*., 2020), can be combined with the body weight of 65.2 kg for teens 12 to <20 years old (Richardson, 2013) to obtain respective dietary Pb intakes of 0.034 and 0.052 µg/kg/d for the teen category.

Gavalek *et al*. (2020) also provides estimates of dietary Pb intake for *adults* (defined as males and females 18 years and older) and for *women of childbearing age* (*WOCBA*; defined as women from 16 to 49 years old), though these data are not mutually exclusive. The mean and 90th percentile dietary Pb intakes are 2.7 and 4.5 µg/d for adults and 2.4 and 4.0 µg/d for WOCBA, respectively. Using an adult body weight of 76.5 kg (Richardson, 2013), the corresponding mean and 90th percentile dietary Pb intakes are 0.035 and 0.059 µg/kg/d for adults and 0.031 and 0.052 µg/kg/d for WOCBA.

For infants, potential dietary sources of Pb are breastmilk and infant formula. Pb intakes from both sources are estimated below:

a) *Pb intake from breast milk*: Only one recent report of Pb concentrations in breast milk in North America was identified (Klein *et al*., 2017), reporting a mean of 0.77 ± 0.45 µg/L in the USA. However, recent breastmilk concentrations have been commonly reported elsewhere in western / industrialized countries. Identified means are as follows: 1.5 ± 0.90 µg/L (Sweden, Bjorklund *et al*., 2012), 1.02 ± 0.26 µg/L (Poland, Klein *et al*., 2017), <0.67 µg/L (median, Norway, Vollset *et al*., 2019), 1.74 ± 0.77 µg/L (Hungary, Ecsedi-Angyal *et al*., 2020), 0.125 ± 0.143 µg/L (South Africa, Olowoyo *et al*., 2021), 0.14 µg/L (median, Spain, Freire *et al*., 2022). In summary, the American mean of 0.77 µg/L falls within the range of central tendency values identified elsewhere (0.125 – 1.74 µg/L). As Klein *et al*. (2017) did not report upper percentile Pb concentrations, an upper estimate of Pb in American breastmilk could be roughly represented by the reported *mean + 2 SD*, equivalent to 1.67 µg/L.

   Assuming a mean infant body weight of 8.1 kg (Richardson, 2013), and a mean breastmilk consumption rate of 0.77 L/d for infants (3 to < 6 months old; US EPA, 2011, Table 15-1), the mean and upper estimate breastmilk Pb concentrations of 0.77 and 1.67 µg/L correspond to mean and upper estimate breastmilk Pb intakes of 0.073 and 0.16 µg/kg/d, respectively.

b) *Pb intake from infant formula*: Most powdered infant formula instructions advise reconstitution at 1 scoop of powder per 2 fluid ounces (~ 60 mL) of water, a scoop generally weighing up to 10 g. Assuming the same intake rate as breastmilk (US EPA, 2011, average intake of reconstituted infant formula would be 770 mL/d, which corresponds to an average intake of 130 g of powdered infant formula per day.

   In a study of infant formulas and other baby foods in the USA (Gardener *et al*., 2019), Pb concentrations were not reported separately for infant formulas. For all baby foods combined, a median Pb concentration could not be calculated as over half the samples were below the detection limit (value not stated); however, for all baby food combined, the 75th and 95th percentile Pb concentrations were 0.0056 and 0.0185 µg/g, respectively. These data are corroborated by a non peer-reviewed study (Houlihan and Brody, 2019) reporting Pb concentrations of 0.0029 µg/g (mean) and 0.0059 µg/g (95th percentile) for 13 American powdered infant formula brands, a mean of 0.0028 ± 0.0008 µg/g reported for powdered infant formulas available in Italy (Astolfi *et al*., 2021), and a mean of 0.0010 µg/g for infant formulas in France (ANSES, 2016).

   With powdered infant formulas, Pb exposure would occur from both the powder itself and the water used to reconstitute the powder. Estimated Pb intakes from both the infant formula and the water for reconstitution are as follows:

   - *Pb in the infant formula alone*: A central tendency Pb intake of 0.047 µg/kg/d can be calculated from an average Pb concentration of 0.0029 µg/g, an average intake rate of powdered formula of 130 g/d (estimated above), and an average body weight of 8.1 kg (Richardson, 2013). An upper estimate Pb intake of 0.30 µg/kg/d can be calculated from an upper estimate Pb concentration of 0.0185 µg/g, 130 g/d average intake of powdered formula, and an average body weight of 8.1 kg.

- *Pb in the tap water used for reconstituting the powdered formula:* A central tendency estimate of 0.095 µg/kg/d for Pb intake from tap water can be calculated from a mean liquid formula intake of 0.77 L/d (assuming same average intake rate as breastmilk, US EPA, 2011), a median tap water Pb concentration of 1 µg/L (for Ontario, 2016–2021, MECP, 2023), and a mean body weight of 8.1 kg. An upper estimate of 0.67 µg/kg/d for Pb intake from tap water can be calculated from a mean liquid formula intake of 0.77 L/d, the 95th percentile tap water concentration of 7 µg/L (for Ontario, 2016–2021, MECP, 2023) and a mean body weight of 8.1 kg.

Pb intakes from infant formula and the water for reconstitution indicate that tap water may be a greater source of Pb for the infant than the powdered infant formula itself. A central tendency estimate of Pb intake from the powdered formula (0.047 µg/kg/d) plus a central tendency estimate of Pb intake from the reconstitution water (0.095 µg/kg/d) results in a total intake of 0.142 µg/kg/d.

Estimated Pb intake from infant formula consumption (central tendency estimate of 0.142 µg/kg/d) is somewhat greater than estimated Pb intake from breastmilk consumption (central tendency estimate of 0.073 µg/kg/d). This range was selected as a central tendency estimate of Pb dietary intake for infants.

3.2.3 Lead in Drinking Water

The median tap water Pb concentration for flushed and standing distribution lines in Ontario from 2016 to 2021 was 1 µg/L (MECP, 2023).

For toddlers, children, teens, and adults, respective mean body weights are 15.3, 35.2, 65.2, and 76.5 kg (Richardson, 2013) and respective mean drinking water intake rates are 0.6, 0.8, 1.0, and 1.5 L/d (Richardson, 1997). Combining these mean body weights and drinking water intake rates with the median tap water Pb concentration results in respective central tendency drinking water Pb intakes of 0.039, 0.023, 0.015, and 0.020 µg/kg/d. For infants, drinking water ingestion occurs mainly through intake of infant formula or is minimal compared to intake of breastmilk.

3.2.4 Lead in Other Media

For the general population, Pb intake from air inhalation is expected to be minimal compared to Pb intakes from the media discussed above.

Intakes from soil Pb were not included in estimates of background Pb intake. Determining SAFs should not include background intake from the medium to which the corresponding TRVs will be applied in the development of criteria. The goal is to determine a remaining proportion of the TRV which is available for developing criteria for the medium of interest after accounting for intakes from other media. As soil is the intended medium of interest for use of the Pb RSDs, soil is not included in estimates of background intake to determine SAFs for Pb. Though property and community soils may both contribute to an individual's soil ingestion, it is difficult to determine the relative contribution of each. For simplicity, soil ingestion is assumed to occur mainly from the property of interest. Since these estimates of background Pb exposure have been calculated conservatively, there is little concern from additional intake that may occur from community soil exposures. Furthermore, as some house dust is of soil origin, Pb in neighbourhood and community soils may be partly represented in measurements of house dust Pb concentrations.

3.3 Estimates of Total Background Exposures to Determine Source Allocation Factors for All Receptors

Comparison of Pb intakes from various media (as described in Sections 3.2.1 to 3.2.4) indicate that Pb intakes from house dust ingestion are similar to or greater than Pb intakes from diet; in addition, Pb intakes from house dust ingestion and from diet are generally greater than Pb intakes from drinking water ingestion.

According to the methodology outlined in Section 3.1 above, total background exposure is calculated using an *upper* estimate of intake from the primary medium of exposure plus *central tendency* estimates from other media. Since house dust is the primary medium of Pb exposure, total background exposure estimates for each receptor category are comprised of upper estimates of exposure from house dust ingestion combined with central tendency estimates of dietary Pb intake and drinking water Pb intake.

Table 3-1 provides a summary of intakes from each relevant medium for each receptor category. Estimated total background exposures are then compared to the relevant RSD (0.5 µg/kg/d for the infant, toddler, child, and teen; 0.63 µg/kg/d for the adult and pregnant woman; EFSA, 2013) in order to provide recommended SAFs for each receptor category. Note that the SAFs recommended are intended for use with the corresponding RSDs.

Table 3-1: Recommended SAFs Determined from Total Background Pb Intakes

Receptor Category	Estimates of Background Pb Intake				Pb RSD (µg/kg/d)	Total Background Pb Intake as a % of RSD	Recommended SAFs	
	Upper Estimates	Central Tendency Estimates		TOTAL Background Pb Intake (µg/kg/d)				
	House Dust Pb Intake (µg/kg/d)	Dietary Pb Intake (µg/kg/d)	Drinking Water Pb Intake (µg/kg/d)				SAF	Rationale
infant	1.3	0.073 – 0.14	*	1.4	0.5	270–290%	20%	Floor SAF of 20% is recommended for soil because total background intake exceeds RSD.
toddler	1.2	0.12	0.039	1.4		270%	20%	
child	0.30	0.063 to 0.10	0.023	0.39 – 0.42		77–85%	20%	Floor SAF of 20% is recommended for soil because total background intake is close to RSD.
teen	0.11	0.034	0.015	0.16		32%	80%	Ceiling SAF of 80% is recommended for soil because total background exposures are relatively low compared to RSD.
adult	0.093	0.035	0.020	0.15	0.63	23%	80%	
pregnant woman	0.093	0.031	0.020	0.14		23%	80%	

* For infants, drinking water ingestion occurs mainly through infant formula intake or is minimal compared to breastmilk intake.

3.4 SAF Adjustment for the Toddler Receptor

Soil ingestion rates (SIRs) are used in conjunction with SAFs to calculate soil criteria. Based on US EPA's (2017) analysis of soil and indoor dust ingestion, the ministry is aware that the toddler SIR of 200 mg/d used in the calculation of the ministry's Brownfields program (MOE, 2011) is more so representative of an upper percentile of the ingestion of soil and house dust *combined*. (This, however, is not the case for the SIRs used for the other receptor categories.) Since house dust ingestion is already incorporated into the ministry's current soil ingestion rate for the toddler, it would be excessively conservative to also include house dust Pb ingestion to estimate total background Pb exposures in the determination of the toddler SAF. Therefore, an alternative SAF is determined for the toddler (when using an SIR of 200 mg/d) as follows:

The 90th percentile dietary Pb intake of 0.20 µg/kg/d reported for toddlers 1–3 years old (Spungen, 2019) is combined with a central tendency estimate of drinking water Pb intake of 0.039 µg/kg/d (according to Section 3.2.3 above) for a total background Pb intake of 0.24 µg/kg/d**. Total background intake is approximately half of the value of the RSD, so the middle SAF of 50% is recommended for the toddler when using an SIR of 200 mg/d.**

Note: The toddler SAF of 50% for Pb was determined in consideration of the ministry's toddler SIR of 200 mg/d (representing an upper percentile of ingestion of soil and house dust combined). With an alternative SIR, *e.g.*, 90 mg/d (US EPA, 2017; recommended upper percentile, soil alone, general population 1 to <2 years old), the SAF would be revised to 20%. This is due to the inclusion of exposure to house dust Pb in the estimation of total background Pb exposure, as calculated in Table 3-1 above. **Accordingly, in HHRAs for contaminated sites and in the development of soil criteria for Pb, the SAF should be matched with the appropriate SIR as follows:**

- **toddler SIR of 200 mg/d with toddler SAF of 50%, or**
- **toddler SIR of 90 mg/d with toddler SAF of 20%.**

Moreover, calculating a soil criterion with an SIR of 200 mg/d and SAF of 50% would only be marginally different if calculated with the SIR of 90 mg/d and SAF of 20%. (In other words, the ratio of SAF to SIR is roughly the same either way.)

4.0 Summary

Table 4-1 presents the RAFs and SAFs selected in this document and recommended for use with the child- and adult-specific risk-specific doses (RSDs) selected by the ministry for lead (Pb) in soil.

Table 4-1: Recommended Relative Absorption Factors (RAFs) and Source Allocation Factors (SAFs) by Receptor Category

Receptor Category	Relevant RSD	Estimated RAF_{ORAL} for Soil Pb	Estimated RAF_{DERMAL} for Soil Pb	SAF
infant	5.0 x 10^{-4} mg/kg/d EFSA (2013) child-specific RSD	60%	0.4%	20%
toddler		60%		50%*
child (5–11 y)		35%		20%
teen (12–19 y)		45%		80%
adult	6.3 x 10^{-4} mg/kg/d EFSA (2013) adult-specific RSD	60%	1%	80%
pregnant woman		100%		

* For the toddler, the SAF of 50% is contingent on the soil ingestion rate of 200 mg/d considered representative of an upper estimate of ingestion of soil and house dust combined. The use of an alternative soil ingestion rate for only soil (no house dust) would require a revision of the SAF to 20%.

5.0 References

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Appendix A: Absorption Rates of Dietary Calcium Across Receptor Categories

Several studies report ***calcium*** (Ca) absorption in humans. Table A-1 displays average Ca absorption rates reported in the identified studies, sorted by receptor category. Note that within each receptor category, reported absorption rates are generally consistent.

Table A-1: Absorption Rates of Dietary Calcium Across Receptor Categories

Receptor Category	Subjects (age/other)	Medium	Average Fractional Absorption	Reference	Notes
infants	22–367 d	soy formula – low Ca	57%	DeVizia *et al*., 1985	Ca absorption rate for infants seems to range from **38% to 76%.** EC-SCF (2003) states that Ca absorption is highest in breastfed infants – **about 60%**.
		soy formula – medium Ca	47%		
		soy formula – high Ca	39%		
	infants	human milk	~60%	Fomon & Nelson, 1993 (cited in Abrams, 2010)	
		infant formula	~40%		
	preterm infants, 38 d	Standard infant formula	49%	Carnielli *et al.,* 1995	
		modified triglycerides formula	64%		
	27–161 d	formula with palm oil	39%	Nelson *et al*., 1996	
		formula without palm oil	48%		
	5–7 mo	human milk	61%	Abrams *et al*., 1997b	
	infants	infant formula	58%	Lifschitz & Abrams, 1998	
	infants	milk-based formula with palm oil	38%	Nelson *et al*., 1998	
		milk-based formula without palm oil	58%		
	8–12 weeks	milk-based formula	67%	Abrams *et al*., 2002	
		milk-based formula, no lactose	56%		
	77 d	milk-based formula with prebiotics	57%	Hicks *et al*., 2012	
		standard milk-based formula	59%		
		human milk	76%		
	69–159 d	milk-based formula with palm	42%	Leite *et al*., 2013	
		milk-based formula without palm	59%		
	68–159 d	milk-based formula with palm	41%	de Souza *et al*., 2017	
		milk-based formula without palm	58%		
toddlers / young children	1–4 y	standard breakfast	46%	Lynch *et al*., 2007	Age range 1–3 y is not a period of rapid bone mineral accrual (Abrams, 2010). Ca absorption decreases in young childhood (EC-SCF, 2003).
	3–5 y	low Ca diet	36%	Ames *et al*., 1999	
		high Ca diet	24%		

Receptor Category	Subjects (age/other)	Medium	Average Fractional Absorption	Reference	Notes
child (4-11 y)	girls, 4-9 y	tracer in diet	30%	Abrams *et al*., 1993	**35%** is a reasonable central tendency value for this group.
	China, 7 y	chocolate milk, low Ca intake	63%	Lee *et al*., 1994	
		chocolate milk, higher Ca intake	55%		
	girls, 7.7 ± 2.1 y	tracer in milk taken with breakfast	28%	Abrams & Stuff, 1994	
	white prepubertal girls 9.2 ± 2.5 y	tracer in milk	30%	Abrams *et al*., 1995	
	black prepubertal girls 9.5 ± 2.1 y		39%		
	Mexican-American girls 7-8 y	Individualized dietary plan based on food preferences	34%	Abrams *et al*., 1999	
	Caucasian American girls 7-8 y		32%		
	girls, 8 y, 9 y, & 10 y	tracer in food	33%, 31%, & 37%	Abrams *et al*., 2000	
	girls, 10-11 y	low-Ca diet	63%	Abrams *et al*., 2004	
		recommended-Ca diet	43%		
	9-13 y	diet with or without fructan	29-39%	Abrams *et al*., 2005a	
	girls 11.0 ± 0.1 y	oral tracer mixed in food	36%	Abrams *et al*., 2005b	
	6-13 y	Ca mixed into milk	33%	Motil *et al*., 2006	
	Texas, 4-8 y	Ca in orange juice	30-34%	Abrams *et al.*, 2013	
	black & white, 9-13 y	standardized breakfast	~43%	Lewis *et al*., 2013	
teen (12-19 y)	10-17 y	$CaCO_3$ or CCM	$CaCO_3$ 26%; CCM 36%	Miller *et al*., 1988	In teens, Ca absorption may be in range of **25–45%**, but this range may be confounded by sociodemographics and pregnancy. EC-SCF (2003) states that Ca absorption rises during puberty.
	girls, 10.9 ± 1.1 y	tracer in milk taken with breakfast	34%	Abrams & Stuff, 1994	
	girls, 15.2 ± 1.3 y		25%		
	white girls, 15.4 ± 0.9 y black girls 13.3 ± 1.3 y	tracer mixed with milk	white 25%; black 44%	Abrams *et al*., 1995	
	girls, 9-17 y	tracer in milk taken with breakfast	58% w/ low Ca intake 26% w/ high Ca intake	O’Brien *et al*., 1996	
	girls, 11–14 y	tracer in food	38%	Wastney *et al*., 1996	
	9.5–14.7 y	tracer in milk taken with breakfast	girls 25%, boys 27%	Abrams et al., 1997a	
	boys, 14-16 y	with or without oligofructose	50-60%	van den Heuvel *et al*., 1999	
	girls, 11.0–13.9 y	Ca w/ sucrose, oligofructose, or inulin+oligofructose	32-38%	Griffin *et al*., 2002	
	adolescent girls	tracer in food	33%, 36%	Griffin *et al*., 2003	
	black girls 12.8 ± 1.2 y white girls 13.7 ± 0.9 y	Ca tracer with food	black 54%; white 38%	Bryant *et al*., 2003	
	postpartum nonlactating girls 15.6±1.6 y	standard diet	33%	O’Brien *et al*., 2003	
	9-13 y	diet with or without fructan	29-39%	Abrams *et al*., 2005a	
	girls, 11-13 y	cereal w/ or w/o long-chain fructoologosaccharides	66-67%	Martin *et al*., 2010	
	girls, 10-13 y	smoothies w/ or w/o galactoologosaccharides	40%	Whisner *et al*., 2013	

Receptor Category	Subjects (age/other)	Medium	Average Fractional Absorption	Reference	Notes
adults	men, 21–33 y	low-fibre diet	61%	O'Brien *et al*., 1993	Excluding the data from the O'Brien *et al*. (1993) study which reports unexpectedly high absorption rates, Ca absorption rates for adults (excluding pregnant or lactating women) seems to range from **17% to 36%.** EC-SCF (2003) states that Ca absorption decreases to **15–20%** in young adults and declines gradually thereafter. Median from several studies reviewed by Shkembi & Huppertz (2022) was **36%**.
		high-fibre diet	37%		
	women, not pregnant, not lactating	standard diet, with or without 1 g/d Ca supplement	36%	Cross *et al*., 1995	
	women 19–31 y	Ca-rich diet	22%	Wastney *et al*., 1996	
	women, not pregnant & not lactating	standard diet + prenatal supplement	33%	Ritchie *et al*., 1998	
	women, never pregnant	standard diet	17%	Moser-Veillon *et al*., 2001	
	25–36 y	standard breakfast + milk with or without Ca enrichment	23%–28%	Lopez-Huertas *et al*., 2006	
	18–27 y	standard breakfast + Ca isotope mixed in vitamin-D fortified orange juice	26%	Abrams et *al*., 2007	
	25–45 y	3% butterfat ice cream	26%	van der Hee *et al*., 2009	
		9% coconut oil ice cream	28%		
		reduced-fat milk	31%		
	women, post-menopause	standard diet	21%	Ramsubeik *et al*., 2014	
	women 60 ± 7	standard diet	22%	Vreede *et al*., 2015	
	men & women	dairy	36% median across 24 studies	Shkembi & Huppertz, 2022	
pregnant women	1st trimester	standard diet	41%	Cross *et al*., 1995	In pregnant women, Ca absorption seems to range from **40 to 88%** which is similar to the infant. **60%** is a reasonable central tendency value for Ca absorption for pregnant women, as it is for infants.
		standard diet + 1 g/d Ca supplement	40%		
	2nd trimester	standard diet	60%		
		standard diet + 1 g/d Ca supplement	54%		
	3rd trimester	standard diet	58%		
		standard diet + 1 g/d Ca supplement	67%		
	1st trimester	standard diet + prenatal supplement	50%	Ritchie *et al*., 1998	
	2nd trimester		50%		
	3rd trimester		54%		
	16.5 ± 1.4 y	standard diet	53%	O'Brien *et al*., 2003	
	early pregnancy	standard diet	71%	O'Brien *et al*., 2006	
	late pregnancy		88%		

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