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This report concerns a study which was conducted for Svensk Kärnbränslehantering AB (SKB). The conclusions and viewpoints presented in the report are those of the authors. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

A pdf version of this document can be downloaded from www.skb.se.

Abstract

Peat and wood can be used as fuel for heating and electricity production. This report is concerned with the assessment of peat and wood combustion in the context of SR-Site (the analysis of long-term repository safety (SR-Site) performed by the Swedish Nuclear Fuel and Waste Management Co (SKB) that constitutes a part of SKB's license application to construct and operate a final repository for spent nuclear fuel in Forsmark, Sweden). If radionuclides would be released from the repository in the future, and transported from deep bedrock to the biosphere, contaminated fuel combustion and resulting exposure to contaminated air is a possible exposure pathway that could result in doses to humans. We here present methods for calculating air activity concentrations and derive dose conversion factors (Sv/y per Bq/kgDW) considering this exposure pathway in two assessment cases; peat and wood combustion for heating in a household (with a 20,000 kWh/y energy consumption) and energy production in a 100 MW power plant. In order to assess the impact of combustion of peat or wood originating from areas of the SR-Site discharge points (here referred to as biosphere objects), the derived dose conversion factors (Sv/y per Bq/kgDW) were multiplied with the activity concentration of peat and wood per unit release rate into each SR-Site biosphere object (Bq/kgDW per Bq/y) and a dilution factor accounting for the proportion of contaminated fuel per total fuel burnt by the household or power plant (kgDW/kgDW). The resulting quantity (Sv/y per Bq/y) was compared to the total dose conversion factors calculated previously in SR-Site (LDFs), where the exposure pathway of peat and wood combustion was omitted. The comparison shows that all annual doses per unit release rate into the biosphere objects are lower than the corresponding LDFs from SR-Site in both assessment cases. For the peat fuelled power plant, the three largest annual doses per unit release rate into the biosphere were obtained for Th-232 (8% of the LDF), Pu-242 (6% of the LDF) and Pu-239 (3% of the LDF). For the peat fuelled household the largest annual doses per unit release rate into the biosphere were obtained for Th-232 (53% of the LDF), Pu-242 (30%), Pu-239 (16%), U-236 (12%) and U-238 (11%). For wood, the annual doses per unit release rate into the biosphere were lower than for peat for most radionuclides, with all radionuclides falling below 1% of the LDF for the power plant and below 6% of the LDF for the household. The most dominant radionuclides for dose in the assessment of high level waste are Ra-226, Ni-59, Se-79 (SKB 2011) but the contribution from combustion of peat and wood were insignificant for these radionuclides. It is therefore concluded that exposure of peat- or wood combustion has insignificant contribution to the total dose in SR-Site. For the most dominant radionuclides, ingestion of water and food instead dominate the dose (Avila et al. 2010).

Contents

1 Introduction

The analysis of long-term repository safety (SR-Site) (SKB 2011) performed by the Swedish Nuclear Fuel and Waste Management Co (SKB) constitutes a part of SKB's license application to construct and operate a final repository for spent nuclear fuel in Forsmark, Sweden. If radionuclides would be released from the repository in the future, and transported from deep bedrock to the biosphere, there are several possible exposure pathways that could result in doses to humans. In SR-Site, many exposure pathways have been considered and resulting theoretical doses to humans are calculated.

Peat and wood can be used as fuel for heating and electricity production. They can, like any other biological material, contain radionuclides if these are present in the surrounding environment. When burning radioactive peat or wood, radionuclides maybe released into the air leading to a radiation dose to humans when exposed to the smoke. This exposure pathway was not included in the analysis of long-term repository safety (SR-Site) which constituted a part of SKB's license application for the repository.

In the review of the safety assessment SR-Site, the Swedish Radiation Safety Authority (SSM) asked for "[…] a justification for not including combustion of peat for energy production as an exposure pathway in SR-Site. In the previous preliminary safety assessment, this exposure pathway was assessed to be an important pathway by SKB (TR-99-14)" (translated from Swedish from SSM (2012)).The exposure via inhalation from peat burning was indeed considered in report TR-99-14 (Bergström et al. 1999) of the previous SKB safety assessment of long-term repository safety (SR-97). However, this assessment concluded that burning of peat was not an important pathway (see Bergström et al. 1999, p 79):

"Several terrestrial exposure pathways are considered in the peat bog module in similarity to the agricultural land module. In addition inhalation of gases from combustion of peat is included. This pathway, however, gives insignificant contributions to any exposure. Inhalation of dust consisting of resuspended particles is on the other hand a major exposure pathway for Zr-93, Sm-151, Ho-166m and actinides"

The intention of this report is to revisit and update the statement from Bergström et al. (1999) and assess the impact of combustion of biofuel on total estimated doses to humans, given a biosphere that has been contaminated by a radionuclide release from a final repository deep underground in Forsmark. Wood is added to the assessment because it is a common fuel type in Sweden (Section 1.1), and because wood combustion for energy production was not included as an exposure pathway in SR-Site. The models account for the exposure from contaminated air to a critical individual (a person located in the vicinity of the maximum obtained ground level air concentration). Although the assessments are done in the context of SR-Site, these methods could be used in other similar assessments.

The following sections present an overview of peat and wood availability in Sweden and their use for energy production (Section 1.1) and the assessment cases included in this report (Section 1.2).

1.1 Background

Approximately 64,000 km^2 of Sweden's total land area (408,000 km^2) is covered by peat land, i.e. a peat layer exceeding 30 cm in depth (Runefelt 2010). This accounts for approximately 15% of the total land area in Sweden (Berglund 2010). The peat lands are unevenly distributed throughout the country. The most extensive parts are in northern Sweden, for example in Jämtland, where they in some parts constitute up to 75% of the land area, while they constitute less than 10% of the land area in the southern part of Sweden (Runefelt 2010).

Peat and peatlands have historically been, and are still today, primarily used as farmlands, as organic fertilizer, substrate in horticulture, for stable bedding and for energy (electricity and heat) generation (Ihse 2010). The use of peat as a household fuel, i.e. combustion of peat for domestic energy purposes, has never been of much significance in Sweden (World Energy Council 2013, Chapter 6). Wood is more likely to be burnt and used as an energy source in Swedish households. To use wood as fuel typically takes less time and work than to use peat, and is probably therefore often preferred. Historically, extraction of peat has followed in the steps of deforestation and lack of wood (Liljegren 2010). Unlike wood biofuel, peat is not a renewable energy source. It can, however, not be characterised as a fossil fuel, and is hence often classified as an own fuel type, with characteristics somewhere in-between fossil fuels and biofuels (e.g. IPCC 2006).

The total energy input into the Swedish energy system is around 600 TWh annually (Statens energimyndighet 2013b). In 2012, peat corresponding to approximately 2.7 TWh was used for energy production in Sweden, which accounted for nearly 0.5% of the country's total energy supply (SCB 2013). The use of peat as an energy source declined with approximately 30% in Sweden in the last three years (2010–2012) (SCB 2013). Current public concerns and political incentives do not favour peat extraction and use as fuel. For example, peat is classified as a fossil fuel in the European Union emission trade system, which affects the competitiveness of peat as an energy source. In the Swedish energy sector, most of the peat is used to produce heat and the rest to produce electricity (SCB 2013). Around thirty of the larger thermal power stations in Sweden today use peat, mostly in combination with other fuel sources (e.g. household waste, biofuel and fossil fuel) (SCB 2013). The largest power plant in Sweden is Västerås thermal power station which in 2012 was co-fuelled with peat to produce electricity and heat corresponding to 720 GWh (Svensk Fjärrvärme n.d.). Another power plant using peat to produce energy is the Sandviken thermal power station, which has a total effect of about 140 MW and was co-fuelled with peat to produce electricity and heat corresponding to about 100 GWh in 2012 (Sandviken Energi 2013, Svensk Fjärrvärme n.d.). To use peat in heat power plants requires substantial quantities of peat. In addition, not all peat types are appropriate for fuel use due to low energy content and high ash and element content. A previous investigation of existing peatlands in Forsmark concluded that future use for fuel production was not likely as the peatland areas were too small, not thick enough, and the ash and sulphur contents were too high to satisfy the demands of the modern peat industry (Fredriksson 2004).

Productive forest lands, i.e. forest lands that can produce an average of 1 m^3 of timber/ ha and year, cover about 230,000 km^2 of the total land area in Sweden, a little more than 57% of the land (SLU 2013). Based on forest area per person, Sweden is one of the most forested countries in the world (Skogsstyrelsen 2013). Coniferous trees (mainly spruce and pine) make up 82% of Swedish forests, but the amount of deciduous trees have generally increased during the last decades (SLU 2013). Forests have the greatest prevalence in the northern parts of Sweden (in Northern Norrland forests make up 45% of the land area), but the largest timber volumes are found in the southern parts of the country (Skogsstyrelsen 2013). Good data on Swedish forests are available from the 1920s and the country's timber volume has increased substantially (by 95%) the last century, mainly due to a forest management oriented towards production and growth (SLU 2013). Certain forest lands are protected within e.g. nature reserves or national parks and may not be cut or otherwise affected. In Swedish forests that are not protected, the estimated volume of timber amounts to 3.0 billion m^3 standing volume (stem volume over bark from stump to tip) (Skogsstyrelsen 2013).

The wood from Swedish forests is primarily used in the wood industry (wood products, manufacture of pulp, paper, paperboard and related products) and in households as subsistence timber and fuelwood (Skogsstyrelsen 2013). Wood fuel is a renewable energy source and the largest Swedish biofuel resource. Biofuel corresponding to approximately 115 TWh was supplied to the Swedish energy sector in 2011, accounting for 19% of the total energy supply (Statens energimyndighet 2013b). Biofuels in Sweden are in descending order used in industries, for heat production and for electricity production (Skogsstyrelsen 2013).There are currently around 230,000 burning boilers in Swedish households. In addition, there are approximately 1.5 million registered local fireplaces, e.g. stoves and open fireplaces, which are generally used to a small extent for so-called comfort heating (Naturvårdsverket 2009). The use of wood, pellets, wood-chips and sawdust (bio-fuel) is the second most common heating method in Swedish households, accounting for 35% of their total energy use for heat and warm water (Statens energimyndighet 2013a). An equivalent of 12 TWh wood fuel was used in 2011 in Swedish households, of which most was firewood (8.9 TWh), followed by wood chips and sawdust (0.5 TWh),and pellets (2.6 TWh) (Skogsstyrelsen 2013). The most common heating method is electricity (Statens energimyndighet 2013a). The use of renewable energy sources in Sweden has increased with 15 percentage points during the last two decades, mainly due to an increased use of biofuels in the electricity and heating production, which is a part of Sweden's ambitions to use more renewable energy and to reduce greenhouse gas emissions (Statens energimyndighet 2013b).

1.2 Assessment cases

When wood or peat is burnt, radionuclides in the wood or peat are either vaporized as gas or contained in the ash with other non-organic material. One part of the ash, the fly ash, may enter the atmosphere through the chimneys together with smoke gases if not caught in particle filters, while the other part of the ash, the bottom ash, is left in the combustion apparatus (Ehdwall et al. 1985). Since peat has a low ash content (about 5%), radioactive material is concentrated in the peat ash with a concentration factor of about 20 compared to the activity concentration in the peat (Statens energiverk 1985, Ehdwall et al. 1985, Möre and Hubbard 2003). The ash content of wood (about 1%, Liss 2005) implies that radioactive elements are concentrated by a factor of about 100 in wood ash. The fly ash generally makes up about 75% of the total ash (Möre and Hubbard 2003), but the distribution of the two ash types and the distribution of radionuclides between them are dependent on the combustion technology used (Ericson 1985, Möre and Hubbard 2003). The amount of radioactivity that is lost to the atmosphere when contaminated fuel is combusted is also highly element-specific and many radionuclides are enriched in the finer fly ash rather than in the bottom ash (Hedvall and Erlandsson 1992). Elements such as carbon (C), iodine (I), radon (Rn) and chlorine (Cl) have been shown to be fully volatile when burnt (Amiro et al. 1996) and the isotopes Pb-210, Ag-110m, Cs-134 and Cs-137 have been observed to be highly concentrated to the fly ash compared to the bottom ash in peat-fired power plants (Hedvall and Erlandsson 1992). Due to regulatory requirements, power plants normally have installed technology for filtering fly ash and cleaning outgoing air, and the regulations are normally stricter for power plants with higher effects (Statens energiverk 1985). High effect power plants in the Nordic countries often have very efficient filters that remove over 99% of the particulates (Ericson 1985).

The radionuclides entering the atmosphere may lead to doses to humans by inhalation, external exposure from the contaminated air, consumption of contaminated food and external exposure from deposited activity on the ground. Exposure pathways related to the exposure to ash and ash products are also known (Möre and Hubbard 2003). This report consider the direct exposure to contaminated air.

The peat and wood that could possibly become contaminated from a future release from the planned repository for spent nuclear fuel is limited to the so called "discharge points" of deep groundwater in the future Forsmark area (SKB 2010). Discharge points are the end positions of modelled flow paths, from the repository to the ground surface, and are used to identify and delineate areas in the landscape that are most likely to be affected by a potential release of radionuclides from the repository. These geographical areas are referred to as biosphere objects and can be seen depicted in Figures 7-11 and 7-12 in report TR-10-09 (SKB 2010). In total, there are 17 biosphere objects of varying sizes and characteristics, and their identity numbers are 101, 105, 107, 108, 114, 116, 117, 118, 120, 123, 124, 125, 126, 136, 121_1, 121_2 and 121_3, respectively (SKB 2010). This report focuses mainly on the combustion of peat and wood found in the biosphere objects, i.e. radionuclide contaminated peat and wood, and subsequent releases to air and exposure to humans.

Two cases are considered in order to assess the combustion of peat or wood with resulting exposure of contaminated air to an individual :

1. Combustion of peat or wood for energy production in a power plant. The power plant is assumed to have an effect of 100 MW and a 100 m stack. The stack height for a power plant generally depends on the size of the facility, and the stack height assumed here is considered to approximate that of the Sandviken power plant, which has a stack height of 90 m (Sandviken Energi 2013). Calculations for a lower stack are also performed. Conservative assumptions that there is no filtration of contaminants from the outgoing air are made.
2. Combustion of peat and wood for heating in a household with release of smoke from a low chimney on the roof of the building.

2 Methodology

This section describes the models and methods that were used in this report to calculate the annual average discharge rates of radionuclides into air as a result of peat and wood combustion (Section 2.1), the activity concentrations in air resulting from the releases at a receptor location (Section 2.2) and the dose conversion factors resulting from the release (Section 2.3). The quantities were calculated for unit activity concentrations in peat or wood. The peat and wood that could potentially be available for energy production in SR-Site was evaluated (Section 2.4) and a comparison of dose factors with the LDFs from SR-Site was performed (Section 2.5). The methodology is illustrated in Figure 2-1.

2.1 Calculation of annual average discharge rate

The annual average discharge rate (Bq/s) resulting from combustion of peat or wood was calculated by multiplying the activity concentrations (Bq/kgDW) in peat and wood respectively by the fuel usage rate (kgDW/s) and the fraction of radionuclides released into the air during combustion:

$$Q = C_p \cdot F_{rate} \cdot F_{released} \qquad \text{2-1}$$

where

Q = Annual average discharge rate [Bq/s].

C_p = Activity concentration in peat or wood [Bq/kgDW].

F_{rate} = Fuel usage rate. The amount of contaminated fuel burnt per second [kgDW/s].

$F_{released}$ = Fraction of radionuclides released into air following combustion [unitless].

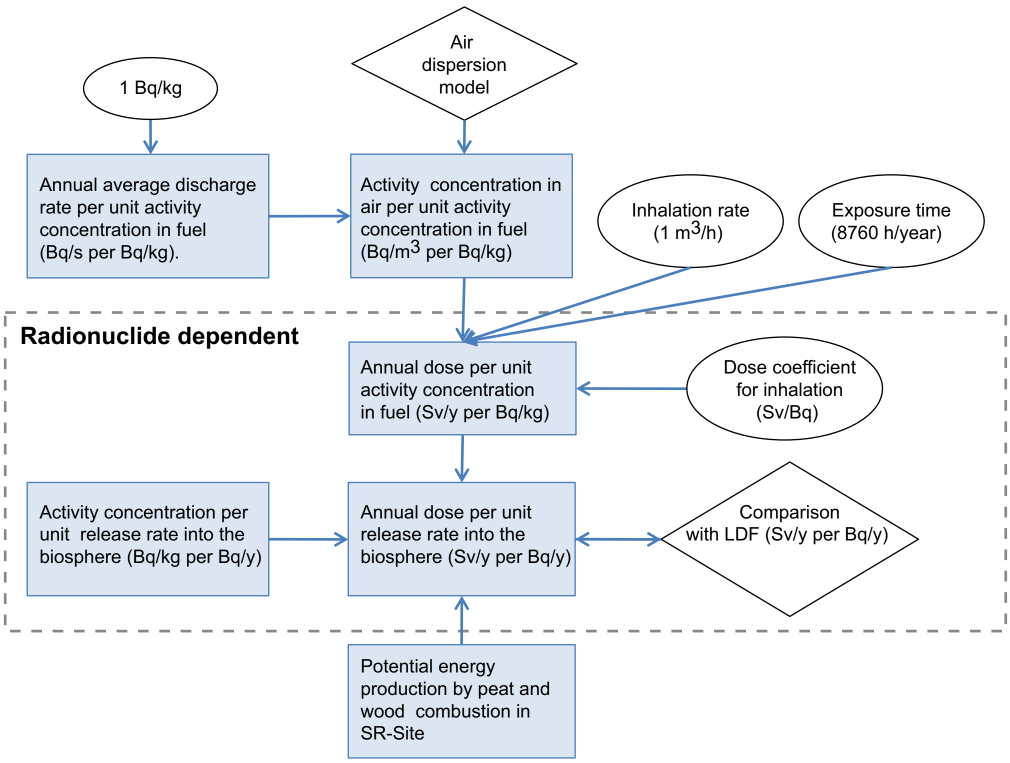

Figure 2-1. *Conceptual model of the methodology used in this report to calculate the dose conversion factors for peat and wood burning. Rectangles illustrate values that were calculated in this report. Ellipses illustrate constants used in the calculations and diamond shapes illustrate methods or procedures that were used in the report.*

The fuel usage rate (F_{rate}) was calculated by dividing the energy consumption of a household or the energy produced by a power plant with the energy content of used fuel (peat or wood):

$$F_{rate} = E/EC \tag{2-2}$$

where

E = Energy consumption of a household or energy production of a power plant [kWh/s].

EC= Energy content of fuel (peat or wood) [kWh/kg].

It was assumed that the household is heated using exclusively peat or wood and that the energy needed to heat the house is 20,000 kWh/y. The assumed energy consumption is slightly larger than the average energy used for heating one- and two dwelling buildings (excluding household electricity) in Sweden 2012 (16,800 kWh, Statens energimyndighet 2013a). The energy produced by the peat fuelled power plant was assumed to be 876 GWh/y, which corresponds to the energy that can be produced by a 100 MW power plant.

The fraction of radionuclides released to the air after combustion, ($F_{released}$) was calculated by multiplying the fraction of radionuclides assumed to be contained in fly ash or gas by the fraction of radionuclides that are not filtered:

$$F_{released} = F_f \cdot \left(1 - F_{eff}\right) \tag{2-3}$$

where

F_f = Fraction of radionuclides contained in fly ash or gas [unitless].

F_{eff} = Efficiency of filter. Fraction of radionuclides in fly ash and gas that are filtered [unitless].

It was conservatively assumed that all activity is released as fly ash or gas (F_f = 1) after combustion, i.e. that no activity is left as bottom ash. It was further assumed that no activity is filtered (F_{eff} = 0). This assumption implies that the total amount of radionuclides contained in the burnt fuel is released to the air, thus not accounting for e.g. losses in filtration systems, deposition in bottom ashes or indoor surfaces.

The calculation of the annual average discharge rate was performed for unit activity concentrations in peat and wood (Bq/s per Bq/kgDW). The parameter values used in the calculations are shown in Table 2-1.

Table 2-1. Parameters used to calculate the annual average discharge rate per unit activity concentration in fuel (Bq/s per Bq/kgDW) from a 100 MW power plant (with a maximum energy production of 876 GWh/y) and a household (with an energy consumption of 20,000 kWh/y).

Parameter	Notation	Value	Unit	Reference
Energy production, power plant	E_{pp}	$867 \cdot 10^6$	kWh/y	Assumed value
Energy consumption	$E_{household}$	20,000	kWh/y	Assumed value
Fuel energy content, peat	EC_{peat}	5.8	kWh/kgDW	Statens energiverk 1985
Fuel energy content, wood	EC_{wood}	5.0	kWh/kgDW	Liss 2005[1)]
Fuel usage rate, power plant, peat	$FR_{pp,peat}$	4.8	kgDW/s	Calculated value
Fuel usage rate power plant, wood	$FR_{pp,wood}$	5.5	kgDW/s	Calculated value
Fuel usage rate, household, peat	$FR_{household,peat}$	1.1E-04	kgDW/s	Calculated value
Fuel usage rate, household, wood	$FR_{household,wood}$	1.3E-04	kgDW/s	Calculated value
Activity concentration in fuel	C_p	1	Bq/kgDW	Assumed value
Fraction of radionuclides contained in fly ash or gas	F_f	1	–	Assumed value
Efficiency of filter	F_{eff}	0	–	Assumed value

[1)] The energy content of wood assumes that the wood is burnt in moist condition. The energy content of wood with a 29.4% moisture content is 3.56 kWh/kg (spruce of high density, Liss 2005). The energy that could be produced by burning is 3.56/(1–0.294) kWh/kgDW.

2.2 Calculation of air activity concentrations

When radionuclides are released into the air, they undergo downwind transport and mixing processes. Estimations of radionuclide air concentrations at a downwind location of a receptor (i.e. an exposed individual) are often performed using mathematical models based on the Gaussian Plume theory (Till and Grogan 2008, IAEA 2001). These models estimate the dispersion of radionuclides given various parameters related to geographic and atmospheric conditions. In this report, the activity concentrations in air resulting from dispersion were calculated using models from the IAEA Safety Reports Series No. 19 (IAEA 2001). These models are appropriate for continuous or long-term intermittent releases with a receptor within a distance of a few kilometres from the source. The air concentration at a given distance from the source depends on wind direction, wind speed and the estimated dispersion of contaminants in air. The degree of dispersion depends on the height of the release and the horizontal distance from the release source to the receptor in the downwind direction.

The wind parameter values that were used to calculate activity concentrations are shown in Table 2-2. The wind was assumed to blow towards the receptor 25% of the time. This is slightly higher than the value for the dominant wind direction observed at Forsmark, which is about 22% for the 30-degree sector that has the dominating wind direction (Johansson and Öhman 2008). The assumed wind speed, however, approximately agrees with the average wind speed observed at the Forsmark station "Högmasten" at 10 m height during 2003–2007 (Johansson and Öhman 2008).

Table 2-2. Wind parameters used to calculate the ground level air concentration for the household and power plant.

Parameter	Notation	Value	Unit	Reference
The fraction of time during a year that the wind blows towards the receptor of interest	P_p	0.25	–	Johansson, Öhman 2008
Geometric mean of the wind speed at the height of release representative of one year	μ_a	1.7	m/s	Johansson, Öhman 2008

2.2.1 Calculation of air activity concentrations following a power plant discharge

The following section describes the methods that were used to calculate the level air activity concentration from the release of peat- or wood combustion in a power plant.

To calculate the activity concentration in air at a receptor location following a release from a power plant it was assumed that the dispersion of the plume is undisturbed by surrounding buildings. Losses from the plume due to deposition and radioactive decay, during the passage of the plume from source to receptor were conservatively neglected. The ground level air activity concentration at a specific downwind distance from the power plant release was calculated as (IAEA 2001, p 18):

$$C_a(x) = \frac{P_p \cdot F(x) \cdot Q}{\mu_a} \qquad \text{2-4}$$

where

$C_a(x)$ = Ground level air concentration at the specified downwind distance x [Bq/m^3].

P_p = Fraction of time during the year that the wind blows towards the receptor [unitless].

$F(x)$ = Gaussian diffusion factor appropriate for the height of release H (m) and the specified downwind distance x [m^{-2}].

Q = Annual average discharge rate [Bq/s].

μ_a = Geometric mean of the wind speed at the height of release representative of one year [m/s].

x = Downwind distance from the release to the receptor [m].

The diffusion factor (F), averaged over a 30-degree sector was calculated as (IAEA 2001, p 18):

$$F(x) = \frac{12}{\sqrt{2\pi^3}} \times \frac{\exp\left[-\left(\frac{H^2}{2\sigma_z^2(x)}\right)\right]}{x\sigma_z(x)} \qquad \text{2-5}$$

where $\sigma_z\ (x)$ is the vertical diffusion (m) and H is the height of the release (m). The diffusion factor was calculated assuming 12 wind direction sectors (IAEA 2001). Two different release heights were assumed: 100 m and 50 m. The assumed wind speed (Table 2-2) was considered to be conservative, as the wind speed at release heights of 50 and 100 m is expected to be stronger.

For a release height of 50 m and neutral atmospheric conditions the vertical diffusion was calculated as (IAEA 2001, p 19):

$$\sigma_z(x) = 0.215x^{0.885} \qquad \text{2-6}$$

and for a 100 m release height it was calculated as (IAEA 2001, p 19):

$$\sigma_z(x) = 0.265x^{0.818} \qquad \text{2-7}$$

2.2.2 Calculation of air activity concentrations following a household discharge

For a release from a household following peat and wood combustion, it was assumed that the receptor stays within 0–200 m from the house during the whole exposure time. The model that was used to calculate the activity concentrations in air accounts for building cavity- or wake effects which arise when the release height is low relative the height of the surrounding buildings (IAEA 2001). The cavity and wake zones are depicted in Figure 2-2. The cavity zone is the relatively isolated space closest to the building wall, which exhibits a larger degree of airflow stagnation than further away from the house (in the wake zone). The boundary between the cavity zone and the wake zone depends on the area of the building wall closest to the receptor. Losses of radionuclides, due to deposition and radioactive decay processes, during the passage of the plume from the source to the receptor location, were conservatively neglected.

When the release height is less than 2.5 times the height of the surrounding buildings and the downwind distance to the receptor is less than $2.5\sqrt{A_B}$, where A_B is the area of the building wall closest to the receptor, the air dispersion can be considered to be inside the cavity zone. Air activity concentrations were in these cases calculated as in Section 3.6 in IAEA (2001):

$$C_a = \frac{P_p Q}{\pi u_a H_B K} \qquad \text{2-8}$$

where

C_a = Ground level air concentration in the cavity zone [Bq/m^3].

P_p = Fraction of time during the year that the wind blows towards the receptor [unitless].

Q = Annual average discharge rate [Bq/s].

μ_a = Geometric mean of the wind speed at the height of release representative of one year [m/s].

H_B = Height of the building wall closest to the receptor [m].

K = Empirical constant value [m].

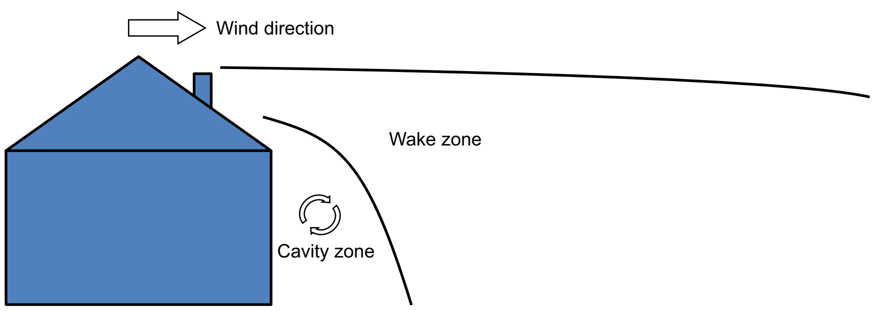

Figure 2-2. *Illustration of the cavity and wake zone in the proximity of a building.*

The parameter values that were used to calculate the air concentration in the cavity zone for the household are shown in Table 2-3. For the constant K, the empirical value of 1 m given in IAEA (2001) was utilized. The difference between the assumed wind speed (Table 2-2) and the wind speed at the lower release height from a household was considered to be negligible. Because no reference house dimensions were available, calculations were performed for two different heights of the building and two different areas of the building wall closest to the receptor. The assumed heights represent a one-story building (3 m and 5 m) and relatively large values were selected for the wall areas. The air concentrations were calculated for the four combinations of building height and wall area.

Table 2-3. Parameters used to calculate the ground level air activity concentration in the cavity and wake zone for a household release. Two different heights (3 m and 5 m) and two different areas (30 m and 60 m) of the wall closest to the receptor were used.

Parameter	Notation	Value	Unit	Reference
Building height 1	H_b	3	m	Assumed value
Building height 2	H_b	5	m	Assumed value
Building wall area 1	A_B	30	m^2	Assumed value
Building wall area 2	A_B	60	m^2	Assumed value
Empirical constant value	K	1	m	IAEA 2001

When the release height is less than or equals 2.5 times the height of the surrounding buildings and the downwind distance from the release is greater than $2.5\sqrt{A_B}$, where A_B is the area of the building wall closest to the receptor, the air dispersion is considered to be inside the wake zone (IAEA 2001). Air activity concentrations were in these cases calculated by conservatively assuming a release at ground level as in Section 3.5 in IAEA (2001):

$$C_a(x) = \frac{P_p B(x) Q}{u_a} \qquad \text{2-9}$$

where

$C_a(x)$ = Ground level air concentration at a specified downwind distance x [Bq/m^3].

P_p = Fraction of time during the year that the wind blows towards the receptor [unitless].

Q = Annual average discharge rate [Bq/s].

μ_a = Geometric mean of the wind speed at the height of release representative of one year [m/s].

$B(x)$ = Diffusion factor at downwind distance x [m^{-2}].

x = Downwind distance from the release to the receptor [m].

The annual average discharge rate (Q) was calculated using Equation 2-1 and the parameters in Table 2-1. The diffusion factor was calculated by:

$$B(x) = \frac{12}{\sqrt{2\pi^3}} \times \frac{1}{x\Sigma_z(x)} \qquad \text{2-10}$$

where

$$\Sigma_z(x) = \left(\sigma_z^2(x) + \frac{A_B}{\pi}\right)^{0.5} \qquad \text{2-11}$$

and A_B is the area of the wall closest to the receptor (m^2) and σ_z (x) is the vertical diffusion (m), which for neutral atmospheric conditions was calculated by (IAEA 2001):

$$\sigma_z(x) = 0.06 \cdot x/\sqrt{1 + 0.0015 \cdot x} \qquad \text{2-12}$$

The diffusion factor (Equation 2-10) was calculated assuming 12 wind direction sectors (IAEA 2001).

2.3 Calculation of dose conversion factors

The annual dose resulting from exposure to contaminated air resulting from combustion of peat or wood was calculated as:

$$DF_{inh} = C_a \cdot R_{inh} \cdot ET \cdot DCC_{inh} \qquad \text{2-13}$$

where

DF_{inh} = Annual dose from inhalation [Sv/y].

C_a = Activity concentration in air [Bq/m^3].

R_{inh} = Inhalation rate [m^3/h].

ET = Exposure time [h/y].

DCC_{inh} = Dose coefficient for inhalation of contaminated air [Sv/Bq].

The parameter values used in the calculation of annual doses are summarized in Table 2-4. The dose coefficients for inhalation are shown in Table 2-5. The dose resulting from external exposure by immersion in air was considered negligible under the assumed inhalation rate and the dose coefficients for immersion in Eckerman and Leggett (1996) and only the dose resulting from inhalation of contaminated air was considered.

Two sets of dose conversion factors were calculated: (1) the annual dose per unit activity concentration in peat or wood (Sv/y per Bq/kgDW) was calculated using the parameter values in Table 2-4, and (2) the annual dose per unit activity concentration in fuel per fuel usage rate (Sv/y per Bq/kgDW per kgDW/s) was derived by dividing the annual dose per unit activity concentration in peat with the fuel usage rate of peat burning from Table 2-1.

Table 2-4. Parameters used to calculate the annual dose per unit activity concentration in peat or wood (Sv/y per Bq/kgDW) as described in Section 2.2.

Parameter	Notation	Value	Unit	Reference
Activity concentration in air per unit activity concentration in peat or wood	C_a	Table 3-1 and Table 3-2	Bq/m^3 per Bq/kgDW	Calculated
Inhalation rate	R_{inh}	1	m^3/h	Nordén et al. 2010
Exposure time	ET	8,760	h/y	Assumed value
Dose coefficient for inhalation	DCC_{inh}	Table 2-5	Sv/Bq	Eckerman and Leggett 1996

Table 2-5. Effective dose coefficients for inhalation of air (Sv/Bq) (Eckerman and Leggett 1996).

Radionuclide	DCC_{inh}	Radionuclide	DCC_{inh}	Radionuclide	DCC_{inh}	Radionuclide	DCC_{inh}
Ac-227	5.51E-04	Cs-134	2.00E-08	Np-237	5.00E-05	Sm-151	4.00E-09
Ag-108m	3.70E-08	Cs-135	8.60E-09	Pa-231	1.40E-04	Sn-126	2.84E-08
Am-241	9.60E-05	Cs-137	3.90E-08	Pb-210	5.60E-06	Sr-90	1.62E-07
Am-242m	9.20E-05	Eu-152	4.20E-08	Pd-107	5.90E-10	Tc-99	1.30E-08
Am-243	9.60E-05	Eu-154	5.30E-08	Pm-147	5.00E-09	Th-228	4.36E-05
Ba-133	1.00E-08	Eu-155	6.90E-09	Po-210	4.30E-06	Th-229	2.41E-04
Be-10	3.50E-08	Fe-55	7.70E-10	Pu-238	1.10E-04	Th-230	1.00E-04
C-14	6.20E-12	Gd-152	1.90E-05	Pu-239	1.20E-04	Th-232	1.10E-04
Ca-41	1.80E-10	H-3	2.60E-10	Pu-240	1.20E-04	U-232	3.70E-05
Cd-113m	1.10E-07	Ho-166m	1.20E-07	Pu-241	2.30E-06	U-233	9.60E-06
Cl-36	7.30E-09	I-129	3.60E-08	Pu-242	1.10E-04	U-234	9.40E-06
Cm-242	5.90E-06	In-115	3.90E-07	Ra-226	9.51E-06	U-235	8.50E-06
Cm-243	6.90E-05	Mo-93	2.30E-09	Ra-228	1.60E-05	U-236	8.70E-06
Cm-244	5.70E-05	Nb-93m	1.80E-09	Ru-106	6.60E-08	U-238	8.01E-06
Cm-245	9.90E-05	Nb-94	4.90E-08	Sb-125	1.30E-08	Zr-93	2.50E-08
Cm-246	9.80E-05	Ni-59	4.40E-10	Se-79	6.80E-09		
Co-60	3.10E-08	Ni-63	1.30E-09	Sm-147	9.60E-06		

2.4 Calculation of potential energy production by peat and wood combustion

In order to calculate the potential energy production from peat or wood, the amount of peat or wood that could theoretically be harvested in the biosphere objects was calculated assuming a long-term sustainable harvest. In SR-Site, human exposure was assessed as the average exposure over the lifetime of an individual living in the Forsmark area and annual exposure during the lifetime of the individual was estimated by averaging predicted lifetime doses over a period of 50 years (SKB 2011).The size of the biosphere objects vary over time and for the purpose of estimating the availability of peat or wood, it was assumed that the terrestrial area of each biosphere object has reached its maximum size.

The maximum amount of peat available in a biosphere object was calculated by multiplying the maximum terrestrial volume of a biosphere object (m^3) with the density of peat ($kgDW/m^3$):

$$Peat_{available} = V_{BioObj} \cdot \rho_p \qquad \text{2-14}$$

where

$Peat_{available}$ = Maximum of available peat in a biosphere object [kgDW].

V_{BioObj} = Maximum terrestrial volume of a biosphere object [m^3].

ρ_p = Peat density [$kgDW/m^3$].

The peat density (ρ_p) was assumed to be 86 kg DW/m^3 (Löfgren 2010, Chapter 13). The long-term harvest of peat (kgDW/y) was calculated by dividing the calculated maximum amount of peat by 50 years.

The maximum sustainable amount of wood that could be harvested per year was calculated by multiplying the maximum terrestrial area of each biosphere object (m^2) with the sustainable harvest of wood per unit area and year ($kgDW/m^2/y$):

$$Wood_{harvest} = A_{BioObj} \cdot Harvest_w \qquad \text{2-15}$$

where

$Wood_{harvest}$ = Maximum amount of sustainable wood harvest in a biosphere object [kgDW/y].

A_{BioObj} = Maximum terrestrial area of a biosphere object [m^2].

$Harvest_W$ = Sustainable wood harvest per unit area and year [$kgDW/m^2/y$].

The sustainable wood harvest ($Harvest_W$) was based on the net primary production of stems and branches from a Norway spruce wetland in Forsmark, which gives a long-term sustainable harvest of 0.225 kg $DW/m^2/y$, (SS1 Löfgren 2010, Chapter 6).

The potential energy production was calculated by multiplying the harvest of peat and wood by their respective energy content (Table 2-1).

The number of households that could sustain their fuel consumption by burning peat or wood was calculated by dividing the estimated potential energy production in each biosphere object by the assumed household energy consumption. If the contaminated peat and wood in each biosphere object is co-fuelled with non-contaminated fuel in the power plant, the contaminants in the peat or wood are diluted. A dilution factor (kgDW contaminated fuel / kgDW burnt fuel), based on the available peat or wood and the total fuel needed to sustain the 100 MW power plant was therefore calculated. The dilution factor for wood was calculated as:

$$D_{wood} = \min(1, \frac{Wood_{harvest} \cdot EC_{wood}}{E_{pp}}) \qquad \text{2-16}$$

and the dilution factor for peat was calculated as:

$$D_{peat} = \min(1, \frac{Peat_{available} \cdot EC_{peat}/50}{E_{pp}}) \qquad \text{2-17}$$

where it was assumed that the available peat is burnt during 50 years. The values for the energy content of peat (EC_{peat}), the energy content of wood (EC_{wood}) and the energy production of the power plant (E_{pp}) are shown in Table 2-1.

2.5 Comparison with LDFs from SR-site

In SR-Site, Landscape Dose Conversion Factors (LDFs) were utilised to estimate doses to humans. LDFs are estimates of radionuclide specific annual effective doses to a receptor based on a constant unit release rate (1 Bq/y) of radionuclides to specific biosphere objects. LDFs are in the unit Sv/y per Bq/y and are multiplied with modelled radionuclide release rates in order to estimate annual doses to humans based on the release rates (Avila et al. 2010). Annual doses per unit release rate to the biosphere, resulting from burning peat or wood in each of the biosphere objects included in the SR-Site radionuclide transport model for the biosphere (Avila et al. 2010), were derived. These doses were then compared with baseline LDFs calculated for the interglacial scenario presented in Avila et al. (2010).

All biosphere objects in SR-site can sustain the fuel consumption of at least one household (Table 3-3 and Table 3-4). Annual doses for the household were therefore calculated assuming that all peat used by the household is contaminated. For the 100 MW power plant, it was assumed that the contaminated peat or wood is co-fuelled with non-contaminated fuel and that the contaminants in the fuel therefore are diluted. For each biosphere object, the annual dose per unit release rate into the biosphere (Sv/y per Bq/y) was calculated by multiplying the annual dose per unit activity concentration in fuel (Sv/y per Bq/kgDW) with the activity concentration per unit release rate into the biosphere in peat or wood (Bq/kgDW per Bq/y) in the biosphere object and a dilution factor:

$$DF_{peat,i} = DF_{inh} \cdot C_{TerRegUp,i} \cdot D$$

2-18

$$DF_{wood,i} = DF_{inh} \cdot C_{TerPrim,i} \cdot CC_{wood} \cdot D$$

where

$DF_{peat,i}$ = Annual dose per unit release rate into the biosphere object *i* for peat [Sv/y per Bq/y].

$DF_{wood,i}$ = Annual dose per unit release rate into the biosphere object *i* for wood [Sv/y per Bq/y].

DF_{inh} = Annual dose by inhalation per unit activity concentration in fuel [Sv/y per Bq/kgDW].

$C_{TerRegUp,i}$ = Activity concentration in the terrestrial upper regolith compartment in biosphere object *i* per unit release rate [per Bq/y].

$C_{TerPrim,i}$ = Activity concentration in terrestrial primary producers in biosphere object *i* per unit release rate [per Bq/y].

CC_{wood} = Carbon content of wood [kgC/kgDW].

D = Dilution of contaminants in the fuel [kgDW/kgDW].

The annual dose by inhalation per unit activity concentration in fuel (Sv/y per Bq/kgDW) from exposure to contaminated air (*DF*) is shown in Section 3.3. The values of $C_{TerRegUp,i}$ and $C_{TerPrim,i}$ were assumed to be the maximum values over time in object *i*. The carbon content of wood (CC_{wood}) was assumed to be 0.48 kC/kgDW (Norway spruce, Löfgren 2010, Chapter 6). The dilution factor was set to 1 for the household (i.e. all fuel needed to sustain the 20,000 kWh/y was assumed to be contaminated). The dilution factors for the power plant depend on the amount of contaminated peat or wood available in each of the biosphere objects and are shown in Table 3-3 for peat and Table 3-4 for wood.

The annual dose per unit release rate into the biosphere was calculated according to Equation 2-18 for peat and wood for the biosphere objects and radionuclides for which LDF's were presented in Avila et al. (2010). The maximum of the calculated dose factors was then calculated as:

$$DF_{peat,max} = \max_{i} DF_{peat,i}$$

2-19

$$DF_{wood,max} = \max_{i} DF_{wood,i}$$

3 Results

This section presents the calculated dose conversion factors for peat and wood burning. Intermediate results of the annual average discharge rate, the air activity concentrations and the potential energy production of peat and wood in the biosphere object are also presented.

3.1 Annual average discharge rate

3.1.1 Annual average discharge rate from a power plant

The annual average discharge rate of radionuclides resulting from burning peat or wood in power plants was calculated as described in Section 2.1, using the parameters in Table 2-1. The calculated discharge rate from the power plant is 4.8 Bq/s per Bq/kgDW in the case of peat burning, and the corresponding discharge rate in the case of wood combustion is 5.5 Bq/s per Bq/kgDW. The annual average discharge rate is larger in wood than in peat because of the higher energy content in peat compared to wood (Table 2-1).

3.1.2 Annual average discharge rate from a household

The annual average discharge rate of radionuclides resulting from burning peat or wood in households was calculated as described in Section 2.1, using the parameters in Table 2-1. The calculated discharge rate from the household is 1.1E-04 Bq/s per Bq/kgDW in the case of peat burning, and the corresponding discharge rate in the case of wood combustion is 1.3E-04. The annual average discharge rate is larger in wood than in peat because of the higher energy content in peat compared to wood (Table 2-1).

3.2 Air activity concentrations

3.2.1 Air activity concentrations following a power plant discharge

The activity concentration at ground level for the power plant was calculated as described in Section 2.2.1 with the annual average discharge rate presented in Section 3.1.1. The air activity concentration at ground level as a function of the downwind distance from the release is depicted in Figure 3-1 for the peat fuelled power plant with a 50 m and a 100 m stack. The figure shows that the ground level air concentration reaches its maximum at a certain downwind distance from the release

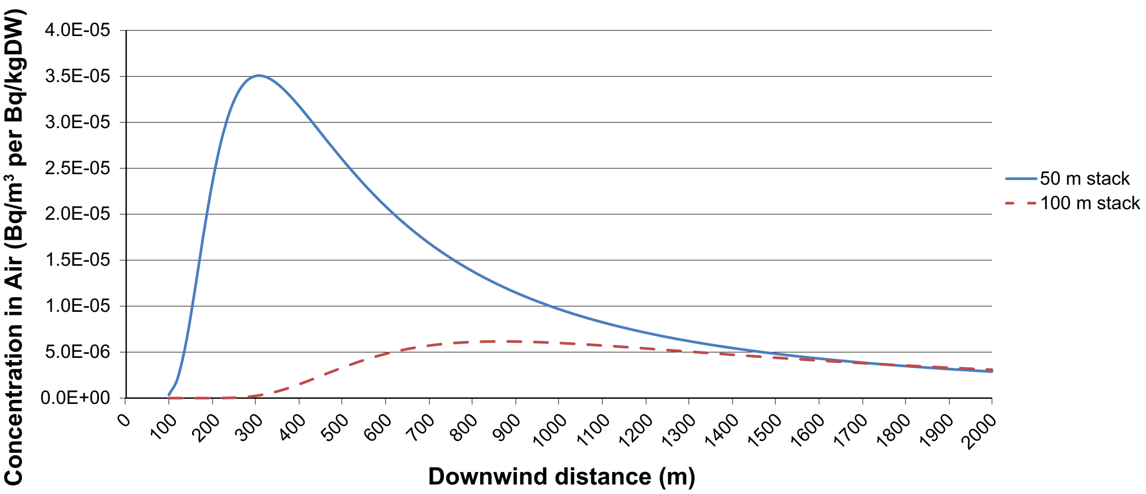

Figure 3-1. *Ground level activity concentrations in air per unit activity concentration in peat (Bq/m³ per Bq/kgDW) for the power plant as a function of downwind distance from the release.*

and then decreases further away from the release (the concentrations resulting from wood burning are directly proportional to the concentrations from peat burning and are not shown in the figure). The maximum activity concentrations (for both peat- and wood burning) are found at approximately 300 m downwind the 50 m high stack and approximately 900 m downwind for the 100 m high stack. The maximum activity concentrations in air per unit activity concentrations in fuel are shown in Table 3-1.

Table 3-1. Ground level activity concentrations in air per unit activity concentration in peat or wood (Bq/m^3 per Bq/kgDW) for the power plant. The concentrations were calculated for downwind distances 300 m downwind for the 50 m stack and at 900 m downwind for the 100 m stack.

Fuel type	Stack height (m)	Downwind distance (m)	Air activity concentration (Bq/m^3 per Bq/kgDW)
Peat	50	300	3.5E-05
	100	900	6.1E-06
Wood	50	300	4.0E-05
	100	900	7.0E-06

3.2.2 Air activity concentrations following a household discharge

The activity concentration at ground level for the household was calculated as described in Section 2.2.2 with the annual average discharge rate presented in Section 3.1.2. The air activity concentration at ground level as a function of the downwind distance from the release is depicted in Figure 3-2 for the household where peat is burnt for heat. The activity concentrations in air were calculated for two different areas (30 m^2 and 60 m^2) and two different heights (3 m and 5 m) of the wall of the house that is closest to the receptor. The activity concentrations closest to the building (in the cavity zone) are higher than further away from the house (Figure 3-2) and these elevated concentrations extend further downwind for the larger wall area (the concentrations resulting from wood burning are directly proportional to the concentrations from peat burning and are not shown in the figure). The air activity concentrations in the cavity zone and as averages over downwind distances 0–200 m for the different house dimensions are shown in Table 3-2.

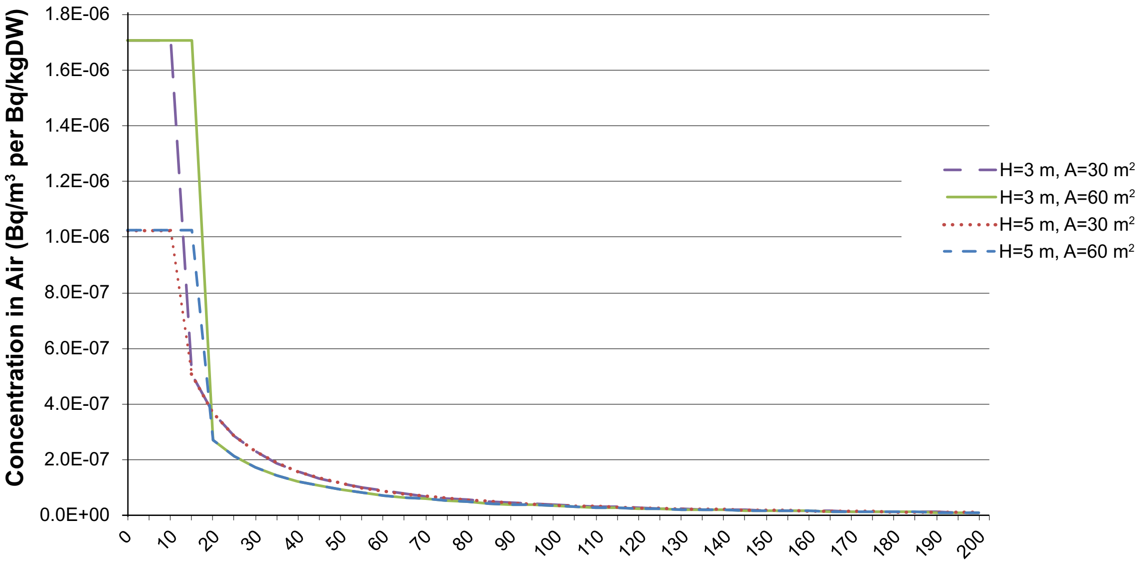

Figure 3-2. Ground level activity concentrations in air per unit activity concentration in peat (Bq/m^3 per Bq/kgDW) for the household as a function of downwind distance from the release. The size of the cavity zone with elevated air concentrations depends on height of the release (H_B) and the area (A_B) of the wall closest to the receptor.

Table 3-2. Ground level activity concentrations in air per unit activity concentration in peat or wood (Bq/m^3 per Bq/kgDW) for the household calculated in the cavity zone and as an average over downwind distances 0–200 m.

Fuel type	Building dimensions		Activity concentrations in air (Bq/m^3 per Bq/kgDW)	
	Height (m)	Wall area (m^2)	Cavity zone	Average 0–200 m
Peat	3	30	1.7E-06	2.0E-07
	3	60	1.7E-06	2.2E-07
	5	30	1.0E-06	1.5E-07
	5	60	1.0E-06	1.5E-07
Wood	3	30	2.0E-06	2.3E-07
	3	60	2.0E-06	2.5E-07
	5	30	1.2E-06	1.7E-07
	5	60	1.2E-06	1.7E-07

3.3 Dose conversion factors

3.3.1 Dose conversion factors for the power plant case

The annual dose for exposure to contaminated air following a release from a power plant were calculated as described in Section 2.3 for unit activity concentration in fuel (Sv/y per Bq/kgDW) and are shown in Table A-1. The doses were calculated for an individual located where the maximum air concentrations were obtained (300 m for the 50 m stack and at 900 m for the 100 m stack). Dose conversion factors per unit activity concentration in fuel per fuel usage rate were also calculated (Sv/y per Bq/kgDW per kgDW/s) and are shown in Table A-2.

3.3.2 Dose conversion factors for the household case

The annual dose for exposure to the contaminated air following a release from a household were calculated as described in Section 2.3 for unit activity concentration in fuel (Sv/y per Bq/kgDW) and are shown in Table A-3. The doses were calculated for (1) an individual staying solely in the cavity zone and (2) an individual moving uniformly within 0–200 m downwind from the release. Dose conversion factors per unit activity concentration in fuel per fuel usage rate (Sv/y per Bq/kgDW per kgDW/s) were also calculated and are shown in Table A-4.

3.4 Potential energy production by peat and wood combustion

Table 3-3 shows the terrestrial volumes of peat in the biosphere objects and the estimated maximum amount of peat that could be harvested in the considered biosphere objects. It also shows the yearly energy production that could result from combustion of the peat and the number of households that could sustain their fuel consumption from this combustion (assuming the peat is burnt during a 50 year period). It was assumed that the terrestrial area of each biosphere object has reached its maximum size over time and thus development of future peatlands and forests is accounted for. The amount of available peat that could be harvested is thought to be overestimated since the mire is believed to be used mainly for agriculture and not energy production.

Table 3-4 shows the terrestrial areas of wood in the biosphere objects and the estimated maximum amount of wood that could be harvested per year, assuming a long-term sustainable harvest. The table also shows the yearly energy production that could result from combustion of the wood in each biosphere object and the number of households that could sustain their fuel consumption from this combustion. It is however considered likely that in the area of a basin (i.e. the sub-catchment), the forest that will be utilized is outside the mire object and that the mire is used mainly for agriculture. Thus the contamination of wood harvested outside the object will be lower, although the production of wood there will be larger.

The three biosphere objects 121_3, 124 and 125 have the largest total activity concentration of radionuclides. The estimated amount of peat in these objects is however low (corresponding roughly to 1% of the total amount of peat or enough to produce 1.7 GWh/y of energy for 50 years). The wood in these objects corresponds roughly to 2% of the total amount of wood or 0.3 GWh/y.

Table 3-3. Estimated maximum amount of peat that could theoretically be available in the biosphere objects and corresponding potential energy production from combustion of the peat (assuming that the peat is burnt during a 50 year period). The number of households that could sustain their energy need from this energy production as well as the dilution (kgDW contaminated peat fuel / kgDW burnt peat fuel) of the contaminated peat if co-fuelled with non-contaminated fuel in the 100 MW power plant.

Biosphere object	Volume (10^4 m^3)	Available (10^4 kgDW)	Energy production (MWh/y)	Households	Dilution (kgDW/kgDW)
101	6.9	595	690	34	7.9E-04
105	154.3	13,272	15,396	770	1.8E-02
107	186.1	16,003	18,563	928	2.1E-02
108	219.3	18,863	21,881	1,094	2.5E-02
114	377.0	32,423	37,611	1,881	4.3E-02
116	188.8	16,234	18,832	942	2.1E-02
117	284.8	24,492	28,411	1,421	3.2E-02
118	37.1	3,193	3,704	185	4.2E-03
120	35.2	3,030	3,515	176	4.0E-03
121_1	17.5	1,504	1,744	87	2.0E-03
121_2	2.5	213	247	12	2.8E-04
121_3	5.7	491	569	28	6.5E-04
123	34.9	3,000	3,480	174	4.0E-03
124	7.1	609	707	35	8.1E-04
125	4.7	402	467	23	5.3E-04
126	69.0	5,936	6,885	344	7.9E-03
136	47.8	4,114	4,772	239	5.4E-03
Total	**1,679**	**144,374**	**167,473**	**8,374**	

Table 3-4. Estimated maximum amount of wood that theoretically could be harvested per year (kgDW/y) in the biosphere objects (assuming a sustainable harvest) and corresponding potential energy production from combustion of the wood. The number of households that could sustain their energy need from this energy production as well as the dilution (kgDW contaminated wood fuel / kgDW burnt wood fuel) of the contaminated wood if co-fuelled with non-contaminated fuel in the 100 MW power plant.

Biosphere object	Area (10^4 m^2)	Harvest (10^4 kgDW/y)	Energy production (MWh/y)	Households	Dilution (kgDW/kgDW)
101	18.0	4.0	204	10	2.3E-04
105	95.8	21.5	1,087	54	1.2E-03
107	136.1	30.6	1,545	77	1.8E-03
108	138.6	31.2	1,573	79	1.8E-03
114	215.4	48.5	2,445	122	2.8E-03
116	155.5	35.0	1,765	88	2.0E-03
117	175.9	39.6	1,997	100	2.3E-03
118	35.3	8.0	401	20	4.6E-04
120	29.3	6.6	332	17	3.8E-04
121_1	22.2	5.0	252	13	2.9E-04
121_2	3.8	0.9	43	2	4.9E-05
121_3	8.2	1.8	93	5	1.1E-04
123	40.7	9.2	462	23	5.3E-04
124	8.3	1.9	95	5	1.1E-04
125	7.6	1.7	87	4	9.9E-05
126	50.4	11.3	572	29	6.5E-04
136	60.6	13.6	688	34	7.8E-04
Total	**1,202**	**270.4**	**13,641**	**682**	

3.5 Comparison with LDFs from SR-site

The annual dose per unit release rate into each biosphere object that was considered in SR-Site was calculated as described in Section 2.5. Table A-5 and Table A-6 show the maximum obtained annual dose per unit release into the biosphere and in which biosphere object the dose was obtained for peat and wood respectively. The LDFs calculated for the interglacial scenario in Avila et al. (2010) and the ratios of the maximum dose factors with the LDFs are also presented. Figure 3-3 illustrates the comparison for peat combustion and Figure 3-4 illustrates the comparison for wood combustion. In the figures, the ratio of the resulting annual dose per unit release rate into the biosphere and the corresponding LDF value are shown. A ratio below 1 indicates that the calculated annual dose per unit release rate into the biosphere falls below the LDF from SR-Site.

All annual doses per unit release rate into the biosphere are lower than corresponding LDFs for all calculation cases and the annual doses for wood burning are lower than for peat burning for all radionuclides except Ca-41, Cl-36, Se-79, Tc-99. For the peat fuelled power plant the three largest annual doses per unit release rate into the biosphere are obtained for Th-232 (8% of the LDF), Pu-242 (6%) and Pu-239 (3%). For the peat fuelled household the largest annual doses per unit release rate into the biosphere are obtained for Th-232 (53% of the LDF), Pu-242 (30%), Pu-239 (16%), U-236 (12%) and U-238 (11%). For wood, the annual doses per unit release rate into the biosphere are lower, with all radionuclides falling below 1% of the LDF for the power plant and below 6% of the LDF for the household.

The most dominant radionuclides for dose in the assessment of high level waste is Ra-226, Ni-59, Se-79 (SKB 2011). The annual dose per unit release rate were less than 0.1% of the LDF for these radionuclides.

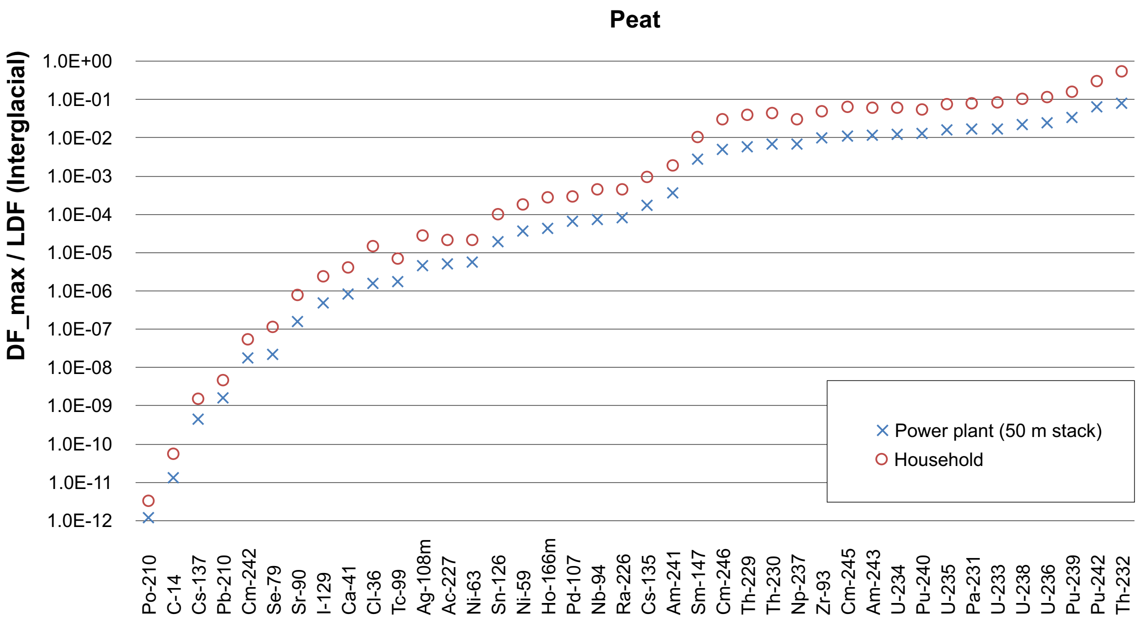

Figure 3-3. *The ratio of the annual dose per unit release rate into the biosphere object (Sv/y per Bq/y) and the LDF from SR-Site for the peat burning in a household (assuming that the individual is moving uniformly 0–200 m from the release) and a power plant with a 50 m stack.*

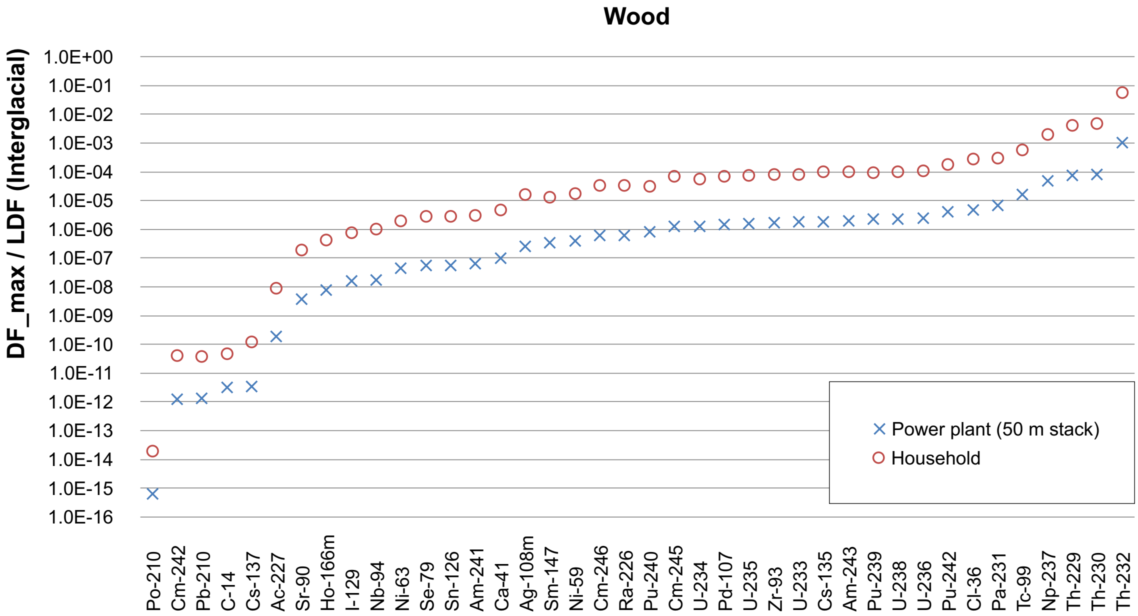

Figure 3-4. *The ratio of the annual dose per unit release rate into the biosphere object (Sv/y per Bq/y) and the LDF from SR-Site for the wood burning in a household (assuming that the individual is moving uniformly 0–200 m from the release) and a power plant with a 50 m stack.*

4 Uncertainty and sensitivity analyses

The uncertainties were divided into three types: (1) System (scenario) uncertainty arising from the imperfection of the predictions of the future including future human behaviour, (2) Model uncertainty arising from the imperfection of the models applied in the assessment and (3) Parameter uncertainty arising from insufficient data for estimating parameter values.

System uncertainty

It is unknown to what extent peat or wood will be used as fuel for combustion for energy production in the future. Peat and wood are known to be used for combustion in power plants but peat has not been a significant fuel in households in Sweden. No preferences were made for any of the fuel types in this report and assessments were performed for combustion of both peat and wood in both the household and power plant setting.

The amount of contaminated peat or wood that potentially could be harvested and burnt for energy production is limited by the size of the geographical area considered to be contaminated and also by the quality and suitability of the peat and wood being used as fuel. The calculation of the amount of available peat and wood in the biosphere objects was performed conservatively with the assumptions that the entire area of the biosphere objects is occupied by peat or wood of sufficient quality to be used for energy production. These are believed to be very conservative assumptions since the mire will most certainly be used also for agriculture. Furthermore, wood is more likely to be harvested from outside the biosphere object (i.e. in the sub-catchment) where the wood is not contaminated.

The exposure to contaminated air depends on the location of the exposed individual with respect to the release. For the power plant, this uncertainty was handled conservatively by calculating doses for an individual staying at the distance where the air concentration reaches its maximum. For the household, highest air concentrations were obtained in the absolute proximity of the building (in the cavity zone). The dose conversion factors were therefore calculated to mimic a more realistic exposure condition, where it was assumed that the exposed individual moves uniformly in the vicinity of the house (downwind from the release); partly in the zone of elevated air concentration close to the house and partly further away from the house. With the assumed exposure time (8,760 h/year), the obtained dose conversion factors are thought to be conservative.

In the dose calculations, it was assumed that exposure to contaminated air occurs outdoors. Any indoor exposure was assumed to be lower than the outdoor exposure because of the shielding of house walls and windows. Potential indoor exposure directly from the furnace was assumed to not lead to continuous and long-term exposure and is not considered in this report.

Model uncertainty

The Gaussian Plume models used in the report are simplified in a number of ways and ignore processes of plume depletion due to radioactive decay, wet deposition (e.g. effects of rain or snow), dry deposition (e.g. effects of sedimentation of aerosols), and the impact of particles or adsorption of gases on obstacles in the path of the wind. The models also do not take into account potential plume rise (i.e. the vertical rise of the plume immediately after leaving the stack or chimney). All of the above simplifications cause overpredictions of air concentrations and resulting doses due to inhalation. The model for air concentrations in the wake zone (Equation 2-9) is conservative since it assumes that the release occurs at ground level.

Parameter uncertainty

The handling of parameter uncertainties is described in Table 4-1. Most selected parameter values are thought to yield conservative results in the estimation of ground level air activity concentrations and dose conversion factors.

Table 4-1. Handling of parameter uncertainties

Parameter	Handling of uncertainty
Energy consumption of a household and energy production of a power plant, *E*	The value selected for the annual average energy consumption for heating of a modern house is assumed to be conservative. It is conservatively assumed that all fuel burnt is contaminated. The energy production of the power plant is unknown. The assumed value is thought to be conservative in respect to the amount of peat burnt in power plants today.
Fraction of radionuclides contained in the fly ash or gas, F_f and efficiency of filter, F_{eff}	Selected values imply that the entire radionuclide inventory in the fuel is released into the air, which is a conservative assumption.
The fraction of the time during the year that the wind blows towards the receptor of interest, P_p	The assumed value means that the wind blows towards the individual of interest 1/4 of the time. This is considered to be a conservative assumption.
Geometric mean of the wind speed, μ_a	The wind speed observed at 10 m height at station Högmasten between 2003–2007 has large seasonal variability between approximately 0.3–5.5 m/s. The observed mean (1.7 m/s) over this time period is considered to yield realistic and still cautious results (IAEA 2001 recommends 2 m/s as a conservative assumption). The wind velocity is not thought to differ much for the household release and is conservative for the release from the power plant.
Stack height	The stack height of the power plant is unknown but is believed to be dependent on the size of the power plant. A 100 m stack was considered to be a good choice for the 100 MW power plant based on information about power plants in Sweden today (e.g. Sandviken power plant with a 90 m stack). A lower (50 m) stack was also considered in the assessment and is believed to provide conservative results.
Building height, H_B and Area of the building wall closest to the receptor, A_B	Calculations of air activity concentrations were performed for two different heights and two different wall areas. The dose conversion factors were calculated for the combination that resulted in the highest average air concentration (Figure 3-2 and Table 3-2). With the 3 m building height the 60 m^2 wall area is considered a conservative assumption.
Downwind distance of the receptor, x	A resident is assumed to be located at the downwind distance where the ground level air concentration is the maximum for the power plant. The dose conversion factors for the household are calculated assuming an individual moving within 0–200 m from the house (i.e. both inside and outside the cavity zone). These assumptions are thought to be conservative.
Inhalation rate	The assumed value (1 m^3/h) is the same as used in Nordén et al. (2010).
Exposure time	The assumed value corresponds to an exposure 24 h/day and is considered conservative.

Sensitivity analysis

The models used for air concentration calculations and annual doses are multiplicative in their input parameters, except for the calculation of the diffusion factors (Equations 2-5 and 2-10), which depends on the release height, building wall dimensions and downwind distance. Thus, many parameters scale proportional to the calculated endpoints (i.e. a change in the parameter value causes a proportional change in the calculated result, if the other parameter values are kept unchanged). Descriptions of the dependencies between parameters and endpoints are shown in Table 4-2.

Table 4-2. Description of dependencies between the calculated endpoints (activity concentrations in air and annual doses) and the selected parameter values. The descriptions of the dependencies assume that all other parameters are kept unchanged.

Parameter	Dependency of endpoints
Energy consumption of a household and energy production of a power plant, *E*	The annual average discharge rate and the resulting air concentration and doses are directly proportional to the energy consumption for the household or the energy production of the power plant.
Fraction of radionuclides contained in the fly ash or gas, F_f	The annual average discharge rate, the activity concentrations in air and the annual doses are directly proportional to this parameter. For example, if 75% of the radionuclides are contained in the fly ash or gas (i.e. 25% is contained in the bottom ash),the annual average discharge rate, and consequently the ground level air concentration and doses, become 75% of the maximum values reported.
Efficiency of filter, F_{eff}	The annual average discharge rate, the activity concentrations in air and the annual doses are proportional to this parameter. If 80% of the radionuclides in the fly ash or gas are filtered (F_{ef} = 0.8), then the annual average discharge rate, and consequently the ground level air concentration and doses, become 20% of the values reported.
The fraction of the time during the year that the wind blows towards the receptor of interest, P_p	The resulting air concentration at the point of the receptor is proportional to the parameter. For example, if the wind blows towards the receptor 50% of the time (P_p = 0.50), the resulting air concentration and doses is twice the air concentrations reported for P_p = 0.25.
Geometric mean of the wind speed, μ_a	The activity concentration in air and the annual doses are inverse proportional to the wind velocity. For example, a wind velocity of 5 m/s results in air concentrations that are about 3 times lower than those reported for the wind velocity of 1.7 m/s
Stack height	The ground level air concentration is non-linearly dependent on the stack height. A higher stack results in lower ground level air concentrations and the maximum ground level air concentration is obtained further away from the stack. Results for two different stack heights are presented in Section 2.2.1.
Building height, H_B and the area of the building wall closest to the receptor, A_B	The air concentration is non-linearly dependent on the height of the building. A lower height of the house (implying a lower release height) causes larger air concentrations in the cavity zone. Air concentrations in the wake zone are calculated assuming a zero height of the release. The air concentration is non-linearly dependent on the area of the building wall. A larger area of the building wall causes the elevated cavity zone air concentration to occur further downwind (results for different wall areas are presented in Section 3.2.2).
Downwind distance of the receptor, x	The ground level air concentration and obtained doses are non-linearly dependent on the downwind distance of the receptor. The effect of the downwind distance for the power plant is shown in Figure 3-1 and for the household in Figure 3-2. For the household the maximum air concentration is obtained closest to the building and then decreases further downwind. For the power plant, the ground level air concentrations reaches a maximum at a critical downwind distance $x_0 > 0$ and then decreases for $x > x_0$.
Inhalation rate	The annual dose is proportional to the inhalation rate. For example, an inhalation rate of 1.5 m^3/h results in 50% higher doses than those reported for 1 m^3/h.
Exposure time	The annual dose is linearly proportional to the exposure time. For example, an exposure time of 12 h/day results in half the doses reported for 24 h/day.

5 Discussion

The calculated annual doses per unit release rate (Sv/y per Bq/y) are higher for the household case compared to the power plant case. This is mainly due to the lower release height of the household compared to the release height of the power plant. In the household case, there is also an elevated concentration close to the building wall due to the cavity zone effect while in the power plant case there is no such effect.

The air activity concentration per activity concentration in fuel (Bq/m^3 per Bq/kgDW) for wood is higher than for peat (Table 3-1 and Table 3-2) due to the higher energy content of peat compared to the energy content of wood. More wood than peat therefore has to be burnt to produce the same amount of energy and more radionuclides is therefore released into the air when wood is used as fuel.

In the assessments made in this report, doses were calculated using the dose conversion factors (Sv/y per Bq/kgDW) in Table A-1 and Table A-3 and a dilution factor accounting for the proportion of fuel that is contaminated (kgDW/kgDW). An alternative approach is to multiply the dose conversion factor (Sv/y per Bq/kgDW per kgDW/s) in Table A-2 and Table A-4 with the amount of contaminated peat or wood burnt per second (kgDW/s) and the activity concentration in peat and wood. For future assessments (i.e. assessments with other biosphere objects and other activity concentrations in peat and wood), either one of the approaches can be used.

In the previous SKB safety assessment of long-term repository safety (SR-97) the activity concentration resulting from peat burning was calculated using a constant value of the relative concentration. Using the air dispersion models in this report, the relative concentration is instead a function of the downwind distance from the release (x) given by $F(x)/\mu_a$ in the expression for the air activity concentration following a release from the power plant (Equation 2-4) or $B(x)/\mu_a$ in the expression for the air activity concentration in the wake zone following a release from the household (Equation 2-9). For the household assessment case, the relative concentration at 100 m distance from the household release were $1.3\ 10^{-3}$ s/m^3 and the relative concentration at distance 200 m from the household release were $3.9\ 10^{-4}$ s/m^3. For the 50 m stack power plant assessment case, the relative concentration at distance 300 m (the point where the maximum ground level concentration was obtained) were $2.9\ 10^{-5}$ s/m^3. The dispersion model used in this report for the 50 m stack power plant thus resulted in approximately the same maximum relative concentration as that used in Bergström et al. (1999), while the dispersion model for the household case resulted in much higher relative concentration than the value used by Bergström et al. (1999). The dose calculations in this report are therefore conservative compared to a dose model which is based on the constant value of the relative concentration used in Bergström et al. (1999).

6 Summary and conclusions

This report presents models and assessments of doses from the exposure of contaminated air to a critical individual when contaminated peat or wood is burned for energy production. Dose conversion factors were calculated for combustion of peat or wood in a household or a power plant. When applied in a specific context (such as SR-Site) the limited availability of contaminated peat or wood that can be used for combustion should be considered. In the biosphere objects of SR-Site, the calculated amount of peat was enough to sustain the fuel consumption of several households (assuming an energy consumption of 20,000 kWh/y) but only enough to sustain a few percent of the fuel consumption of a 100 MW power plant. The availability of wood was shown to be even less than peat.

An assessment of doses from the combustion of peat or wood from the SR-Site biosphere objects were performed by calculating annual doses per constant unit release rate (Sv/y per Bq/y) and comparing them with the landscape dose conversion factors (LDFs) of SR-Site. The comparison shows that all annual doses per unit release rate into the biosphere are less than the corresponding LDFs and that the annual doses for wood burning are lower than for peat burning for most radionuclides. The most dominant radionuclides for dose in the assessment of high level waste were Ra-226, Ni-59, Se-79 (SKB 2011) but the dose from combustion of peat or wood is insignificant for these radionuclides. For the most dominant radionuclides, ingestion of water and food instead dominate the dose (Avila et al. 2010). The results show that the doses from exposure to contaminated air from the combustion of peat or wood does not impact the results of the previous assessments in SR-Site in any significant way.

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Appendix A

Table A-1. Annual dose per unit activity concentration in peat or wood (Sv/y per Bq/kgDW) for the 100 MW power plant. The maximum energy production corresponds to a fuel usage rate of 4.8 kgDW/s for peat and 5.5 kgDW/s for wood (Table 2-1). The annual doses calculated for maximum air concentration obtained at approximately 300 m for the 50 m stack and at approximately 900 m for the 100 m stack.

Radionuclide	Annual dose per unit activity concentration in peat (Sv/y per Bq/kgDW)		Annual dose per unit activity concentration in wood (Sv/y per Bq/kgDW)	
	50 m stack	100 m stack	50 m stack	100 m stack
Ac-227	1.69E-04	2.93E-05	1.94E-04	3.37E-05
Ag-108m	1.14E-08	1.97E-09	1.31E-08	2.27E-09
Am-241	2.95E-05	5.11E-06	3.39E-05	5.88E-06
Am-242m	2.82E-05	4.90E-06	3.25E-05	5.63E-06
Am-243	2.95E-05	5.11E-06	3.39E-05	5.88E-06
Ba-133	3.07E-09	5.32E-10	3.53E-09	6.12E-10
Be-10	1.07E-08	1.86E-09	1.24E-08	2.14E-09
C-14	1.90E-12	3.30E-13	2.19E-12	3.80E-13
Ca-41	5.52E-11	9.58E-12	6.36E-11	1.10E-11
Cd-113m	3.37E-08	5.85E-09	3.88E-08	6.73E-09
Cl-36	2.24E-09	3.88E-10	2.58E-09	4.47E-10
Cm-242	1.81E-06	3.14E-07	2.08E-06	3.61E-07
Cm-243	2.12E-05	3.67E-06	2.44E-05	4.22E-06
Cm-244	1.75E-05	3.03E-06	2.01E-05	3.49E-06
Cm-245	3.04E-05	5.27E-06	3.50E-05	6.06E-06
Cm-246	3.01E-05	5.21E-06	3.46E-05	6.00E-06
Co-60	9.51E-09	1.65E-09	1.09E-08	1.90E-09
Cs-134	6.14E-09	1.06E-09	7.06E-09	1.22E-09
Cs-135	2.64E-09	4.58E-10	3.04E-09	5.27E-10
Cs-137	1.20E-08	2.07E-09	1.38E-08	2.39E-09
Eu-152	1.29E-08	2.23E-09	1.48E-08	2.57E-09
Eu-154	1.63E-08	2.82E-09	1.87E-08	3.24E-09
Eu-155	2.12E-09	3.67E-10	2.44E-09	4.22E-10
Fe-55	2.36E-10	4.10E-11	2.72E-10	4.71E-11
Gd-152	5.83E-06	1.01E-06	6.71E-06	1.16E-06
H-3	7.98E-11	1.38E-11	9.18E-11	1.59E-11
Ho-166m	3.68E-08	6.38E-09	4.24E-08	7.35E-09
I-129	1.10E-08	1.92E-09	1.27E-08	2.20E-09
In-115	1.20E-07	2.07E-08	1.38E-07	2.39E-08
Mo-93	7.06E-10	1.22E-10	8.12E-10	1.41E-10
Nb-93m	5.52E-10	9.58E-11	6.36E-10	1.10E-10
Nb-94	1.50E-08	2.61E-09	1.73E-08	3.00E-09
Ni-59	1.35E-10	2.34E-11	1.55E-10	2.69E-11
Ni-63	3.99E-10	6.92E-11	4.59E-10	7.96E-11
Np-237	1.53E-05	2.66E-06	1.77E-05	3.06E-06
Pa-231	4.30E-05	7.45E-06	4.94E-05	8.57E-06
Pb-210	1.72E-06	2.98E-07	1.98E-06	3.43E-07
Pd-107	1.81E-10	3.14E-11	2.08E-10	3.61E-11
Pm-147	1.53E-09	2.66E-10	1.77E-09	3.06E-10
Po-210	1.32E-06	2.29E-07	1.52E-06	2.63E-07
Pu-238	3.37E-05	5.85E-06	3.88E-05	6.73E-06
Pu-239	3.68E-05	6.38E-06	4.24E-05	7.35E-06
Pu-240	3.68E-05	6.38E-06	4.24E-05	7.35E-06
Pu-241	7.06E-07	1.22E-07	8.12E-07	1.41E-07
Pu-242	3.37E-05	5.85E-06	3.88E-05	6.73E-06
Ra-226	2.92E-06	5.06E-07	3.36E-06	5.83E-07
Ra-228	4.91E-06	8.52E-07	5.65E-06	9.81E-07
Ru-106	2.02E-08	3.51E-09	2.33E-08	4.04E-09
Sb-125	3.98E-09	6.89E-10	4.58E-09	7.93E-10
Se-79	2.09E-09	3.62E-10	2.40E-09	4.16E-10
Sm-147	2.95E-06	5.11E-07	3.39E-06	5.88E-07
Sm-151	1.23E-09	2.13E-10	1.41E-09	2.45E-10
Sn-126	8.72E-09	1.51E-09	1.00E-08	1.74E-09
Sr-90	4.96E-08	8.59E-09	5.70E-08	9.89E-09
Tc-99	3.99E-09	6.92E-10	4.59E-09	7.96E-10
Th-228	1.34E-05	2.32E-06	1.54E-05	2.67E-06
Th-229	7.39E-05	1.28E-05	8.51E-05	1.48E-05
Th-230	3.07E-05	5.32E-06	3.53E-05	6.12E-06
Th-232	3.37E-05	5.85E-06	3.88E-05	6.73E-06
U-232	1.14E-05	1.97E-06	1.31E-05	2.27E-06
U-233	2.95E-06	5.11E-07	3.39E-06	5.88E-07
U-234	2.88E-06	5.00E-07	3.32E-06	5.75E-07
U-235	2.61E-06	4.52E-07	3.00E-06	5.20E-07
U-236	2.67E-06	4.63E-07	3.07E-06	5.33E-07
U-238	2.46E-06	4.26E-07	2.83E-06	4.90E-07
Zr-93	7.67E-09	1.33E-09	8.83E-09	1.53E-09

Table A-2. Annual dose per unit activity concentration in peat or wood per unit fuel usage rate (Sv/y per Bq/kgDW per kgDW/s) for the 100 MW power plant. The maximum energy production corresponds to a fuel usage rate of 4.8 kgDW/s for peat and 5.5 kgDW/s for wood (Table 2-1). The annual doses calculated for maximum air concentration obtained at approximately 300 m for the 50 m stack and at approximately 900 m for the 100 m stack.

Radionuclide	Annual dose per unit activity concentration in fuel per fuel usage rate (Sv/y per Bq/kgDW per kgDW/s)	
	50 m stack	100 m stack
Ac-227	3.53E-05	6.12E-06
Ag-108m	2.37E-09	4.11E-10
Am-241	6.15E-06	1.07E-06
Am-242m	5.89E-06	1.02E-06
Am-243	6.15E-06	1.07E-06
Ba-133	6.41E-10	1.11E-10
Be-10	2.24E-09	3.89E-10
C-14	3.97E-13	6.89E-14
Ca-41	1.15E-11	2.00E-12
Cd-113m	7.05E-09	1.22E-09
Cl-36	4.68E-10	8.11E-11
Cm-242	3.78E-07	6.55E-08
Cm-243	4.42E-06	7.66E-07
Cm-244	3.65E-06	6.33E-07
Cm-245	6.34E-06	1.10E-06
Cm-246	6.28E-06	1.09E-06
Co-60	1.99E-09	3.44E-10
Cs-134	1.28E-09	2.22E-10
Cs-135	5.51E-10	9.55E-11
Cs-137	2.50E-09	4.33E-10
Eu-152	2.69E-09	4.67E-10
Eu-154	3.40E-09	5.89E-10
Eu-155	4.42E-10	7.66E-11
Fe-55	4.93E-11	8.55E-12
Gd-152	1.22E-06	2.11E-07
H-3	1.67E-11	2.89E-12
Ho-166m	7.69E-09	1.33E-09
I-129	2.31E-09	4.00E-10
In-115	2.50E-08	4.33E-09
Mo-93	1.47E-10	2.55E-11
Nb-93m	1.15E-10	2.00E-11
Nb-94	3.14E-09	5.44E-10
Ni-59	2.82E-11	4.89E-12
Ni-63	8.33E-11	1.44E-11
Np-237	3.20E-06	5.55E-07
Pa-231	8.97E-06	1.56E-06
Pb-210	3.59E-07	6.22E-08
Pd-107	3.78E-11	6.55E-12
Pm-147	3.20E-10	5.55E-11
Po-210	2.75E-07	4.78E-08
Pu-238	7.05E-06	1.22E-06
Pu-239	7.69E-06	1.33E-06
Pu-240	7.69E-06	1.33E-06
Pu-241	1.47E-07	2.55E-08
Pu-242	7.05E-06	1.22E-06
Ra-226	6.10E-07	1.06E-07
Ra-228	1.03E-06	1.78E-07
Ru-106	4.23E-09	7.33E-10
Sb-125	8.30E-10	1.44E-10
Se-79	4.36E-10	7.55E-11
Sm-147	6.15E-07	1.07E-07
Sm-151	2.56E-10	4.44E-11
Sn-126	1.82E-09	3.16E-10
Sr-90	1.03E-08	1.79E-09
Tc-99	8.33E-10	1.44E-10
Th-228	2.79E-06	4.84E-07
Th-229	1.54E-05	2.68E-06
Th-230	6.41E-06	1.11E-06
Th-232	7.05E-06	1.22E-06
U-232	2.37E-06	4.11E-07
U-233	6.15E-07	1.07E-07
U-234	6.02E-07	1.04E-07
U-235	5.45E-07	9.44E-08
U-236	5.57E-07	9.66E-08
U-238	5.13E-07	8.90E-08
Zr-93	1.60E-09	2.78E-10

Table A-3. Annual dose per unit activity concentration in peat or wood (Sv/y per Bq/kgDW) for the combustion of peat or wood in a household with an energy consumption of 20,000 kWh/y. The energy consumption corresponds to a fuel usage rate of 1.1E-04 kgDW/s for peat and 1.3E-04 kgDW/s for wood (Table 2-1). The doses are calculated for (1) an individual staying solely in the cavity zone and (2) an individual moving uniformly within 0–200 m downwind from the release.

Radionuclide	Annual dose per unit activity concentration in peat (Sv/y per Bq/kgDW)		Annual dose per unit activity concentration in wood (Sv/y per Bq/kgDW)	
	Cavity zone	Average 0–200 m	Cavity zone	Average 0–200 m
Ac-227	8.23E-06	1.04E-06	9.47E-06	1.20E-06
Ag-108m	5.53E-10	7.01E-11	6.36E-10	8.06E-11
Am-241	1.43E-06	1.82E-07	1.65E-06	2.09E-07
Am-242m	1.38E-06	1.74E-07	1.58E-06	2.01E-07
Am-243	1.43E-06	1.82E-07	1.65E-06	2.09E-07
Ba-133	1.49E-10	1.89E-11	1.72E-10	2.18E-11
Be-10	5.23E-10	6.63E-11	6.02E-10	7.63E-11
C-14	9.27E-14	1.17E-14	1.07E-13	1.35E-14
Ca-41	2.69E-12	3.41E-13	3.10E-12	3.92E-13
Cd-113m	1.64E-09	2.08E-10	1.89E-09	2.40E-10
Cl-36	1.09E-10	1.38E-11	1.26E-10	1.59E-11
Cm-242	8.82E-08	1.12E-08	1.01E-07	1.29E-08
Cm-243	1.03E-06	1.31E-07	1.19E-06	1.50E-07
Cm-244	8.52E-07	1.08E-07	9.80E-07	1.24E-07
Cm-245	1.48E-06	1.87E-07	1.70E-06	2.16E-07
Cm-246	1.46E-06	1.86E-07	1.69E-06	2.14E-07
Co-60	4.63E-10	5.87E-11	5.33E-10	6.76E-11
Cs-134	2.99E-10	3.79E-11	3.44E-10	4.36E-11
Cs-135	1.29E-10	1.63E-11	1.48E-10	1.87E-11
Cs-137	5.83E-10	7.39E-11	6.71E-10	8.50E-11
Eu-152	6.28E-10	7.95E-11	7.22E-10	9.15E-11
Eu-154	7.92E-10	1.00E-10	9.12E-10	1.16E-10
Eu-155	1.03E-10	1.31E-11	1.19E-10	1.50E-11
Fe-55	1.15E-11	1.46E-12	1.32E-11	1.68E-12
Gd-152	2.84E-07	3.60E-08	3.27E-07	4.14E-08
H-3	3.89E-12	4.92E-13	4.47E-12	5.67E-13
Ho-166m	1.79E-09	2.27E-10	2.06E-09	2.62E-10
I-129	5.38E-10	6.82E-11	6.19E-10	7.85E-11
In-115	5.83E-09	7.39E-10	6.71E-09	8.50E-10
Mo-93	3.44E-11	4.36E-12	3.96E-11	5.01E-12
Nb-93m	2.69E-11	3.41E-12	3.10E-11	3.92E-12
Nb-94	7.32E-10	9.28E-11	8.43E-10	1.07E-10
Ni-59	6.58E-12	8.33E-13	7.57E-12	9.59E-13
Ni-63	1.94E-11	2.46E-12	2.24E-11	2.83E-12
Np-237	7.47E-07	9.47E-08	8.60E-07	1.09E-07
Pa-231	2.09E-06	2.65E-07	2.41E-06	3.05E-07
Pb-210	8.37E-08	1.06E-08	9.63E-08	1.22E-08
Pd-107	8.82E-12	1.12E-12	1.01E-11	1.29E-12
Pm-147	7.47E-11	9.47E-12	8.60E-11	1.09E-11
Po-210	6.43E-08	8.14E-09	7.40E-08	9.37E-09
Pu-238	1.64E-06	2.08E-07	1.89E-06	2.40E-07
Pu-239	1.79E-06	2.27E-07	2.06E-06	2.62E-07
Pu-240	1.79E-06	2.27E-07	2.06E-06	2.62E-07
Pu-241	3.44E-08	4.36E-09	3.96E-08	5.01E-09
Pu-242	1.64E-06	2.08E-07	1.89E-06	2.40E-07
Ra-226	1.42E-07	1.80E-08	1.64E-07	2.07E-08
Ra-228	2.39E-07	3.03E-08	2.75E-07	3.49E-08
Ru-106	9.86E-10	1.25E-10	1.14E-09	1.44E-10
Sb-125	1.94E-10	2.45E-11	2.23E-10	2.82E-11
Se-79	1.02E-10	1.29E-11	1.17E-10	1.48E-11
Sm-147	1.43E-07	1.82E-08	1.65E-07	2.09E-08
Sm-151	5.98E-11	7.57E-12	6.88E-11	8.72E-12
Sn-126	4.25E-10	5.38E-11	4.89E-10	6.19E-11
Sr-90	2.41E-09	3.06E-10	2.78E-09	3.52E-10
Tc-99	1.94E-10	2.46E-11	2.24E-10	2.83E-11
Th-228	6.51E-07	8.25E-08	7.50E-07	9.50E-08
Th-229	3.60E-06	4.56E-07	4.15E-06	5.25E-07
Th-230	1.49E-06	1.89E-07	1.72E-06	2.18E-07
Th-232	1.64E-06	2.08E-07	1.89E-06	2.40E-07
U-232	5.53E-07	7.01E-08	6.36E-07	8.06E-08
U-233	1.43E-07	1.82E-08	1.65E-07	2.09E-08
U-234	1.40E-07	1.78E-08	1.62E-07	2.05E-08
U-235	1.27E-07	1.61E-08	1.46E-07	1.85E-08
U-236	1.30E-07	1.65E-08	1.50E-07	1.90E-08
U-238	1.20E-07	1.52E-08	1.38E-07	1.75E-08
Zr-93	3.74E-10	4.73E-11	4.30E-10	5.45E-11

Table A-4. Annual dose per unit activity concentration in peat or wood per fuel usage rate (Sv/y per Bq/kgDW per kgDW/s) for the combustion of peat or wood in a household with an energy consumption of 20,000 kWh/y. The energy consumption corresponds to a fuel usage rate of 1.1E-04 kgDW/s for peat and 1.3E-04 kgDW/s for wood (Table 2-1). The doses are calculated for (1) an individual staying solely in the cavity zone and (2) an individual moving uniformly within 0–200 m downwind from the release.

Radionuclide	Annual dose per unit activity concentration in fuel per fuel usage rate (Sv/y per Bq/kgDW per kgDW/s)	
	Cavity zone	Average 0–200 m
Ac-227	7.53E-02	9.54E-03
Ag-108m	5.06E-06	6.41E-07
Am-241	1.31E-02	1.66E-03
Am-242m	1.26E-02	1.59E-03
Am-243	1.31E-02	1.66E-03
Ba-133	1.37E-06	1.73E-07
Be-10	4.78E-06	6.06E-07
C-14	8.47E-10	1.07E-10
Ca-41	2.46E-08	3.12E-09
Cd-113m	1.50E-05	1.91E-06
Cl-36	9.98E-07	1.26E-07
Cm-242	8.06E-04	1.02E-04
Cm-243	9.43E-03	1.20E-03
Cm-244	7.79E-03	9.87E-04
Cm-245	1.35E-02	1.71E-03
Cm-246	1.34E-02	1.70E-03
Co-60	4.24E-06	5.37E-07
Cs-134	2.73E-06	3.46E-07
Cs-135	1.18E-06	1.49E-07
Cs-137	5.33E-06	6.75E-07
Eu-152	5.74E-06	7.27E-07
Eu-154	7.24E-06	9.18E-07
Eu-155	9.43E-07	1.20E-07
Fe-55	1.05E-07	1.33E-08
Gd-152	2.60E-03	3.29E-04
H-3	3.55E-08	4.50E-09
Ho-166m	1.64E-05	2.08E-06
I-129	4.92E-06	6.23E-07
In-115	5.33E-05	6.75E-06
Mo-93	3.14E-07	3.98E-08
Nb-93m	2.46E-07	3.12E-08
Nb-94	6.70E-06	8.49E-07
Ni-59	6.01E-08	7.62E-09
Ni-63	1.78E-07	2.25E-08
Np-237	6.83E-03	8.66E-04
Pa-231	1.91E-02	2.42E-03
Pb-210	7.65E-04	9.70E-05
Pd-107	8.06E-08	1.02E-08
Pm-147	6.83E-07	8.66E-08
Po-210	5.88E-04	7.45E-05
Pu-238	1.50E-02	1.91E-03
Pu-239	1.64E-02	2.08E-03
Pu-240	1.64E-02	2.08E-03
Pu-241	3.14E-04	3.98E-05
Pu-242	1.50E-02	1.91E-03
Ra-226	1.30E-03	1.65E-04
Ra-228	2.19E-03	2.77E-04
Ru-106	9.02E-06	1.14E-06
Sb-125	1.77E-06	2.24E-07
Se-79	9.29E-07	1.18E-07
Sm-147	1.31E-03	1.66E-04
Sm-151	5.47E-07	6.93E-08
Sn-126	3.88E-06	4.92E-07
Sr-90	2.21E-05	2.80E-06
Tc-99	1.78E-06	2.25E-07
Th-228	5.96E-03	7.55E-04
Th-229	3.29E-02	4.17E-03
Th-230	1.37E-02	1.73E-03
Th-232	1.50E-02	1.91E-03
U-232	5.06E-03	6.41E-04
U-233	1.31E-03	1.66E-04
U-234	1.28E-03	1.63E-04
U-235	1.16E-03	1.47E-04
U-236	1.19E-03	1.51E-04
U-238	1.09E-03	1.39E-04
Zr-93	3.42E-06	4.33E-07

Table A-5. The ratio of the annual dose per unit release rate into the biosphere object (Sv/y per Bq/y) and the LDF from SR-Site for the peat burning in a household (assuming that the individual is moving uniformly 0–200 m from the release) and a power plant with a 50 m stack. DF_{max} is the maximum annual dose per unit release rate (Sv/y per Bq/y) over all biosphere object and Obj_{max} is the specific biosphere object where the maximum annual dose per unit release rate is obtained.

	Power plant (50 m stack)			Household			
	DF_{max}	Obj_{max}	DF_{max}/LDF	DF_{max}	Obj_{max}	DF_{max}/LDF	LDF (Interglacial)
Ac-227	4.11E-17	120	5.14E-06	1.73E-16	125	2.16E-05	8.0E-12
Ag-108m	3.26E-18	120	4.58E-06	1.97E-17	125	2.77E-05	7.1E-13
Am-241	5.47E-16	117	3.65E-04	2.85E-15	124	1.90E-03	1.5E-12
Am-243	1.73E-14	118	1.16E-02	8.96E-14	124	5.97E-02	1.5E-12
C-14	7.21E-23	117	1.33E-11	2.94E-22	121_03	5.44E-11	5.4E-12
Ca-41	8.02E-20	118	8.10E-07	4.15E-19	121_03	4.20E-06	9.9E-14
Cl-36	9.35E-19	108	1.61E-06	8.42E-18	121_03	1.45E-05	5.8E-13
Cm-244	1.54E-20	120	1.77E-08	4.69E-20	125	5.39E-08	8.7E-13
Cm-245	1.73E-14	117	1.08E-02	1.01E-13	124	6.31E-02	1.6E-12
Cm-246	8.08E-15	117	5.05E-03	5.01E-14	124	3.13E-02	1.6E-12
Cs-135	6.91E-18	117	1.73E-04	3.72E-17	124	9.30E-04	4.0E-14
Cs-137	5.42E-23	120	4.51E-10	1.82E-22	125	1.52E-09	1.2E-13
Ho-166m	2.49E-18	117	4.21E-05	1.65E-17	124	2.79E-04	5.9E-14
I-129	3.14E-16	117	4.84E-07	1.59E-15	121_03	2.44E-06	6.5E-10
Nb-94	2.89E-16	117	7.22E-05	1.84E-15	124	4.60E-04	4.0E-12
Ni-59	2.69E-18	118	3.63E-05	1.36E-17	124	1.84E-04	7.4E-14
Ni-63	6.68E-21	117	5.57E-06	2.55E-20	125	2.13E-05	1.2E-15
Np-237	3.31E-13	118	6.90E-03	1.47E-12	121_03	3.07E-02	4.8E-11
Pa-231	1.39E-13	118	1.71E-02	6.47E-13	124	7.99E-02	8.1E-12
Pb-210	8.38E-21	120	1.64E-09	2.42E-20	125	4.74E-09	5.1E-12
Pd-107	4.51E-19	108	6.73E-05	1.93E-18	124	2.88E-04	6.7E-15
Po-210	1.05E-23	120	1.18E-12	2.99E-23	125	3.36E-12	8.9E-12
Pu-239	6.53E-14	118	3.44E-02	3.04E-13	121_03	1.60E-01	1.9E-12
Pu-240	2.45E-14	118	1.29E-02	1.03E-13	124	5.45E-02	1.9E-12
Pu-242	1.21E-13	118	6.36E-02	5.66E-13	121_03	2.98E-01	1.9E-12
Ra-226	3.11E-16	117	8.19E-05	1.73E-15	124	4.56E-04	3.8E-12
Se-79	2.61E-17	118	2.18E-08	1.38E-16	121_03	1.15E-07	1.2E-09
Sm-151	2.03E-18	120	2.82E-03	7.42E-18	125	1.03E-02	7.2E-16
Sn-126	4.78E-16	118	1.91E-05	2.48E-15	124	9.90E-05	2.5E-11
Sr-90	3.56E-20	117	1.62E-07	1.78E-19	124	8.08E-07	2.2E-13
Tc-99	1.58E-18	118	1.76E-06	6.42E-18	121_03	7.13E-06	9.0E-13
Th-229	2.09E-14	117	5.79E-03	1.42E-13	124	3.95E-02	3.6E-12
Th-230	8.72E-14	117	6.71E-03	5.75E-13	124	4.43E-02	1.3E-11
Th-232	1.38E-13	117	8.12E-02	9.08E-13	124	5.34E-01	1.7E-12
U-233	4.36E-14	118	1.74E-02	2.11E-13	124	8.46E-02	2.5E-12
U-234	4.50E-14	118	1.25E-02	2.18E-13	124	6.05E-02	3.6E-12
U-235	4.50E-14	118	1.61E-02	2.16E-13	124	7.72E-02	2.8E-12
U-236	4.60E-14	118	2.42E-02	2.21E-13	124	1.16E-01	1.9E-12
U-238	4.24E-14	118	2.23E-02	2.04E-13	124	1.07E-01	1.9E-12
Zr-93	2.76E-16	118	9.86E-03	1.35E-15	124	4.83E-02	2.8E-14

Table A-6. The ratio of the annual dose per unit release rate into the biosphere object (Sv/y per Bq/y) and the LDF from SR-Site for the wood burning in a household (assuming that the individual is moving uniformly 0–200 m from the release) and a power plant with a 50 m stack. DF_{max} is the maximum annual dose per unit release rate (Sv/y per Bq/y) over all biosphere object and Obj_{max} is the specific biosphere object where the maximum annual dose per unit release rate is obtained.

	Power plant (50 m stack)			Household			
	DF_{max}	Obj_{max}	DF_{max}/LDF	DF_{max}	Obj_{max}	DF_{max}/LDF	LDF (Interglacial)
Ac-227	1.56E-21	120	1.95E-10	6.93E-20	125	8.66E-09	8.0E-12
Ag-108m	1.88E-19	125	2.64E-07	1.17E-17	125	1.65E-05	7.1E-13
Am-241	9.39E-20	136	6.26E-08	4.55E-18	124	3.04E-06	1.5E-12
Am-243	3.05E-18	118	2.03E-06	1.46E-16	124	9.71E-05	1.5E-12
C-14	1.69E-23	116	3.14E-12	2.57E-22	121_03	4.75E-11	5.4E-12
Ca-41	9.69E-21	118	9.79E-08	4.67E-19	121_03	4.72E-06	9.9E-14
Cl-36	2.73E-18	121_03	4.71E-06	1.59E-16	121_03	2.74E-04	5.8E-13
Cm-244	1.06E-24	120	1.22E-12	3.44E-23	125	3.95E-11	8.7E-13
Cm-245	1.98E-18	136	1.24E-06	1.09E-16	124	6.84E-05	1.6E-12
Cm-246	9.51E-19	136	5.94E-07	5.43E-17	124	3.39E-05	1.6E-12
Cs-135	7.50E-20	118	1.88E-06	3.94E-18	124	9.86E-05	4.0E-14
Cs-137	4.21E-25	120	3.51E-12	1.50E-23	125	1.25E-10	1.2E-13
Ho-166m	4.54E-22	124	7.69E-09	2.60E-20	124	4.40E-07	5.9E-14
I-129	1.05E-17	118	1.61E-08	4.94E-16	121_03	7.61E-07	6.5E-10
Nb-94	7.16E-20	124	1.79E-08	4.10E-18	124	1.02E-06	4.0E-12
Ni-59	2.86E-20	118	3.87E-07	1.34E-18	124	1.81E-05	7.4E-14
Ni-63	5.52E-23	136	4.60E-08	2.30E-21	125	1.92E-06	1.2E-15
Np-237	2.37E-15	118	4.93E-05	9.76E-14	121_03	2.03E-03	4.8E-11
Pa-231	5.47E-17	118	6.75E-06	2.36E-15	124	2.91E-04	8.1E-12
Pb-210	6.59E-24	120	1.29E-12	2.00E-22	125	3.92E-11	5.1E-12
Pd-107	9.84E-21	118	1.47E-06	4.69E-19	124	7.00E-05	6.7E-15
Po-210	5.79E-27	120	6.50E-16	1.74E-25	125	1.96E-14	8.9E-12
Pu-239	4.22E-18	118	2.22E-06	1.81E-16	121_03	9.53E-05	1.9E-12
Pu-240	1.57E-18	118	8.29E-07	6.17E-17	124	3.25E-05	1.9E-12
Pu-242	7.81E-18	118	4.11E-06	3.38E-16	121_03	1.78E-04	1.9E-12
Ra-226	2.31E-18	136	6.09E-07	1.29E-16	124	3.40E-05	3.8E-12
Se-79	6.84E-17	118	5.70E-08	3.35E-15	121_03	2.79E-06	1.2E-09
Sm-151	2.53E-22	120	3.51E-07	9.75E-21	125	1.35E-05	7.2E-16
Sn-126	1.43E-18	118	5.73E-08	6.85E-17	124	2.74E-06	2.5E-11
Sr-90	8.45E-22	136	3.84E-09	4.08E-20	124	1.85E-07	2.2E-13
Tc-99	1.42E-17	118	1.58E-05	5.23E-16	121_03	5.82E-04	9.0E-13
Th-229	2.67E-16	124	7.42E-05	1.53E-14	124	4.24E-03	3.6E-12
Th-230	1.08E-15	124	8.32E-05	6.18E-14	124	4.75E-03	1.3E-11
Th-232	1.71E-15	124	1.00E-03	9.75E-14	124	5.74E-02	1.7E-12
U-233	4.43E-18	118	1.77E-06	1.99E-16	124	7.95E-05	2.5E-12
U-234	4.58E-18	118	1.27E-06	2.05E-16	124	5.68E-05	3.6E-12
U-235	4.58E-18	118	1.63E-06	2.03E-16	124	7.26E-05	2.8E-12
U-236	4.68E-18	118	2.46E-06	2.08E-16	124	1.09E-04	1.9E-12
U-238	4.31E-18	118	2.27E-06	1.91E-16	124	1.01E-04	1.9E-12
Zr-93	4.94E-20	118	1.76E-06	2.24E-18	124	7.98E-05	2.8E-14