Final Report **Project UKRSR03**

Development of a Framework for Assessing the Suitability of Controlled Landfills to Accept Disposals of Solid Low-Level Radioactive Waste: Technical Reference Manual

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EXECUTIVE SUMMARY

This report forms part of a research project aimed at establishing a framework for assessing the suitability of controlled landfills to accept disposals of solid low-level radioactive waste. The disposal of radioactive waste alongside other wastes at landfill sites is a disposal route aimed at small users rather than at the nuclear industry, and it is restricted to relatively low activity wastes. For the purpose of this project, it has been assumed that all SPB disposals will be made to non-hazardous landfill sites. The framework therefore may not be applicable to inert and hazardous landfill sites.

The framework comprises the overall process for determining the suitability of landfill sites for accepting certain types of low-level radioactive waste. The framework comprises four principal stages:

- Initial screening for potentially suitable sites.
- Development of the assessment context and methodology.
- Calculation.
- Authorisation decision and conditions.

The framework is aimed at assessing new sites, or sites that have not previously accepted radioactive waste.

Assessments of landfill sites in terms of their environmental impacts require the identification of the sources, pathways and receptors through which environmental harm could arise. A generic set of these that encompasses the activities and environmental setting of landfill sites has been identified. This report provides brief qualitative descriptions of these elements of the conceptual models for the assessment, together with detailed descriptions of the mathematical models that will be used to calculate the radiological capacity of suitable sites.

The assessment framework aims to ensure that a consistent approach is taken to the assessment of different sites. The framework therefore includes an assessment context that includes as many generic elements as possible. The remaining elements of the assessment context will be established on a site-specific basis. This report includes generic data for use in the assessments, and also some default values for site-specific elements.

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1 Introduction

1. The Scottish Environment Protection Agency (SEPA), the Environment and Heritage Service, Northern Ireland (EHS), and the Environment Agency for England and Wales (EA), are responsible for the regulation of radioactive waste disposal in the UK. The Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) has commissioned research on behalf of these UK regulatory agencies to establish a framework for assessing the suitability of controlled landfills to accept disposals of solid low-level radioactive waste.

2. A set of key principles has been identified on which the assessment framework should be based. These principles include high-level principles relating to policy and strategy, as well as principles relating to environmental and specifically radiological assessments. A description of the assessment framework and the underlying principles is provided in the companion "Principles Document" (SNIFFER 2005). For the purpose of this project, it has been assumed that all SPB disposals will be made to non-hazardous landfill sites. The framework therefore may not be applicable to inert and hazardous landfill sites.

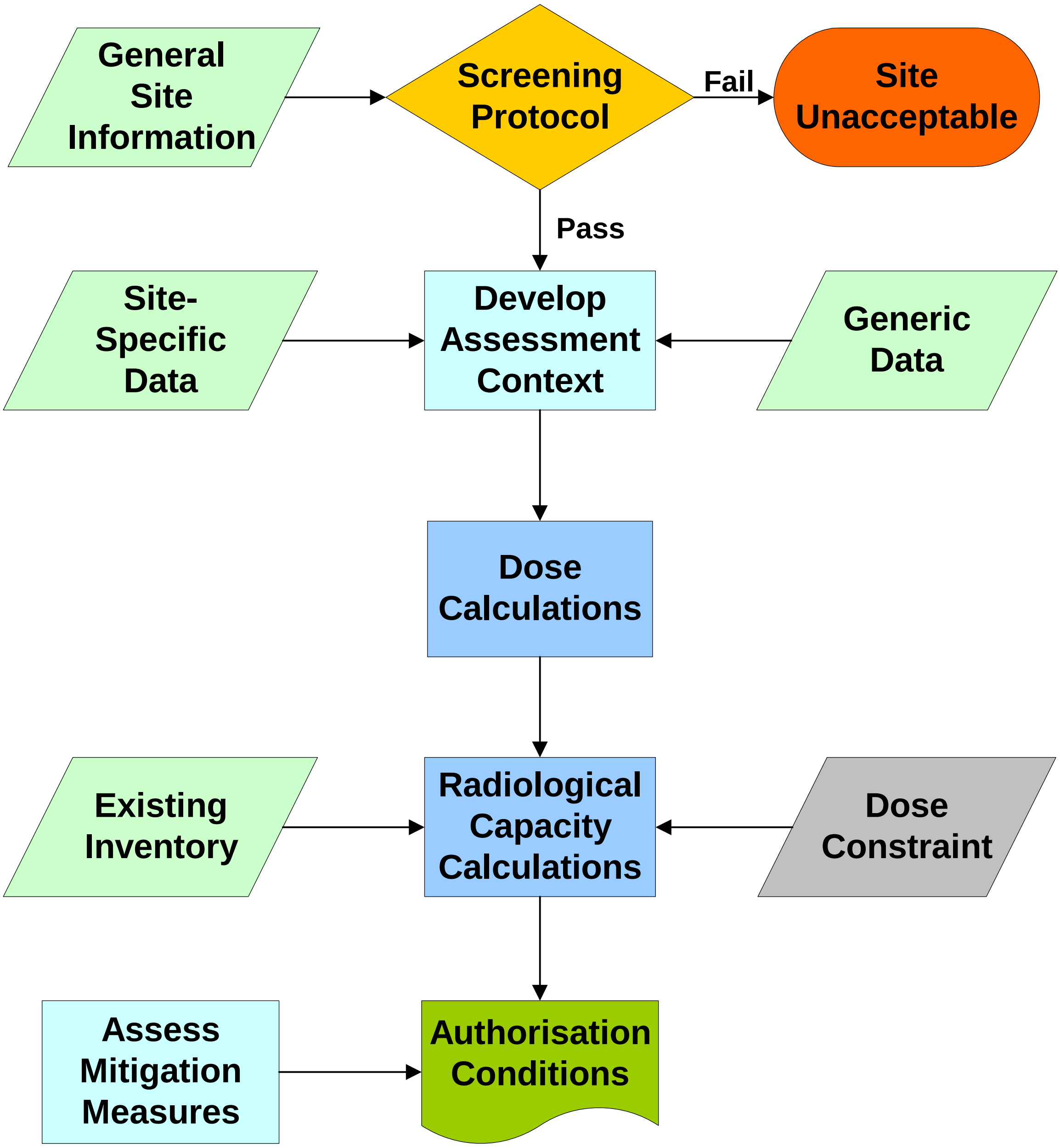
3. The overall framework for the assessment of an SPB site is illustrated in Figure 1. The principal stages of the approach are:

- an initial screening stage, intended to determine whether a more detailed assessment is justified;
- establishing the assessment context;
- undertaking dose calculations;
- calculating the potential radiological capacity for a site; and
- determining the implications of the assessment for the authorisation of disposals at the site.

4. These stages are described in more detail in the Principles Document (SNIFFER 2005). The purpose of this report is to present details of the models that will underpin the dose calculations and hence the calculation of the potential radiological capacity. These models and the calculation of potential radiological capacities have been implemented in an Assessment Model (SNIFFER 2006a), available as an Excel spreadsheet. The Assessment Model has been used in a Case Study (SNIFFER 2006b) to investigate the radiological capacity of a generic site, based on different assessment assumptions. The Case Study also demonstrates the key sensitivities of the Assessment Methodology.

5. The calculation of potential doses arising from radionuclides in a landfill site using the Assessment Model is based on a set of models and scenarios that represent key activities at the site and other aspects of the assessment context. The scenarios identified as potentially important are summarised in Chapter 2, along with descriptions of the conceptual models that could be used to assess these scenarios. Details of the mathematical and numerical models corresponding to each of these are presented in Appendix A.

Figure 1: Overall Approach to the Assessment of SPB Sites.



6. These models require a mixture of generic and site-specific data. The site-specific data will be input at the time of the assessment (see SNIFFER 2006a). Generic data, and also default data for some site-specific information, are presented in Appendix B.

7. The scenarios and conceptual models described in this report will not necessarily apply to all sites considered. The Assessment Model guides the user through the identification of the potential source-receptor-pathways at a particular site, with dose calculations then being undertaken for the appropriate scenarios and conceptual models.

8. The overall aim of the Assessment Methodology is to assess the suitability of controlled landfill sites for the disposal of LLW. This is done through calculation of a radiological capacity for each site, such that potential doses from any pathway can be shown to be below 20 μSv / yr. To ensure that the dose calculations and subsequent capacity determinations are robust, and

comparable between sites, the modelling approach adopted uses conservative assumptions, and does not otherwise consider variability or uncertainty in site-specific conditions. This means that the models used may be less detailed than other models developed for a particular site (e.g., as part of an IPCC application).

9. Other, more detailed, approaches to dose assessment and radiological capacity calculations could be adopted on a site-specific basis, and an explicit treatment of uncertainties might increase the assessed capacity if alternative regulatory criteria (i.e., risk) and authorisation conditions were adopted. These approaches are beyond the scope of the Assessment Methodology described here.

2 Scenarios and Conceptual Models

10. The Principles Document (SNIFFER 2005) discusses the derivation of scenarios relevant to the assessment of potential SPB sites. The scenarios selected are divided into pre-closure (operations and the control period if appropriate) and post-closure (after the loss of control over the site). Scenarios are further sub-divided according to whether they are expected to occur (normal evolution) or are uncertain.

11. The scenarios to be considered in assessments are described in Section 2.1.

12. The conceptual model for a dose calculation comprises a description of the source, the pathway and the receptor, and of the processes that take place along this source-pathway-receptor chain. Each scenario may comprise more than one conceptual model if, for example, there is more than one pathway involved. The possible sources, pathways, and receptors considered in developing conceptual models are described in Section 2.2. A full list of the conceptual models for each of the scenarios is presented in the Principles Document (SNIFFER 2005).

2.1 Scenarios

13. During the operational period (Table 1), the expected evolution of the site, waste, and leachate management is assumed to be as envisaged in the application for a waste management license. Four scenarios are considered for releases of radioactivity to the environment that are not certain to occur:

- Failure of the engineered barrier around and beneath the landfill is considered through a scenario of release of leachate to groundwater.

- Failure of the leachate management is considered through a scenario of spillage of leachate to a nearby surface water body (if one exists).

- Releases to the atmosphere (dust, gases and vapour) are considered through a scenario of a fire in the waste, including spontaneous combustion.

- Exposure of site workers is considered through a scenario covering operations to remediate or re-engineer the site (e.g., to repair a failed barrier or enlarge the site), during which workers handle or are exposed to radioactive waste.

14. The last two of these scenarios are considered to encompass the range of other events that may result in a site worker being exposed, such as short-term contact with leachate.

Table 1: Operational scenarios considered in the Assessment Methodology, and the associated hazards.

Scenario name	Description	Hazards
Normal operations	Expected operation of the landfill up to capping and closure, as approved by the relevant Agency. Doses to site workers and to the public are considered.	Gas Release
		Liquid release (leachate)
		Aerosols (leachate)
		Direct irradiation
Barrier failure	Failure of the artificial sealing liner and geological barrier during operations. Doses to the public are considered.	Liquid release (leachate)
Leachate spillage	Unintentional release of leachate to surface water. Doses to the public are considered.	Liquid release (leachate)
Site remediation or re-engineering	Workers expose waste during operations to remediate containment failure or to enlarge or otherwise re-engineer site.	Solid release (dust while uncovered)
		Direct irradiation
Fire	Fire releases radioactivity. Doses to site workers and to the public are considered.	Solid release (dust), gases and vapour

15. During normal post-closure evolution, the engineered barriers are assumed to degrade slowly, allowing more leachate to potentially migrate into groundwater. Following cessation of control over the site, it is considered possible that houses could be built and occupied on top of the landfill cover. Occupants of these houses could be exposed to both gas releases and direct irradiation (attenuated by the landfill cover).

16. Two post-closure scenarios that are not certain to occur are also considered for the post-closure period (Table 2):

- An abandoned drainage system may begin to clog and, if this occurs while the seals are still effective, bathtubbing (the build-up of leachate until it flows over the sides of the engineered barriers) might occur, thereby forcing leachate into and over the site cover.
- Knowledge of the former site may be lost, or the risks not appreciated, and the site may be inadvertently excavated during an activity such as road building or residential development.

Table 2: Post-closure scenarios included in the Assessment Methodology, and the associated hazards.

Scenario name	Description	Hazards
Normal post-closure evolution	During this time, the landfill engineering is assumed to gradually degrade. Doses to the public are considered.	Gas Release
		Liquid release (leachate)
		Direct irradiation (through cover)
Bathtubbing	Blockage of the drainage system causes overflow of leachate laterally from the landfill onto the soil. Doses to the public are considered.	Liquid release (leachate)
Inadvertent excavation	Waste is inadvertently excavated and re-distributed, e.g., during building or farming. Doses to the intruder and the subsequent user of the site are considered.	Direct irradiation
		Solid release (dust)
		Solid release (waste)

2.2 Conceptual Models

17. This section provides brief, qualitative descriptions of the conceptual models that will be used in the assessment of different scenarios. The conceptual models are divided into descriptions of the sources, pathways and receptors. Each of the conceptual models may be relevant to more than one scenario.

18. The mathematical models developed to implement these conceptual models are presented in Appendix A. However, since the implementation for different scenarios may use different parameters and/or parameter values, the mathematical models are presented on a scenario-by-scenario basis.

2.2.1 Sources

19. Radioactive waste disposed of at SPB sites is generated by a range of small users, such as hospitals, universities and research establishments, who use radioactive materials for a wide range of purposes. Potentially, therefore, there will be a large number of different radionuclides present in SPB sites. Each radionuclide has different physical and chemical properties, resulting in each radionuclide being responsible for a different potential dose via the different exposure pathways over time.

20. Assessments of potential SPB sites will consider a number of key radionuclides or groups of radionuclides that might be disposed to landfill through SPB, as identified through both a review of current practice and waste production and a consideration of radionuclide properties, such as half-life and sorption characteristics.

21. The distribution of radionuclides in SPB sites is treated in two different ways in the assessment calculations, depending on the source and pathway concerned. For the pathways involving the transport of radionuclides in liquid, the radioactive source is assumed to be evenly distributed across the disposal cell or landfill (depending how leachate is collected and

managed). This is a reasonable assumption, as the liquid (leachate) transporting the radioactivity will mix with the liquid coming from other parts of the landfill, so that receptors will not be exposed to leachate from only one small part of the site. This approach also applies in the case of pathways involving dust arising from contaminated soil and from fires. In the former case, the soil is contaminated by leachate and so the same assumption about mixing is made. In the latter case, it is assumed that a fire will affect a larger volume of waste than just the radioactive waste, and so, effectively, radioactivity in the dust inhaled by receptors will be diluted.

22. A different approach is taken for pathways that involve direct irradiation, the handling of waste or inhalation of radioactive gases. These pathways do not involve the diluting effects of mixing leachate or dust from different parts of the site, and it would be unreasonable to assume that the waste was widely dispersed across the whole landfill. In the case of radioactive gases, there will be some mixing with other gases generated within the landfill, but a worker standing near the waste or a resident living on the closed site will be exposed to gas from a relatively small volume of the overall landfill. For these pathways, therefore, all of the SPB disposals to the landfill are assumed to be concentrated into a small volume (10 m^3) of waste.

2.2.2 Pathways

23. The potential pathways by which radionuclides can rise to doses that are considered in the Assessment Methodology are:

- External irradiation from standing near to radioactively-contaminated waste. This pathway will be minimised when the waste is covered, and will then mostly apply to gamma-emitting wastes.

- External irradiation from handling radioactively-contaminated waste. This pathway will not exist for normal operations. However, a worker may inadvertently handle contaminated waste during intervention to re-engineer the site, or excavation during development of the site after closure.

- Inhalation of contaminated dust. Because SPB waste will be emplaced in sacks and be buried on emplacement, creation of contaminated dust is not considered as an exposure pathway during the normal operation of the landfill. However, deliberate intervention to remediate or re-engineer the site, or inadvertent excavation during unrelated development of the site after closure, could lead to the creation of contaminated dust.

- Inhalation of aerosols from leachate. If leachate from the site is managed in such a way as to generate aerosols (e.g., by spraying it back onto the surface of the landfill), aerosols could be inhaled by workers or members of the public near the site.

- Inhalation of dust, particles and gases from fires. Fires are a potential hazard at landfill sites. A fire at an SPB site could lead to the release of radioactive particles and dust that could be inhaled by workers and members of the public downwind of the site, and could also lead to some gaseous releases.

- Inhalation of radioactive gas, i.e., $^{14}CO_2$, $^{14}CH_4$, ^3H, and radon. The first three may be generated through microbial degradation or corrosion of the radioactive waste. Radon is generated through the decay of Ra-226, which in turn is a decay product of Th-230.

- Ingestion of contaminated water. This pathway arises mainly through the leakage of leachate through the engineering and into groundwater (Figure 2). Once groundwater is contaminated, ingestion can occur through:
  - extraction of contaminated groundwater via a well for drinking; and
  - discharge of contaminated groundwater to surface water used for drinking.

  Surface water may also be contaminated by the unintentional release of contaminated leachate.

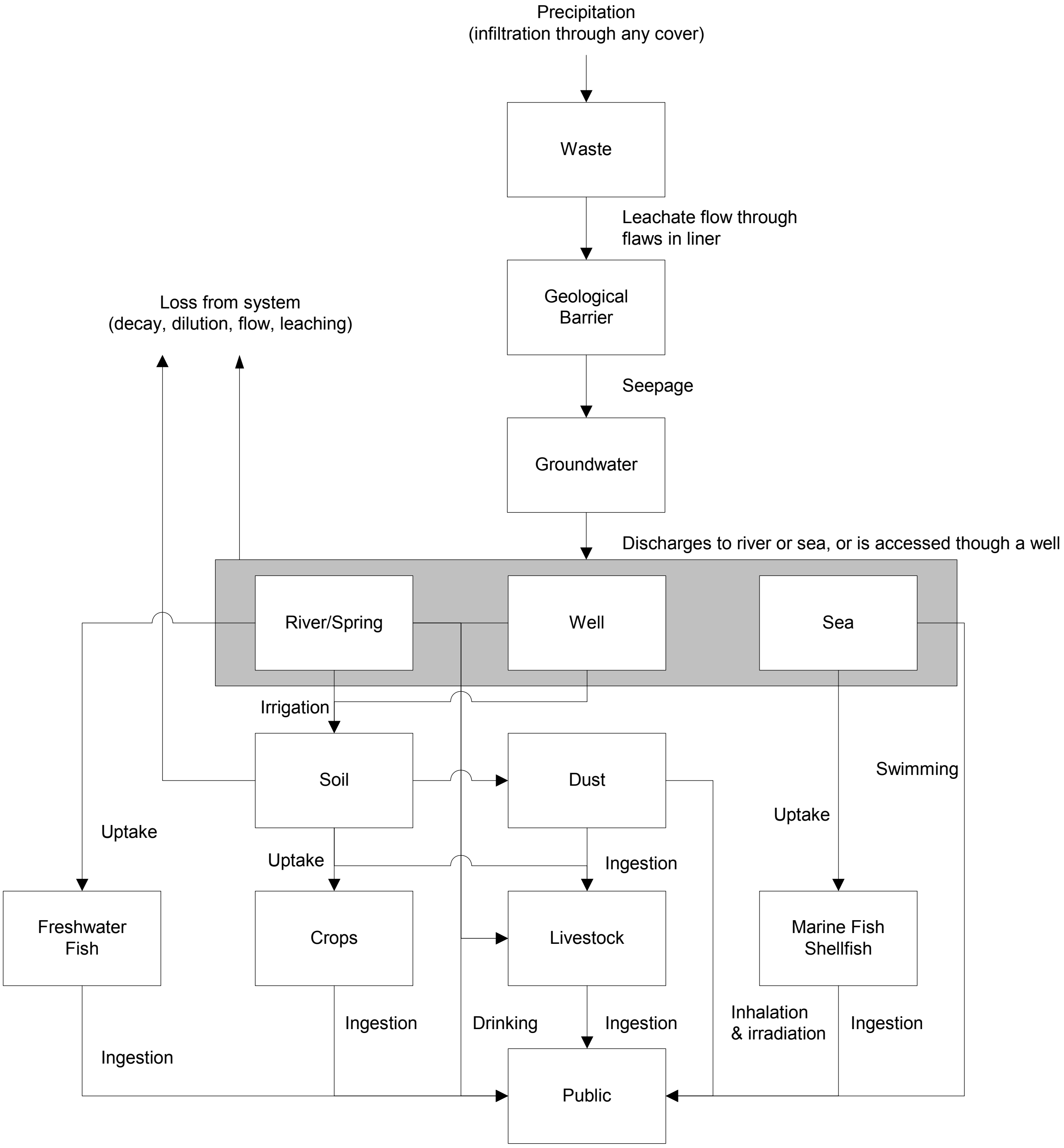
- Ingestion of contaminated food. This pathway arises mainly through the leakage of leachate through the engineering and into groundwater. Once in the groundwater, radioactivity can contaminate food supplies through:
  - extraction of groundwater for irrigation, thereby contaminating soil used for farming, or for stock watering;
  - discharge of contaminated groundwater to surface water used for irrigation, thereby contaminating soil used for farming, or for stock watering; and
  - discharge of contaminated groundwater to surface water or marine water that is used for fishing.

  Surface water may also be contaminated by the unintentional release of contaminated leachate, and soil may be contaminated by the lateral discharge of leachate directly from the site after blockage of the drainage system (bathtubbing).

- Inhalation of dust from contaminated soil. This pathway arises mainly through the leakage of leachate through the engineering and into groundwater. Once in the groundwater, radioactivity can contaminate soil through:
  - capillary rise of contaminated groundwater into the soil;
  - discharge of contaminated groundwater to surface water and subsequent flooding;
  - extraction of groundwater for irrigation, thereby contaminating soil; and
  - discharge of contaminated groundwater to surface water used for irrigation, thereby contaminating soil.

  Soil may also be contaminated by the lateral discharge of leachate directly from the site after blockage of the drainage system (bathtubbing).

Figure 2: Groundwater exposure pathways for the normal operations and post-closure evolution scenarios in the framework.



2.2.3 Receptors

24. The receptors or critical groups to be considered in the assessments of potential SPB sites are assembled from realistic combinations of the critical habits and average habits of populations living, or likely to be living, in the vicinity of an SPB site. The critical habits are those lifestyles or activities that result in the maximum calculated dose being received from each pathway. The doses from each exposure pathway experienced by an individual are additive.

25. For the purposes of assessing potential SPB sites, five groups have been identified, two groups of workers, and three groups comprising members of the public.

- Workers 1. This group comprises workers operating the site during the normal operations phase. The site operators will have the highest occupancy (i.e., period of time spent on the site), and so will receive the highest doses from the exposure pathways associated with the surface of the landfill. For the normal operations scenario, the pathways are irradiation from the landfill surface, inhalation of aerosols from leachate and potentially inhalation of radioactive gases and dust or particles from fires.

- Workers 2. This group comprises workers engaged in site remediation of re-engineering, who may excavate radioactive material. A group with similar habits may also be involved in inadvertent intrusion of the landfill after closure.

- Public 1. This group comprises members of the public living sufficiently close to the site to be affected directly by site operations. Members of this group may inhale aerosols from leachate spraying, dust or particles from fires, and dust from remediation, re-engineering or excavation activities.

- Public 2. This group comprises members of the public living at the point of groundwater discharge or surface water consumption where they will receive the highest dose associated with contaminated groundwater. The same groundwater pathways and exposed public apply for the normal post-closure scenario and to the failure of barrier and spillage of leachate scenarios.

- Public 3. This group comprises members of the public living on or in close proximity to the site after capping and closure. There are three sets of exposure pathways that could affect this group. The first relates to the continued, normal evolution of the site and comprises inhalation of radioactive gases. The second comprises the ingestion of soil and food contaminated during a bathtubbing incident. The third set of pathways relate to contamination after an intrusion, when it is assumed that the land will be levelled, and that the new soil layer may contain a component of the radioactive waste. Doses are calculated for a member of the public residing on this land and farming it for crops and livestock.

26. For some landfill sites, it is possible that two or more of the public groups may coincide. For example, people residing on the cover of the site after closure (Public 3) may also use groundwater (Public 2).

3 References

Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) (2005). *Development of a Framework for Assessing the Suitability of Controlled Landfills to Accept Disposals of Solid Low-Level Radioactive Waste: Principles Document*. SNIFFER, Edinburgh.

Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) (2006a). *Development of a Framework for Assessing the Suitability of Controlled Landfills to Accept Disposals of Solid Low-Level Radioactive Waste: User Manual*. SNIFFER, Edinburgh.

Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) (2006b). *Development of a Framework for Assessing the Suitability of Controlled Landfills to Accept Disposals of Solid Low-Level Radioactive Waste: Case Study*. SNIFFER, Edinburgh.

Appendix A: Mathematical Models

This Appendix presents the mathematical models used to describe the scenarios and pathways by which receptors (exposed groups) might receive doses from LLW disposed of at SPB sites. Section A.1 describes the scenarios and pathways arising during the normal evolution of the site during both the operational and post-closure periods:

- Radioactive gas pathway (Section A.1.1)
- Leakage of leachate and groundwater pathway (Section A.1.2)
- Aerosol pathway (from leachate treatment) (Section A.1.3)
- External irradiation pathway (from buried waste) (Section A.1.4)

Sections A.2 to A.7 describe the calculation of potential doses from uncertain scenarios and pathways:

- Fire (Section A.2)
- Barrier failure (Section A.3)
- Leachate spillage (Section A.4)
- Site re-engineering (Section A.5)
- Inadvertent excavation (Section A.6)
- Bathtubbing (Section A.7)

These mathematical models have been implemented in an Assessment Model, available as an Excel spreadsheet (SNIFFER, 2006a).

A.1 Normal Evolution Scenarios (Operations and Post-Closure)

A.1.1 Radioactive Gas Pathway

Landfill gas may be made up of differing proportions of methane, carbon dioxide, hydrogen, and hydrogen sulphide, with only trace quantities of other gases. Burning off the gas to avoid the risk of explosions creates water vapour and sulphur dioxide from the methane, hydrogen, and hydrogen sulphide. Therefore, isotopes of hydrogen, oxygen, carbon, and sulphur can be released via the gas pathway. For disposal of radioactive wastes, an additional potential contribution to the gas exposure pathway is Rn-222, a gaseous radionuclide produced by ingrowth from Ra-226.

There are no radioisotopes of oxygen that will be disposed of by SPB. The main radioisotope of sulphur, S-35, has a very short half-life (87 days). Therefore, the only radioisotopes considered for the gas pathway are H-3, C-14, and Rn-222.

The model implemented in the Assessment Model (SNIFFER, 2006a) comprises a radioactive gas release model (including radioactive decay), and separate dose assessment models for the operational and post-closure periods.

Radioactive Gas Release

For H-3 (in hydrogen, water, or methane) and C-14 (in carbon dioxide or methane), the release rate of radioactive gas, $R_{Rn,gas}$ (Bq year^{-1}), at time t (years) is given by:

$$R_{Rn,gas}(t) = \frac{A_{Rn,waste} e^{-\lambda_{Rn} t} \cdot f_{gas}}{\tau_{gas}} \qquad \text{(A.1)}$$

where: $A_{Rn,waste}$ is the initial activity of radionuclide Rn in the waste (Bq).

λ_{Rn}	is the decay constant of radionuclide *Rn* (year^{-1}).
f_{gas}	is the fraction of the activity associated with each gas (dimensionless).
τ_{gas}	is the average timescale of generation of each gas (years).

For radon (Rn-222), the release rate at time *t* is given by:

$$R_{radon}(t) = \lambda_{Rn-222} \cdot a \cdot C_{\mathrm{Ra\text{-}226,waste}}\, e^{-\lambda_{Ra-226}t} \cdot \rho_{\mathrm{waste}} \cdot \tau \cdot \mathrm{H}_1 \cdot \mathrm{e}^{\frac{-\mathrm{h}_2}{H_2}} \qquad \text{(A.2)}$$

where: λ	is the decay constant of the indicated radionuclide(year^{-1}).
a	is the surface area of the disposal unit (m^2).
$C_{Ra\text{-}226,waste}$	is the initial Ra-226 concentration in the waste (Bq kg^{-1}).
ρ_{waste}	is the bulk density of the waste (kg m^{-3}).
τ	is the emanation factor, defined as the fraction of the radon atoms produced which escape from the solid phase of the waste into the pore spaces (dimensionless).
H_1	is the effective diffusion relaxation length for the waste (m).
h_2	is the thickness of the cover (m).
H_2	is the effective relaxation length of the cover (m).

Dose Calculations (Operations)

A site worker is assumed to receive the dose. A resident close to the site might also receive a dose. The dose is received by inhalation of gas while outdoors. The peak dose will be received on emplacement (*t* = 0 years), assuming that the gas generation is constant and starts immediately.

The associated air concentration of a radionuclide, $C_{Rn,gas,outdoors}$ (Bq m^{-3}), can be approximated by dividing by the air volume into which the activity released per year is diluted:

$$C_{Rn,gas,outdoors} = \frac{R_{Rn,gas}}{\left(W \cdot u \cdot h \cdot 3.16\mathrm{E}+07\right)} \qquad \text{(A.3)}$$

where: $R_{Rn,gas}$	is the release rate of the radionuclide in gas (Bq year^{-1}) at the time of interest (see equations A.1 and A.2).
W	is the width of the source perpendicular to the wind direction (m).
u	is the mean wind speed (m s^{-1}).
h	is the height for vertical mixing (m).
3.16E+07	is the number of seconds in a year (s year^{-1}).

The dose from gases other than radon is given by:

$$Dose_{gas,outdoors} = C_{Rn,gas,outdoors} \cdot B \cdot O_{out} \cdot D_{inh}^{Rn} \qquad \text{(A.4)}$$

where: O_{out}	is the time spent in the gas plume by the human (years year^{-1}).
B	is the breathing rate (m^3 year^{-1}).
D_{inh}	is the dose coefficient for inhalation of radionuclide *Rn* (Sv Bq^{-1}).

The dose calculation for radon must account for the effect of the daughters of Rn-222 in the body, and has several additional terms:

$$Dose_{radon,outdoors} = C_{radon,outdoors} \cdot K_1 \cdot B \cdot O_{out} \cdot \psi \cdot K_2 \qquad \text{(A.5)}$$

where: K_1	is the effective dose equivalent corresponding to an absorbed energy of 1 joule (Sv J^{-1}).
ψ	is the equilibrium factor (dimensionless).
K_2	is the potential α-energy of Rn-222 in equilibrium with its daughters (J Bq^{-1}).

Dose Calculations (Post-Closure)

For calculation of peak dose, it is assumed that a house is constructed on top of the landfill cap immediately after closure. The dose is calculated for indoor exposure of the house resident to gas accumulating in the dwelling. The release rate of the gases is corrected to allow for decay of the inventory up to closure. Additional loss of activity through release in leachate is not considered.

The calculation of dose from gas indoors is similar to that for outdoors, except that the area and ventilation properties of the house must be taken into account in the calculation of the concentration of the gas.

Doses from inhalation of radioactive gases (excluding radon) are calculated from:

$$Dose_{gas,indoors} = D_{inh}^{Rn} \cdot B \cdot O_{in} \cdot \left[R_{Rn,gas}(t) \cdot \frac{a_H}{a} \cdot \left(\frac{1}{kV} \right) \right] \tag{A.6}$$

where: B	is the breathing rate (m^3 $year^{-1}$).
O_{in}	is the occupancy of the house (years $year^{-1}$).
$R_{Rn,gas}(t)$	is the release rate of gas at time t (Bq $year^{-1}$) (see equation A.1).
a_H/a	is the horizontal area of a dwelling divided by the area over which the radioactive gas is being released (i.e., the facility footprint) (dimensionless).
k	is a turnover rate to account for release of the gas by ventilation ($year^{-1}$).
V	is the volume of the house (m^3).
D_{inh}	is the dose coefficient for inhalation of radionuclide *Rn* (Sv Bq^{-1}).

As for the outdoor calculation, the dose calculation for radon must account for the effect of the daughters of Rn-222 in the body:

$$Dose_{radon,indoors} = K_1 \cdot \psi \cdot K_2 \cdot B \cdot O_{in} \cdot \left[R_{radon}(t) \cdot \frac{a_H}{a} \cdot \left(\frac{1}{kV} \right) \right] \tag{A.7}$$

where the terms are the same as those given for equations A.2, A.5, and A.6.

A.1.2 Groundwater Pathway (Leakage of Leachate)

There are four key components for radionuclides to travel via the groundwater pathway:

1. Infiltration of rainwater into the landfill, and dissolution of radionuclides from the waste.
2. Leakage of the leachate (rainwater / degraded waste components) through the sealing liner.
3. Transport vertically downwards through the unsaturated natural / artificial geological barrier.
4. Mixing into groundwater and transport towards a discharge or abstraction point.

It is assumed that the landfill will conform to current landfill regulations, and that its design will comply with those for a landfill accepting non-hazardous waste. A basal sealing liner, a geological barrier, and a sealing cover after closure are, therefore, assumed to be present.

The management of leachate and the properties of the landfill engineering will change over time. The following assumptions are made to form a framework for the assessment calculations:

- During operations, leachate management is practiced and releases of leachate are only modelled through holes in the sealing liner. The remaining leachate is assumed to be recirculated, such that there is no additional loss of radioactivity from the landfill, e.g., through evaporation or discharge of leachate to rivers. Exposures through practices such as leachate treatment on or off-site and accidental discharge of leachate are considered elsewhere in the assessment framework, but loss of activity through these practices is not accounted for in the assessment of the groundwater pathway.

- After operations, a cap is emplaced, which is initially 100% efficient in reducing infiltration, but gradually becomes less effective to 0% efficient after 100 years.

- After closure, leachate management ceases and the sealing liner ceases to be effective. However, the natural /artificial geological barrier remains effective for the duration of the assessment.

- Assessment calculations for the groundwater pathway are only undertaken for radionuclides with a half-life in excess of one year (see Appendix B). Effective leachate management and engineering will prevent significant releases of radionuclides with shorter half-lives via the groundwater pathway.

The model implemented in the Assessment Model (SNIFFER, 2006a) comprises calculation of infiltration through the cap, a simple source term for radionuclides in leachate, seepage through the liner and the geological barrier, flow and transport within the underlying groundwater system, use of the water and/or dilution within contaminated resources and dose calculations for a range of pathways. Radioactive decay is considered both within the source term and along the transport pathways.

The implementation of a groundwater flow model in the Assessment Model is not intended to duplicate or provide an alternative to the models used for the hydrogeological risk assessment for the site. Rather, the model used in the Assessment Model is intended to provide an estimate of groundwater flow in the vicinity of a site which, combined with conservative assumptions about radionuclide concentrations in leachate and sorption along the transport pathway, will provide robust estimates of environmental concentrations and potential doses for use in calculations of radiological capacity.

Infiltration through the Cap

The water that is available to infiltrate the landfill is a function of the annual precipitation and the efficiency of the cap in diverting this precipitation.

$$P_{eff} = \left(P_{total} - AE - runoff\right) \cdot \left[1 - E_0\left(1 - \frac{t}{t_f}\right)\right] \text{ for } t \le t_f \qquad \text{(A.8)}$$

where P_{eff}	is the potential rate of water infiltration through the cap of the landfill (m year^{-1}).
P_{total}	is the total precipitation (m year^{-1}).
AE	is the amount of precipitation that is lost by evapotranspiration (m year^{-1}).
runoff	is the amount of precipitation lost by runoff (m year^{-1}).
E_0	is the initial cap efficiency (a dimensionless fraction of the infiltration water initially deflected by the cap).
t	is the time after closure (years).
t_f	is the time of cap failure (years).

Prior to closure and emplacement of the cap, and after the time of cap failure, t_f, the right-hand term in the square brackets for cap efficiency is not included. The infiltration rate v_{inf} (m year^{-1}) of water to the waste is determined by either P_{eff}, or the hydraulic conductivity of the waste, K_{waste} (m year^{-1}), whichever is the smaller. The infiltration volume, q_{inf} (m^3 year^{-1}), is the product of the infiltration rate and the area of the landfill, $a_{landfill}$ (m^2).

Source Term

To implement the series of transport equations given above for the groundwater pathway, a radionuclide concentration in the leachate leaking from the landfill is required, and radioactive decay must be taken into account. The leachate leaking from the landfill is modelled as a single, well mixed volume, containing an inventory, A_{Rn} (Bq), of each radionuclide. Radionuclides will dissolve from the waste on contact with the pore water: it is assumed that dissolution is instantaneous up to a concentration for each element that is determined by a distribution coefficient, $K_{d,waste}$ (m^3 kg^{-1}), for each element that represents the equilibrium distribution between the dissolved radionuclide concentration in the porewater, $C_{Rn,leachate}$ (Bq m^{-3}), and the concentration of the radionuclide sorbed onto the waste, $C_{Rn,waste}$ (Bq kg^{-1}):

$$C^{sorbed}_{Rn,waste}(t) = C_{Rn,leachate}(t) \cdot K^{Rn}_{d,waste} \tag{A.9}$$

The dissolved radionuclide concentration in the leachate associated with the inventory remaining in the landfill at time t, $A_{Rn}(t)$ (Bq), is given by:

$$C_{Rn,leachate}(t) = \frac{A_{Rn}(t)}{V_{landfill} \cdot \left(\phi_{waste}\varepsilon + \rho_{waste} K^{Rn}_{d,waste}\right)} \tag{A.10}$$

where $V_{landfill}$	is the volume of the waste (m^3).
φ_{waste}	is the porosity of the waste (dimensionless).
ε	is the degree of saturation of the waste (dimensionless).
ρ_{waste}	is the bulk density of the waste (kg m^{-3}).
$K_{d,waste}$	is the distribution coefficient for radionuclide *Rn* in the waste (m^3 kg^{-1}).

This concentration equation holds for each radionuclide, provided the solubility limit for the element is not reached. Given the low inventory of disposals and the potentially large volume of leachate, this is not considered likely. If the solubility limit is reached, the assessment model will over-estimate dissolved concentrations.

The assumption that radionuclides will be instantaneously released from the waste under equilibrium conditions is pessimistic, as radionuclide release from the waste will be slowed by the rate of dissolution of the waste material. An alternative to the use of distribution coefficients is to use release coefficients, based on empirical measurements at existing waste sites, such as Drigg (e.g., Smith et al. 1988).

The release of radioactivity over time into the geological barrier and the change in the inventory remaining in the landfill as a result of releases and radioactive decay is calculated from:

$$\text{Activity out per year} = \lambda^{Rn}_{waste} \cdot A_{Rn}(t) \qquad \text{(A.11)}$$

$$\lambda^{Rn}_{waste,before} = \frac{q_{out}}{V_{landfill} \cdot \left(\phi_{waste}\varepsilon + \rho_{waste} K^{Rn}_{d,waste}\right)} \text{ before closure} \qquad \text{(A.12)}$$

$$\lambda^{Rn}_{waste,after} = \frac{q_{barrier}}{V_{landfill} \cdot \left(\phi_{waste}\varepsilon + \rho_{waste} K^{Rn}_{d,waste}\right)} \text{ after closure} \qquad \text{(A.13)}$$

$$A_{Rn}(t) = A_{Rn,initial}\, e^{-\left(\lambda_{Rn} + \lambda^{Rn}_{waste,before}\right)t} \text{ before closure} \qquad \text{(A.14)}$$

$$A_{Rn}(t) = e^{-\left(\lambda_{Rn} + \lambda^{Rn}_{waste.after}\right)\left(t - t_{op}\right)} \cdot \left(A_{Rn,initial}\, e^{-\left(\lambda_{Rn} + \lambda^{Rn}_{waste,before}\right)t_{op}}\right) \text{ after closure} \qquad \text{(A.15)}$$

where q_{out}	is the volume of the water flowing through the liner before closure (m^3 $year^{-1}$).
$q_{barrier}$	is the volume of the water flowing out of the landfill into the geological barrier after closure(m^3 $year^{-1}$).
t_{op}	is the time of operations (years).
t	is the time (years).
λ_{Rn}	is the decay constant of radionuclide *Rn* ($year^{-1}$).
$A_{Rn,initial}$	is the initial inventory of each radionuclide (Bq).
-	other symbols as for equation A.10.

Seepage through Sealing Layer

This part of the assessment model is based on the modelling guidance in DOE (1996). All non-hazardous landfills will need to have an artificial sealing layer under the new landfill regulations. Seepage through a geomembrane sealing layer is dominated by leaks through flaws (holes) in the liner. The number of holes will depend on the effectiveness of the quality control during emplacement, but some holes will occur in all cases. Large holes will generally be detected, and so smaller holes or pinholes will be most common. For a geomembrane liner underlain by a mineral layer or host geology, the flow, q_{out} (m^3 $year^{-1}$), through holes in the liner is given by:

$$q_{out} = c \cdot a^{0.1}_{holes} \cdot h^{0.9} \cdot K^{0.74}_{barrier} \cdot 3.16E+07 \qquad \text{(A.16)}$$

where c	is a constant depending on the contact between the liner and the material beneath (0.21 for good contact, 1.15 for poor contact) (dimensionless).
a_{holes}	is the area of the holes (m^2).
h	is the head of leachate (m).
$K_{barrier}$	is the hydraulic conductivity of the barrier (material beneath the liner) ($m\ s^{-1}$).
3.16E+07	is the number of seconds in a year ($s\ year^{-1}$).

The area of the holes will initially depend on the quality control during emplacement, and will gradually increase as the liner degrades. The head of leachate will depend on the rate and volume of water infiltrating into the landfill and on the efficiency of the drainage system. After closure, as the cap degrades and the waste settles, the rate of water inflow may increase and the efficiency of the drainage system may decrease. For the purposes of the assessment model, the liner is assumed to be effective only during the operation of the landfill, and constant properties are assigned for its behaviour during this period. It is assumed that the flow out, q_{out}, is less than the infiltration volume, q_{inf}, for the operational period.

Seepage through the Geological Barrier to the Groundwater

Under the new landfill regulations, non-hazardous waste sites must have a geological barrier or artificial equivalent to protect groundwater, soil, and surface water. The performance of the barrier must be equivalent to a layer with a hydraulic conductivity $\leq 1.0 \times 10^{-9}$ m s^{-1} and a thickness ≥ 1 metres.

Modelling the geological barrier and unsaturated zone as a single unit of thickness, D (m), the advective transfer of radionuclide Rn through the unit, $\lambda_{barrier}$ (year^{-1}), is given by:

$$\lambda_{barrier}^{Rn} = \frac{q_{barrier}}{D \cdot a_{landfill} \cdot \left(\phi_{barrier}\varepsilon + \rho_{barrier} K_{d,barrier}^{Rn}\right)} \qquad \text{(A.17)}$$

where $q_{barrier}$	is the volume of the water flowing through the barrier (m^3 year^{-1}).
$\varphi_{barrier}$	is the porosity of the barrier (dimensionless).
ε	is the degree of saturation of the barrier (dimensionless).
$K_{d,barrier}$	is the distribution coefficient for radionuclide Rn in the barrier (m^3 kg^{-1}).
$\rho_{barrier}$	is the bulk density of the barrier (kg m^{-3}).
$a_{landfill}$	is the area of the landfill (m^2).
D	is the depth of the barrier (m).

For the period of operation of the landfill, $q_{barrier}$ is set to be q_{out} flowing through the sealing liner. After closure, $q_{barrier}$ is set to be the infiltration volume into the landfill, q_{inf} (m^3 year^{-1}), or the product of the area of the landfill, $a_{landfill}$ (m^2) and the hydraulic conductivity of the unit, $K_{barrier}$ (m year^{-1}), whichever is the smaller.

This approach ignores any dispersion effects in the unsaturated zone.

Transport in the Groundwater

The necessarily generic nature of component models within the Assessment Methodology, and the overall context of the groundwater flow modelling within this methodology, has led to the implementation of a one-dimensional compartment model for groundwater transport, based on assumptions that advective transport in the groundwater underlying a landfill obeys Darcy's Law, and that flow occurs horizontally, with longitudinal and transverse dispersion. More complex models, such as those used in site hydrogeological studies, would require implementation and parameterisation on a site-by-site basis and would therefore not be suitable for the type of capacity assessment described here. Ten compartments represents a reasonable compromise between model complexity and sensitivity.

The groundwater path length is divided into a series of units or compartments, with the transfer of radionuclide Rn from each unit to the next downstream, λ_{gw} (year^{-1}), being given by:

$$\lambda_{gw}^{Rn} = \frac{K_{gw} \cdot \Delta H}{L \cdot \left(\phi_{gw} + \rho_{gw} K_{d,rock}^{Rn}\right)} \qquad \text{(A.18)}$$

where K_{gw}	is the hydraulic conductivity of the rock in which the groundwater flow is occurring (m year^{-1}).
ΔH	is the hydraulic gradient (dimensionless).
φ_{gw}	is the porosity of the groundwater pathway (dimensionless).

$K_{d,rock}$ is the distribution coefficient for radionuclide *Rn* in the rock ($m^3\,kg^{-1}$).
ρ_{gw} is the bulk density of the groundwater pathway ($kg\,m^{-3}$).
L is the length of each groundwater compartment (m).

Longitudinal dispersion is approximated implicitly by dividing the path length into ten units. Transverse dispersion is approximated by successively increasing the width (and, thereby, the volume) of each downstream unit to account for spreading of the plume of contaminated groundwater. The width, *W* (m), at a distance, *Δx* (m), downstream is given by:

$$W^2 = W_0^2 + 24\alpha_T \Delta x \tag{A.19}$$

where W_o is the initial width of the unit in which the groundwater flow is occurring (m).
Δx is the distance downstream (m).
α_T is the transverse dispersion length (m), assumed to be one tenth of the initial width.

River / Sea Contamination

Contaminated groundwater reaches the biosphere either by discharging into a river or the sea, or by being abstracted in a borehole and used for irrigation and/or drinking. For discharges, the last downstream groundwater compartment is assumed to flow into a volume of water that represents a portion of a river or the sea. The transfer is calculated from equation A.11. The width of the river or sea compartment is assumed to be the same as the discharging groundwater compartment (see equation A.12).

Once in the river or sea compartment, the rate of transfer of a radionuclide *Rn* out of the compartment, λ_{water} ($year^{-1}$), to become more widely dispersed is given by:

$$\lambda_{water}^{Rn} = \frac{q_{flow}}{V_{water}} \tag{A.20}$$

where q_{flow} is the volume of the water flowing through the river or sea compartment per year ($m^3\,year^{-1}$).
V_{water} is the volume of water being modelled (m^3).

The concentration of a radionuclide in the river water or sea water compartment receiving the groundwater discharge at time *t*, $C_{Rn,water}(t)$ ($Bq\,m^{-3}$), is simply the activity remaining divided by the volume of the water compartment. The interaction of radioactivity with suspended particles in the water is not considered.

Abstraction

If water is abstracted from a borehole into one of the groundwater compartments included in the assessment model, then the concentration of a radionuclide in the abstracted water at time *t*, $C_{Rn,water}(t)$ ($Bq\,m^{-3}$), is given by:

$$C_{Rn,water}(t) = \frac{A_{Rn,gw}(t)}{V_{gw} \cdot \left(\phi_{gw} + \rho_{gw} K_{d,rock}^{Rn}\right)} \tag{A.21}$$

where $A_{Rn,gw}(t)$ is the activity in the groundwater compartment at time *t* (Bq).
V_{gw} is the volume of the groundwater compartment (m^3).
φ_{gw} is the porosity of the groundwater pathway (dimensionless).

K_d	is the distribution coefficient for radionuclide *Rn* in the rock ($m^3\,kg^{-1}$).
ρ_{gw}	is the bulk density of the rock for the groundwater pathway ($kg\,m^{-3}$).

Irrigation

The change in concentration of radionuclides in soil, $C_{Rn,soil}$ ($Bq\,kg^{-1}$), that is irrigated with contaminated water is given by:

$$\frac{dC_{Rn,soil}}{dt} = C_{Rn,water}(t)\cdot\left(\frac{Irrig_{rate}}{\rho_{soil}\cdot d_{soil}}\right) - \lambda_{eff}\cdot C_{Rn,soil}(t) \tag{A.22}$$

where $C_{Rn,water}(t)$	is the concentration of radionuclide in the water used for irrigation at time *t* ($Bq\,m^{-3}$).
$Irrig_{rate}$	is the rate of irrigation ($m\,year^{-1}$).
d_{soil}	is the depth of the soil layer being irrigated (m).
ρ_{soil}	is the density of the soil ($kg\,m^{-3}$).
λ_{eff}	is an effective decay coefficient that considers radioactive decay, leaching from the soil, uptake by plants, and erosion ($year^{-1}$), given by:

$$\lambda_{eff} = \lambda_{Rn} + \left(\frac{P_{total} - AE - runoff}{d_{soil}\cdot\left(\phi_{soil}\varepsilon + \rho_{soil}K_{d,soil}^{Rn}\right)}\right) + \left(\frac{TF_{plant}^{Rn}\cdot Yield_{plant}}{\rho_{soil}\cdot d_{soil}}\right) + \lambda_{erosion} \tag{A.23}$$

where P_{total}	is the total precipitation ($m\,year^{-1}$).
AE	is the amount of precipitation that is lost by evapotranspiration ($m\,year^{-1}$).
$runoff$	is the amount of precipitation lost by runoff ($m\,year^{-1}$).
$Yield_{plant}$	is the plant yield ($kg\,m^{-2}\,year^{-1}$).
TF_{plant}	is the soil to plant transfer factor for radionuclide, *Rn* ($Bq\,kg^{-1}$ fresh weight of crop per $Bq\,kg^{-1}$ of soil).
d_{soil}	is the depth of the soil layer being irrigated (m).
ρ_{soil}	is the bulk density of the soil ($kg\,m^{-3}$).
φ_{soil}	is the porosity of the soil (dimensionless).
ε	is the degree of saturation (dimensionless).
$K_{d,soil}$	is the distribution coefficient for radionuclide *Rn* in the soil ($m^3\,kg^{-1}$).
λ_{Rn}	is the decay constant of radionuclide *Rn* ($year^{-1}$).
$\lambda_{erosion}$	is the loss of radioactivity owing to erosion of the soil ($year^{-1}$).

The contaminated water is assumed to come from the river compartment into which the groundwater discharges, or from an abstraction borehole. In both cases, the removal of activity from the groundwater or river compartment through the irrigation process is not tracked.

Radioactive Decay

The change in activity in the landfill for the calculation of the source term (equations A.14 and A.15), and the change in activity in irrigated soil (equation A.23) directly account for radioactive decay. Radioactive decay along the groundwater pathway is accounted for by applying the radioactive decay law to the activity remaining in each unsaturated flow and groundwater compartment at the end of each timestep or transfer. The timesteps used are short in relation to the half-lives of the radionuclides considered, and the errors introduced by this approach will be insignificant.

Dose Calculations

If a well or river is used for irrigation, then doses can result from ingestion of foodstuffs raised on contaminated soil, inhalation of dust from the soil, and external exposure to the soil. Drinking of contaminated water from a well or river is also a potential exposure pathway. If contaminated groundwater discharges to surface water (spring, river, sea), then ingestion of foodstuffs from the surface water is a potential exposure pathway.

Total potential dose is given by:

$$\begin{aligned} Dose_{groundwater} &= Dose_{drink} + Dose_{ing,fish} + Dose_{ing,soil} + Dose_{ing,crops} \\ &+ Dose_{ing,animals} + Dose_{inh,soil} + Dose_{irr,soil} \end{aligned} \quad (A.24)$$

Activity in the soil is only calculated if irrigation is practised. Otherwise, the dose pathways are reduced to the potential for drinking abstracted water and ingestion of fish and livestock that use contaminated water. The individual terms are defined below.

Dose from drinking contaminated water is given by:

$$Dose_{drink} = Q_{water} \cdot C_{Rn,water}(t) \cdot D_{ing}^{Rn} \quad (A.25)$$

where Q_{water} is the water consumption rate (m^3 year^{-1}).
$C_{Rn,water}(t)$ is the concentration of radionuclide in the water used for drinking at time t (Bq m^{-3}).
D_{ing} is the dose coefficient for ingestion of radionuclide, Rn (Sv Bq^{-1}).

Dose from eating fish and other products harvested from a contaminated water body is given by:

$$Dose_{ing,fish} = \sum_{fish} \left\{ Q_{fish} \cdot C_{Rn,water}(t) \cdot TF_{fish}^{Rn} \right\} \cdot D_{ing}^{Rn} \quad (A.26)$$

where Q_{fish} is the fish (aquatic foodstuff) consumption rate (kg year^{-1}).
$C_{Rn,water}(t)$ is the concentration of radionuclide in the water from which the food is harvested at time t (Bq m^{-3}).
TF_{fish} is the water to fish transfer factor for radionuclide, Rn (m^3 kg^{-1}).
D_{ing} is the dose coefficient for ingestion of radionuclide, Rn (Sv Bq^{-1}).

Dose from ingesting contaminated soil that may be attached to crops is given by:

$$Dose_{ing,soil} = Q_{soil} \cdot C_{Rn,soil}(t) \cdot D_{ing}^{Rn} \quad (A.27)$$

where Q_{soil} is the soil consumption rate (kg year^{-1}).
$C_{Rn,soil}(t)$ is the concentration of radionuclide in the soil at time t (Bq kg^{-1}).
D_{ing} is the dose coefficient for ingestion of radionuclide, Rn (Sv Bq^{-1}).

Dose from crops grown on contaminated soil is given by:

$$Dose_{ing,crops} = \sum_{crop} \left\{ Q_{crop} \cdot \left[C_{Rn,water}(t) \cdot \left(\frac{Irrig_{rate} \cdot Int_{crop} \cdot F_{crop}}{Yield_{crop}} \right) + C_{Rn,soil}(t) \cdot TF_{crop}^{Rn} \right] \right\} \cdot D_{ing}^{Rn} \quad (A.28)$$

where Q_{crop} is the crop consumption rate (kg year^{-1}).
$Irrig_{rate}$ is the rate of irrigation (m year^{-1}).
Int_{crop} is the effective interception factor (dimensionless).

F_{crop}	is the fraction remaining after processing (dimensionless).
$Yield_{crop}$	is the crop yield (kg m^{-2}).
TF_{crop}	is the soil to crop transfer factor for radionuclide, *Rn* (Bq kg^{-1} fresh weight of crop per Bq kg^{-1} of soil).
$C_{Rn,water}(t)$	is the concentration of radionuclide in the water used for irrigation at time *t* (Bq m^{-3}).
$C_{Rn,soil}(t)$	is the concentration of radionuclide in the crop soil at time *t* (Bq kg^{-1}).
D_{ing}	is the dose coefficient for ingestion of radionuclide, *Rn* (Sv Bq^{-1}).

Dose from livestock and associated products (e.g., milk) raised on contaminated ground and fed with contaminated water and/or crops is given by:

$$Dose_{ing,animal} = \sum_{animal}\left\{\left[Q_{animal}\cdot\left(\begin{array}{l} q_{water}\cdot C_{Rn,water}(t)+q_{soil}\cdot C_{Rn,soil}(t)+ \\ \sum_{crop}\left(q_{crop}\cdot C_{Rn,soil}(t)\cdot TF^{Rn}_{crop}\right)\end{array}\right)\right]\cdot TF^{Rn}_{animal}\right\}\cdot D^{Rn}_{ing} \tag{A.29}$$

where Q_{animal}	is the animal foodstuff consumption rate (kg $year^{-1}$).
q_{water}	is the water consumption rate by the animal (m^3 day^{-1}).
q_{soil}	is the soil consumption rate by the animal (kg day^{-1}).
q_{crop}	is the crop consumption rate by the animal (kg day^{-1}).
TF_{crop}	is the soil to crop transfer factor for radionuclide, *Rn* (Bq kg^{-1} fresh weight of crop per Bq kg^{-1} of soil).
TF_{animal}	is the animal product transfer factor for radionuclide, *Rn* (days kg^{-1}).
$C_{Rn,water}(t)$	is the concentration of radionuclide in the water used for drinking by livestock at time *t* (Bq m^{-3}).
$C_{Rn,soil}(t)$	is the concentration of radionuclide in the pasture and crop soil at time *t* (Bq kg^{-1}).
D_{ing}	is the dose coefficient for ingestion of radionuclide, *Rn* (Sv Bq^{-1}).

Dose from external irradiation while living or working on contaminated soil is given by:

$$Dose_{irr,soil} = \left(O_{out} + O_{in}\cdot sf\right)\cdot C_{Rn,soil}(t)\cdot D^{Rn}_{irr,slab} \tag{A.30}$$

where: O_{out}	is the time spent outside exposed to the soil (years $year^{-1}$).
O_{in}	is the time spent inside (years $year^{-1}$).
sf	is the shielding factor from the ground when indoors (dimensionless).
$C_{Rn,soil}(t)$	is the concentration of radionuclide in the soil at time *t* (Bq kg^{-1}).
$D_{irr,slab}$	is the dose conversion factor for irradiation from radionuclide *Rn* (Sv $year^{-1}$ Bq^{-1} kg), based on the receptor being 1 m from the ground and assuming a semi-infinite slab of contamination.

Dose from inhaling dust derived from contaminated soil is given by:

$$Dose_{inh,soil} = B\cdot O_{dust}\cdot C_{Rn,soil}(t)\cdot dustload\cdot D^{Rn}_{inh} \tag{A.31}$$

where: O_{dust}	is the time spent exposed to dust from the soil (years $year^{-1}$).
B	is the breathing rate (m^3 $year^{-1}$).
$C_{Rn,soil}(t)$	is the concentration of radionuclide in the soil at time *t* (Bq kg^{-1}).
$dustload$	is the dust concentration (kg m^{-3} of air).
D_{inh}	is the dose coefficient for inhalation of radionuclide *Rn* (Sv Bq^{-1}).

The variation in dust loads and breathing rates owing to different locations and different activities, e.g., during ploughing, is not considered.

A.1.3 Aerosol Pathway (Leachate Treatment)

This pathway is associated with the treatment of leachate recovered from a landfill during operations. There is a variety of both on-site and off-site treatment options for this leachate, with different options leading to different levels of exposure for different exposed groups. For the purpose of the Assessment Model (SNIFFER, 2006a), the leachate is assumed to be sprayed back onto the surface of the landfill. Although this treatment option is no longer widely practised, it provides the most conservative assumptions for doses via this pathway, since it leads to the generation of contaminated aerosols and also results in doses to the same exposed groups (workers and members of the public living around the site) as other pathways considered.

The Assessment Model for the aerosol pathway considers the same radionuclides as for the groundwater pathway. The concentration of aerosols at time *t*, $C_{Rn,air,aero}(t)$ (Bq m^{-3}), created during leachate spraying is assumed to be equivalent to the concentration of the leachate being sprayed (given by equation A.10) diluted by the aerosol load:

$$C_{Rn,air,aero}(t) = \frac{aerosol}{1000} \cdot C_{Rn,leachate}(t) \qquad \text{(A.32)}$$

where *aerosol* is the aerosol concentration (kg m^{-3} of air).
$C_{Rn,leachate}$ is the activity of radionuclide, *Rn*, in the leachate at time *t* (Bq m^{-3}) – from equation A.10.
1000 is the density of water (kg m^{-3}).

The above equation cautiously assumes that the aerosol created by the spraying is non-depleting during passage towards the exposed individual.

Activity from the aerosol may also be deposited on the ground. The surface concentration of a radionuclide, $C_{Rn,surf,aero}$ (Bq m^{-2}), resulting from deposition is given by:

$$C_{Rn,surf,aero}(t) = C_{Rn,air,aero}(t) \cdot t_{dep,aero} \cdot \left(V_{dep,aero} + W_{out,aero} \cdot h_{aero}\right) \qquad \text{(A.33)}$$

where $t_{dep,aero}$ is the time over which deposition occurs, i.e., the time taken for spraying (s).
$V_{dep,aero}$ is the aerosol deposition velocity (m s^{-1}).
$W_{out,aero}$ is the washout coefficient (s^{-1}).
h_{aero} is the height of the contaminated plume (m).

Dose to workers only considers the aerial pathways of inhalation and external irradiation. Dose to the public also considers the pathways of external irradiation and ingestion related to soil contaminated by surface deposition of the aerosol.

Dose from inhalation is calculated from:

$$Dose_{inh,aero} = B \cdot O_{plume} \cdot C_{Rn,air,aero}(t) \cdot D_{inh}^{Rn} \qquad \text{(A.34)}$$

where: O_{plume} is the time spent exposed to the aerosol (hours $year^{-1}$), based on the time spraying the leachate and the number of spraying events per year.

B	is the breathing rate (m^3 $hour^{-1}$).
D_{inh}	is the dose coefficient for inhalation of radionuclide, *Rn* (Sv Bq^{-1}).

Dose from external irradiation while standing in the aerosol plume is calculated from:

$$Dose_{irr,aero} = O_{plume} \cdot C_{Rn,air,aero}(t) \cdot D^{Rn}_{irr,cloud} \qquad \text{(A.35)}$$

where: O_{plume}	is the time spent exposed to the aerosol (hours $year^{-1}$), based on the time spraying the leachate and the number of spraying events per year.
$D_{irr,cloud}$	is the dose coefficient for irradiation from cloudshine by radionuclide *Rn* (Sv $hour^{-1}$ Bq^{-1} m^3).

Dose from irradiation by aerosol deposited on the ground surface is given by:

$$Dose_{irr,surf} = C_{Rn,surf,aero}(t) \cdot \left(\frac{1 - e^{-\lambda_{Rn} t_{\exp}}}{\lambda_{Rn} t_{\exp}} \right) \left(sf \cdot O_{in} + O_{out} \right) \cdot D^{Rn}_{irr,ground} \qquad \text{(A.36)}$$

where: O_{out}	is the time spent outdoors (years $year^{-1}$).
O_{in}	is the time spent indoors (years $year^{-1}$).
sf	is the shielding factor from the surface concentration while indoors (dimensionless).
λ_{Rn}	is the half-life of radionuclide *Rn* ($year^{-1}$).
t_{exp}	is the time since deposition on the surface (years).
$D_{irr,ground}$	is the dose coefficient for irradiation from groundshine by radionuclide, *Rn* (Sv $year^{-1}$ Bq^{-1} m^2).

If the surface concentration from one spraying event can be assumed to remain constant over the duration of the exposure (e.g., for one year), then the decay term in equation A.36 can be neglected.

Dose from consumption of crops contaminated by aerosol deposited on the ground surface is given by:

$$Dose_{ing,surf} = \sum_{veg} \left\{ Q_{veg} \cdot \left(\frac{Int_{veg} \cdot F_{veg}}{Yield_{veg}} \right) \cdot C_{Rn,surf,aero}(t) \cdot \left(\frac{1 - e^{-(\lambda_{Rn} + \lambda_w) t_r}}{(\lambda_{Rn} + \lambda_w)} \right) \right\} \cdot N_{aero} \cdot D^{Rn}_{ing}$$

(A.37)

where: Q_{veg}	is the vegetable consumption rate (kg $year^{-1}$).
Int_{veg}	is the effective interception factor (dimensionless).
F_{veg}	is the fraction remaining after processing (dimensionless).
$Yield_{veg}$	is the vegetable yield (kg m^{-2}).
λ_{Rn}	is the half-life of radionuclide *Rn* ($year^{-1}$).
λ_w	is the weathering rate of the radionuclide from the vegetable ($year^{-1}$).
t_r	is the time following release over which the vegetables are consumed (years).
N_{aero}	is the number of aerosol releases per year, i.e., the number of spraying events ($year^{-1}$).
D_{ing}	is the dose coefficient for ingestion of radionuclide, *Rn* (Sv Bq^{-1}).

Compared to equation A.36, equation A.37 considers that the radionuclide concentration on the vegetable crop will not be constant over one year, but may be replenished by multiple spraying events.

The aerosol pathway is assumed to be much more significant than exposures resulting from dust from the surface of the landfill, which will be much less contaminated than a leachate aerosol. The same equations could be used to evaluate the dust pathway.

A.1.4 External Irradiation Pathway

This pathway relates to external irradiation from the waste. The waste is assumed to be covered to a depth of 1.5 m on emplacement, as is required by the SPB regulations. Therefore, alpha and beta radiation will be attenuated, and doses to workers during normal operations will only arise from some strong gamma-emitting radionuclides.

Initially, SPB disposals are assumed to be restricted to a small part of the site, and irradiation doses to workers are calculated on this basis. At closure, the activity in the waste is considered to be distributed throughout the entire landfill, leading to external irradiation doses to members of the public living on the site. The cap is assumed to attenuate alpha and beta radiation for this pathway. Releases of radionuclides through normal operations or accident scenarios that result in contamination of soil may also give rise to doses through external irradiation. No attenuation is assumed for radiation arising from contaminated soils.

$$Dose_{irr} = D_{irr,slab}^{Rn} \cdot \left(O_{out} + O_{in} \cdot sf\right) \cdot \left(\frac{A_{Rn,waste}(t)}{V_{waste} \cdot \rho_{waste}}\right) \cdot e^{-\mu^{Rn} x(t)} \qquad \text{(A.38)}$$

where:	O_{out}	is the time spent outside exposed to the waste (years year^{-1}).
	O_{in}	is the time spent inside (years year^{-1}).
	sf	is the shielding factor from the ground when indoors (dimensionless).
	$A_{Rn,\ waste}(t)$	is the activity of the radionuclide, *Rn* (Bq), in the waste at time *t* (from equations A.14 and A.15).
	$D_{irr,slab}$	The dose conversion factor for irradiation from radionuclide *Rn* (Sv year^{-1} Bq^{-1} kg), based on the receptor being 1 m from the ground and the contamination being spread out so as to approximate a semi-infinite slab.
	V_{waste}	is the volume of material in which radioactivity is present (m^3).
	ρ_{waste}	is the bulk density of the waste (kg m^{-3}).
	μ^{Rn}	is the attenuation coefficient for radionuclide *Rn* (m^{-1}).
	$x(t)$	is the thickness of cover material at time *t* (m).

Prior to closure, only workers who might stand on the surface of the landfill are exposed, and O_{in} is assumed to be zero. After closure, a dwelling might be constructed on the surface of the landfill (Public 3), and O_{in} is included.

A.2 Fire Scenario

The calculation of doses as the result of a fire is similar to the calculation for exposure to aerosols (Section A.1.3), but with the exposure resulting from particles in the smoke. The concentration of a radionuclide in air contaminated by fire smoke, $C_{air,fire}(t)$ (Bq m^{-3}) is given by:

$$C_{air,fire}(t) = C_{iac,fire} \cdot \left(\frac{V_{fire}}{V_{landfill}}\right) \cdot \frac{A_{Rn}(t) \cdot f_{Rn,fire}}{t_{fire}} \qquad \text{(A.39)}$$

where $C_{iac,fire}$ is the time-integrated air concentration at ground level at a given distance for the prevalent atmospheric conditions (Bq hour m^{-3} Bq^{-1}).
$f_{Rn,fire}$ is the release fraction for the radionuclide (dimensionless).
V_{fire} is the volume of the waste consumed in the fire (m^3).
$V_{landfill}$ is the volume of the landfill (m^3).
$A_{Rn}(t)$ is the inventory of radionuclide *Rn* in the landfill at time *t*, assuming that it is evenly spread throughout the landfill (Bq) (from equations A.14 and A.15).
t_{fire} is the duration of the fire (hours).

It is conservatively assumed that the associated plume is neutrally buoyant and that the plume is non-depleting during passage towards the exposed individual.

Activity from the smoke may also be deposited on the ground by dry and wet deposition. The surface concentration of a radionuclide, $C_{surf,fire}(t)$ (Bq m^{-2}), resulting from dry and wet deposition is given by:

$$C_{surf,fire}(t) = C_{air,fire}(t) \cdot t_{dep,fire} \cdot \left(v_{dep,fire} + W_{out,fire} \cdot h_{fire}\right) \qquad \text{(A.40)}$$

where $C_{air,fire}(t)$ is the concentration of a radionuclide in the smoke (Bq m^{-3})
$t_{dep,fire}$ is the time over which deposition occurs (s).
$v_{dep,fire}$ is the dry deposition velocity (m s^{-1}).
$W_{out,fire}$ is the washout coefficient (s^{-1}).
h_{fire} is the height of the smoke plume (m).

Dose to workers only considers the aerial pathways of inhalation and external irradiation. Dose to the public also considers the pathways of external irradiation and ingestion related to soil contaminated by surface deposition from the smoke.

Doses are calculated assuming the concentration of radioactivity in fire smoke is constant for all fires occurring in the same year. Dose from inhalation of smoke is given by:

$$Dose_{inh,fire} = B \cdot O_{fire} \cdot C_{air,fire}(t) \cdot D_{inh} \cdot N_{fire} \qquad \text{(A.41)}$$

where O_{fire} is the time spent exposed to the smoke (hours).
B is the breathing rate (m^3 $hour^{-1}$).
D_{inh} is the dose coefficient for inhalation of radionuclide *Rn* (Sv Bq^{-1}).
N_{fire} is the number of fires per year ($year^{-1}$).

Dose from external irradiation while standing in the smoke plume is calculated from:

$$Dose_{irr,fire} = O_{fire} \cdot C_{air,fire}(t) \cdot D^{Rn}_{irr,cloud} \cdot N_{fire} \qquad \text{(A.42)}$$

where O_{fire} is the time spent exposed to the smoke (hours).
$D_{irr,cloud}$ is the dose coefficient for irradiation from cloudshine by radionuclide *Rn* (Sv $hour^{-1}$ Bq^{-1} m^3).
N_{fire} is the number of fires per year ($year^{-1}$).

Dose from irradiation by dust deposited on the ground surface is given by:

$$Dose_{irr,surf,fire} = C_{surf,fire}(t) \cdot \left(\frac{1 - e^{-\lambda_{Rn} t_{\exp}}}{\lambda_{Rn} t_{\exp}} \right) \left(sf \cdot O_{in} + O_{out} \right) \cdot D^{Rn}_{irr,ground} \qquad \text{(A.43)}$$

where O_{out}	is the time spent outdoors (years year^{-1}).
O_{in}	is the time spent indoors (years year^{-1}).
sf	is the shielding factor from the surface dust concentration while indoors (dimensionless).
λ_{Rn}	is the half-life of radionuclide *Rn* (year^{-1}).
t_{exp}	is the time since deposition (years).
$D_{irr,ground}$	is the dose coefficient for irradiation from groundshine by radionuclide, *Rn* (Sv year^{-1} Bq^{-1} m^2).

Dose from consumption of crops contaminated by dust deposited on the ground surface is given by:

$$Dose_{ing,surf,fire} = \sum_{veg} \left\{ Q_{veg} \cdot \left(\frac{Int_{veg} \cdot F_{veg}}{Yield_{veg}} \right) \cdot C_{surf,fire}(t) \cdot \left(\frac{1 - e^{-(\lambda_{Rn} + \lambda_w) t_r}}{(\lambda_{Rn} + \lambda_w)} \right) \right\} \cdot N_{fire} \cdot D^{Rn}_{ing} \qquad \text{(A.44)}$$

where Q_{veg}	is the vegetable consumption rate (kg year^{-1}).
Int_{veg}	is the effective interception factor (dimensionless).
F_{veg}	is the fraction remaining after processing (dimensionless).
$Yield_{veg}$	is the vegetable yield (kg m^{-2}).
λ_{Rn}	is the half-life of radionuclide *Rn* (year^{-1}).
λ_w	is the weathering rate of the radionuclide from the vegetable (year^{-1}).
t_r	is the time following release over which the vegetables are consumed (years).
N_{fire}	is the number of fires per year (year^{-1}).
D_{ing}	is the dose coefficient for ingestion of radionuclide, *Rn* (Sv Bq^{-1}).

This scenario considers all radionuclides that might be disposed through SPB, both long-lived and short-lived. The time of the fire is assumed to be immediately after emplacement of the waste, i.e., no radioactive decay is assumed to have occurred to reduce the source term in equation A.39.

A.3 Barrier Failure Scenario

The mathematical models for this scenario are the same as for the groundwater pathway (Section A.1.2), with the exception that seepage through the liner and geological barrier is replaced with a more rapid transit model. Failure is assumed to be immediate and to be undetected, i.e., no remedial action is taken. The flow rates used as the numerators in equations A.16 and A.17 (q_{out} and $q_{barrier}$) are replaced by the maximum rate of infiltration of water into the landfill, represented by q_{inf} (m^3 year^{-1}) calculated from equation A.8.

A.4 Leachate Spillage Scenario

This is an operational accident scenario. Accidental leakage of leachate through the bottom of a landfill into groundwater is covered by the Accidental Barrier Failure scenario (Section A.3). It is assumed that if leachate is accidentally spilled onto land during, for example, leachate management practices, then the land will be remediated appropriately. Overflow of leachate onto land after control of the landfill has ceased is covered in the Accidental Bathtubbing Scenario (Section A.6). Therefore, the Accidental Spillage scenario considers only the situation where a nearby surface water body is accidentally contaminated during the operation of a landfill.

The contamination is assumed to relate to a one-off event, but the resulting radioactive contamination, $C_{Rn,water,spill}$ (Bq m^{-3}), is assumed to remain constant for one year (i.e., no dilution by throughflow):

$$C_{Rn,water,spill} = \frac{C_{Rn,leachate}(t) \cdot V_{spill}}{V_{water}} \qquad (A.45)$$

where $C_{Rn,leachate}(t)$ is the concentration of radionuclide in the leachate at the time of the spill, t (Bq m^{-3}) – see equation A.10.
V_{spill} is the volume of leachate in the spill (m^3).
V_{water} is the volume of the surface water body (m^3).

The resulting doses to the public depend on the use of the surface water body. If the body is used for irrigation, then a one-off soil concentration, $C_{Rn,soil,spill}$ (Bq kg^{-1}), is calculated from:

$$C_{Rn,soil,spill} = C_{Rn,water,spill} \cdot \left(\frac{Irrig_{rate}}{\rho_{soil} \cdot d_{soil}} \right) \qquad (A.46)$$

where $Irrig_{rate}$ is the amount of irrigation in one year (m).
d_{soil} is the depth of the soil layer being irrigated (m).
ρ_{soil} is the density of the soil (kg m^{-3}).

The exposure pathways from contaminated irrigated soil are given in equations A.27 to A.31. Exposure may also result from ingestion of organisms taken from the water and/or from drinking of the water (see equations A.26 and A.25, respectively).

This scenario considers both short- and long-lived radionuclides.

A.5 Site Re-Engineering Scenario

The Worker 2 exposed group is potentially exposed via two scenarios that are not certain to occur. A worker being inadvertently exposed to contaminated waste during potential future engineering operations on the site is modelled in the same manner as for a worker inadvertently excavating into the site after site closure (see Section A.6.1), but with the inclusion of short-lived radionuclides that may be present during the operational period.

A.6 Inadvertent Excavation Scenario

This scenario considers the possibility of development activity after the site has closed inadvertently disturbing and redistributing the waste. A generic worst-case activity of an individual or group of workers directly excavating and contacting the waste is modelled to capture all of the potential activities that might lead to inadvertent intrusion of a closed site in the future. Only the long-lived radionuclides considered for the groundwater pathway (half-lives > 1 year) are modelled, as shorter-lived radionuclides will have decayed to insignificant levels prior to closure of the landfill site.

A.6.1 Dose to the Excavator

The excavator will receive a dose from irradiation, inhalation, and ingestion:

$$Dose_{\text{excavator}} = D_{irr,slab}^{Rn} TC_{Rn,waste}(t) + D_{inh}^{Rn} TBM_{inh} C_{Rn,waste}(t) + D_{ing}^{Rn} TM_{ing} C_{Rn,waste}(t) \tag{A.47}$$

where M_{inh} is the dust load of contaminated waste inhaled by the excavator (kg m^{-3}).
M_{ing} is the rate of ingestion of dust from the material (kg hour^{-1}).
T is the time the excavator is exposed to the material (hours year^{-1}).
B is the breathing rate (m^3 hour^{-1}).
$D_{irr,slab}$, D_{inh}, and D_{ing} are the dose coefficients for radionuclide *Rn* (Sv hour^{-1} Bq^{-1} kg; Sv Bq^{-1}; and Sv Bq^{-1}, respectively).
$C_{Rn,waste}(t)$ is the concentration of radionuclide *Rn* (Bq kg^{-1}) in the waste at the time of excavation, *t*. This assumes that all of the material contacted by the excavator over the exposure period is contaminated. For the purposes of this scenario, rather than assuming that activity is distributed throughout the landfill, the activity is assumed to be concentrated in a smaller volume of excavated waste, giving:

$$C_{Rn,waste}(t) = \frac{A_{Rn}(t)}{V_{excavate} \cdot \rho_{waste}} \tag{A.48}$$

where $A_{Rn}(t)$ is the activity of radionuclide *Rn* in the landfill at the time of excavation, *t* (Bq) – see equation A.15.
$V_{excavate}$ is the volume of the excavated waste in which the activity is assumed to be contained (m^3).
ρ_{waste} is the density of the waste (kg m^{-3}).

The exposure from external irradiation is assumed to come from proximity to contaminated material, approximated by a semi-infinite slab. The excavator might also receive a dose through direct contact with contaminated waste dust on hands and face:

$$Dose_{\text{skin,hands}} = \left(\left(\frac{C_{Rn,waste}(t) \cdot d_{hands} \cdot \rho_{waste}}{10^4} \right) \cdot \left(D_{gamma7}^{Rn} + D_{beta40}^{Rn} \right) \right) \cdot W_{skin} \cdot \frac{Area_{hands}}{Area_{body}} \cdot T \tag{A.49}$$

where $C_{Rn,waste}(t)$ is the concentration of radionuclide *Rn* (Bq kg^{-1}) in the waste at the time of excavation, *t*.
D_{gamma7} is the skin equivalent dose rate for radionuclide *Rn* to the basal layer of the skin epidermis for gamma irradiation (Sv h^{-1} per Bq cm^{-2}).
D_{beta40} is the skin equivalent dose rate for radionuclide *Rn* to the basal layer of the skin epidermis for hands for beta irradiation, skin thickness 400 μm (40mg cm^{-2}), (Sv h^{-1} per Bq cm^{-2}).
10^4 converts Bq m^{-2} to Bq cm^{-2}.
d_{hands} is the thickness of the contaminated layer on the hands (m).
ρ_{waste} is the density of the waste (kg m^{-3}).
W_{skin} is the tissue weighting factor for skin (dimensionless).
$Area_{hands}$ is the area of skin in contact with the contaminated dust (cm^2).
$Area_{body}$ is the total exposed skin area of the adult body (cm^2).
T is the time the worker is exposed to the material (hours year^{-1}).

$$Dose_{\text{skin,face}} = \left(\left(\frac{C_{Rn,waste}(t) \cdot d_{face} \cdot \rho_{waste}}{10^4} \right) \cdot \left(D_{gamma7}^{Rn} + D_{beta4}^{Rn} \right) \right) \cdot W_{skin} \cdot \frac{Area_{face}}{Area_{body}} \cdot T \tag{A.50}$$

where	$C_{Rn,waste}(t)$	is the concentration of radionuclide Rn (Bq kg^{-1}) in the waste at the time of excavation, t.
	D_{gamma7}	is the skin equivalent dose rate for radionuclide Rn to the basal layer of the skin epidermis for gamma irradiation (Sv h^{-1} per Bq cm^{-2}).
	D_{beta4}	is the skin equivalent dose rate for radionuclide Rn to the basal layer of the skin epidermis for face for beta irradiation, skin thickness 40 μm (4 mg cm^{-2}), (Sv h^{-1} per Bq cm^{-2}).
	10^4	converts Bq m^{-2} to Bq cm^{-2}.
	d_{face}	is the thickness of the contaminated layer on the face (m).
	ρ_{waste}	is the density of the waste (kg m^{-3}).
	W_{skin}	is the tissue weighting factor for skin (dimensionless).
	$Area_{face}$	is the area of skin in contact with the contaminated dust (cm^2).
	$Area_{body}$	is the total exposed skin area of the adult body (cm^2).
	T	is the time the worker is exposed to the material (hours year^{-1}).

A.6.2 Dose to Site Resident after Excavation

It is assumed that following, or as part of the reason for, the excavation, the waste and the cover are mixed together and re-laid, creating a soil layer partly contaminated with the radioactivity that was in the waste. The initial concentration of radionuclide Rn in the material, $C_{Rn,soil,excavate}$ (Bq kg^{-1}), immediately after the excavation event is calculated by:

$$C_{Rn,soil,excavate} = \frac{A_{Rn}(t) \cdot Dil}{V_{landfill} \cdot \rho_{soil}} \qquad \text{(A.51)}$$

where	$A_{Rn}(t)$	is the activity of radionuclide Rn in the landfill at the time of excavation, t (Bq) – see equation A.15.
	Dil	is the dilution factor given by the ratio of the volume of contaminated landfill waste to the volume of other material that is mixed in to form the soil (dimensionless).
	$V_{landfill}$	is the volume of the landfill (m^3).
	ρ_{soil}	is the density of the soil (kg m^{-3}).

Once the initial soil concentration resulting from the excavation has been calculated, the dose to a site resident through use of, and contact with, the contaminated soil are as for those used in the leachate leakage model to calculate dose to a member of the public who uses soil contaminated by irrigation (equations A.27 to A.31; Section A.1.2). However, under the inadvertent excavation scenario, rather than residing at the point where water contaminated by the landfill is used for irrigation, the member of the public resides on the landfill. The peak dose is assumed to occur immediately after excavation. Therefore, no account is taken of subsequent radioactive decay and leaching of radioactivity.

A.7 Bathtubbing Scenario

When a “bath-tub” effect is considered it is necessary to evaluate the concentration of radionuclides in the overflowing leachate, $C_{Rn,leachate}$ (Bq m^{-3}). At time t, this is given by equation A.10.

The volume of the overflow is assumed to be spread over a growing area that is sufficiently large to provide the total crop and livestock products for the exposed group. This gives a soil concentration for the growing area at time t, $C_{Rn,soil,bathtub}$ (Bq kg^{-1}) of:

$$C_{Rn,soil,bathtub} = \frac{C_{Rn,leachate}(t) \cdot V_{bathtub}}{G_{area} \cdot d_{soil} \cdot \rho_{soil}} \tag{A.52}$$

where $C_{Rn,leachate}(t)$ is the concentration of radionuclide in the leachate at time t (Bq m^{-3}) – see equation A.10.

$V_{bathtub}$ is the volume of leachate that overflows into the growing area through the bathtub event (m^{3}).

G_{area} is the growing area of soil required to raise crops / livestock (m^{2}).

d_{soil} is the depth of the soil layer (m).

ρ_{soil} is the density of the soil (kg m^{-3}).

It is assumed that the bathtubbing is transient, with the overflow occurring within the timeframe of one year. No account is taken of the leaching of radioactivity from the soil after the contamination has occurred, or of the possible build up of contamination though multiple overflows over several years. Only the long-lived radionuclides considered for the groundwater pathway (half-lives > 1 year) are modelled.

Once the soil concentration resulting from the bathtub incident has been calculated, the dose calculations are as for those used in leachate leakage model to calculate dose to a member of the public who uses land contaminated by irrigation (equations A.27 to A.31; Section A.1.2). However, under the accidental bathtubbing scenario, rather than residing at the point where water contaminated by the landfill is used for irrigation, the member of the public resides on the land contaminated by the leachate overflow.

A.8 References

DOE (Department of the Environment). (1996). *Landfill Design, Construction and Operational Practice*. ISBN 0 11 753185 5. London: The Stationery Office.

Smith, G.M., Fearn, H.S., Smith, K.R., Davis, J.P. and Klos, R. (1988). *Assessment of the Radiological Impact of Disposal of Solid Radioactive Waste at Drigg*. National Radiological Protection Board Report NRPB-M148.

Appendix B: Model Parameterisation

This Appendix discusses the data requirements for the mathematical models described in Appendix A of this report and implemented in the Assessment Model (SNIFFER, 2006a). Many of the model parameters have been assigned default values which should be applicable to a range of landfills. The basis for these values is presented here and should be considered by users in determining whether the default values are applicable to a particular site or whether alternative parameter values are required. Other parameter values are site-specific and must be provided by the user. These data are discussed in general terms here and suggested data sources are provided in the User Manual for the Assessment Model (SNIFFER, 2006a).

Section B.1 describes the selection of radionuclides for assessment calculations and provides radionuclide-specific data. Sections B.2 to B.5 describe the data used in assessing doses arising from the Normal Evolution scenario through four principal pathways:
- Radioactive gas pathway (Section B.2)
- Groundwater pathway (Section B.3)
- Aerosol pathway (Section B.4)
- External irradiation pathway (Section B.5)

Sections B.6 to B.11 describe the data used in assessing potential doses from uncertain scenarios and pathways:
- Fire (Section B.6)
- Barrier failure (Section B.7)
- Leachate spillage (Section B.8)
- Site re-engineering (Section B.9)
- Inadvertent excavation (Section B.10)
- Bathtubbing (Section B.11)

B.1 Baseline Radionuclide-Specific Data

There are potentially a large number of different radionuclides that could be considered for disposal through controlled burial. Based on an analysis of the likely sources of waste for this disposal route, Table B.1 lists the radionuclides for which data are provided as part of the baseline data set in the Assessment Model (SNIFFER, 2006a). These data should be sufficient for the majority of analyses. The user can enter further data if capacity calculations for radionuclides not included in Table B.1 are required.

The radionuclides are divided into long-lived and short-lived categories in Table B.1. The short-lived radionuclide category (half-lives less than one year) is considered for doses to workers (through the external irradiation and aerosol pathways) and the public (through the aerosol pathway) during normal operations, and for doses to workers and the public arising from the Fire and Site Re-Engineering Scenarios.

Several of the radionuclides listed in Table B.1 decay to daughter radionuclides as part of a decay chain (ingrowth). Radionuclides marked with an asterisk decay via one or more short-lived radionuclides (half-lives of less than 30 days). These short-lived daughters are not included in the set of radionuclides available for modelling. Instead, the parent and short-lived daughters are assumed to be in secular equilibrium, and the properties assigned to the parent reflect the entire chain. The exception to this rule is the short-lived daughter of Ra-226; generation of Rn-222 (radon) is considered as part of the gas exposure pathway, assuming that the gas can migrate over the timescale of its short half-life.

In the case of chains with longer-lived daughters, the Assessment Methodology does not explicitly calculate ingrowth or doses from daughters. Instead, the user must select the daughters to be considered and assess the impact of these on radiological capacity. The User Manual for the Assessment Model (SNIFFER, 2006a) provides further information on this approach.

The half-lives and decay constants of the radionuclides listed in Table B.1 are provided in Table B.2; data are taken from Lide (1996). Dose coefficients for the ingestion, inhalation, and external irradiation of the radionuclides are provided in Table B.3. Inhalation and ingestion dose coefficients are effective doses to members of the public, taken from EC (1996 – Tables A and B of Annex III), which, in turn, is consistent with IAEA (1996). Where a number of values are provided in EC (1996) covering, for example, different age groups and clearance rates, the adult public values with worst-case clearance rates have been used. Effective irradiation cloudshine and groundshine dose coefficients are from Eckerman and Legett (1996) via Health Canada (1999). Eckerman and Legett (1996) calculated effective dose coefficients based on the same data as Eckerman and Ryman (1993), but based on updated International Commission on Radiological Protection (ICRP) tissue weighting specifications (ICRP, 1991). Effective irradiation slab dose coefficients are not available from Health Canada (1999), and these are taken from Eckerman and Ryman (1993) assuming an infinite depth of contamination and a soil density of 1,600 kg m^{-3} for conversion of units. Suggested values for attenuation coefficients are derived from Hung (2000). Radionuclide-specific factors for calculating the dose to skin from contaminated material on the face and hands are provided in Table B.4. Data are taken from CEC (1993) and Asselineau *et al.* (1995).

Table B.1: Radionuclides included in the baseline data set of the Assessment Model.

Radio-nuclide	Half-life (years)	Short-lived chains	Daughter(s)
H-3	12		
Be-10	1.6 M		
C-14	5,730		
Na-22	2.6		
Cl-36	301,000		
Ca-41	140,000		
Mn-54	0.9		
Fe-55	2.7		
Co-57	0.7		
Ni-59	75,000		
Co-60	5.3		
Ni-63	96		
Zn-65	0.7		
Se-79	65,000		
Sr-90	29		
Zr-93	1.5 M		
Nb-94	20,300		
Zr-95	0.2		
Tc-99	213,000		
Ru-106	1.0		
Pd-107	6.5 M		
Ag-108m	127		
Ag-110m	0.7		
Sb-125	2.8		
Te-125m	0.2		
Sn-126	100,000		
I-129	15.7 M		
Ba-133	11		
Cs-134	2.1		
Cs-135	2.3 M		
Cs-137	30	*	
Ce-144	0.8		
Pm-147	2.6		
Sm-147	106,000 M		
Sm-151	90		
Eu-152	13		
Eu-154	8.8		
Eu-155	5.0		
Pb-210	22	*	→Po-210
Po-210	0.4		
Ra-226	1,600	*	→Pb-210→ Po-210
Ra-228	22	*	→Th-228
Ac-227	5.8	*	
Th-228	1.9	*	
Th-229	7,340	*	

Radio-nuclide	Half-life (years)	Short-lived chains	Daughter(s)
Th-230	77,000		→Ra-226→ Pb-210→ Po-210
Th-232	14,000 M		→Ra-228→ Th-228
Pa-231	32,700		→Ac-227
U-233	158,000		→Th-229
U-234	244,000		→Th-230→ Ra-226→ Pb-210→ Po-210
U-235	704 M	*	→Pa-231→ Ac-227
U-236	23.4 M		→Th-232→ Ra-228→ Th-228
U-238	4,470 M	*	→U-234→ Th-230→ Ra-226→ Pb-210→ Po-210
Np-237	2.14 M		→ U-233→ Th-229
Pu-238	88		→U-234→ Th-230→ Ra-226→ Pb-210→ Po-210
Pu-239	24,100		→U-235→ Pa-231→ Ac-227
Pu-240	6,540		→U-236→ Th-232→ Ra-228→ Th-228
Pu-241	14	*	→Am-241→ Np-237→ U-233→ Th-229
Pu-242	376,000		→U-238→ U-234→ Th-230→ Ra-226→ Pb-210→ Po-210
Cm-242	0.4		→Pu-238→ U-234→ Th-230→ Ra-226→ Pb-210→ Po-210
Am-241	432		→Np-237→ U-233→ Th-229
Am-242	152	*	→(branching ratio 8.23E-1) Cm-242→ Pu-238→ U-234→ Th-230 → Ra-226→ Pb-210→ Po-210
			→(branching ratio 1.72E-1) Pu-242→ U-238→ U-234→ Th-230 → Ra-226→ Pb-210→ Po-210
			→(branching ratio 4.76E-3) Pu-238→ U-234→ Th-230→ Ra-226 → Pb-210→ Po-210
Am-243	7,380	*	→Pu-239→ U-235→ Pa-231→ Ac-227
Cm-243	29		→(branching ratio 9.98E-1) Pu-239→ U-235→ Pa-231→ Ac-227
			→(branching ratio 2.40E-3) Am-243→ Pu-239→ U-235→ Pa-231 → Ac-227
Cm-244	18		→Pu-240→ U-236→ Th-232→ Ra-228→ Th-228
Cm-245	8,500		→Pu-241→ Am-241→ Np-237→ U-233→ Th-229
Cm-246	4,730		→Pu-242→ U-238→ U-234→ Th-230→ Ra-226→ Pb-210→ Po-210

Table B.2: Half-lives and decay constants for radionuclides included in the baseline data set of the Assessment Model (all data from Lide, 1996).

Radionuclide	**Half-life (years)**	**Decay constant (year^{-1})**	**Decay constant (s^{-1})**
H-3	1.23E+01	5.63E-02	1.79E-09
Be-10	1.60E+06	4.33E-07	1.37E-14
C-14	5.73E+03	1.21E-04	3.83E-12
Na-22	2.60E+00	2.66E-01	8.43E-09
Cl-36	3.01E+05	2.30E-06	7.30E-14
Ca-41	1.40E+05	4.95E-06	1.57E-13
Mn-54	8.55E-01	8.11E-01	2.57E-08
Fe-55	2.70E+00	2.57E-01	8.13E-09
Co-57	7.42E-01	9.34E-01	2.96E-08
Ni-59	7.50E+04	9.24E-06	2.93E-13
Co-60	5.27E+00	1.31E-01	4.17E-09
Ni-63	9.60E+01	7.22E-03	2.29E-10
Zn-65	6.68E-01	1.04E+00	3.29E-08
Se-79	6.50E+04	1.07E-05	3.38E-13
Sr-90	2.91E+01	2.38E-02	7.55E-10
Zr-93	1.53E+06	4.53E-07	1.44E-14
Nb-94	2.03E+04	3.41E-05	1.08E-12
Zr-95	1.75E-01	3.96E+00	1.25E-07
Tc-99	2.13E+05	3.25E-06	1.03E-13
Ru-106	1.01E+00	6.86E-01	2.17E-08
Pd-107	6.50E+06	1.07E-07	3.38E-15
Ag-108m	1.27E+02	5.46E-03	1.73E-10
Ag-110m	6.84E-01	1.01E+00	3.21E-08
Sb-125	2.77E+00	2.50E-01	7.93E-09
Te-125m	1.59E-01	4.36E+00	1.38E-07
Sn-126	1.00E+05	6.93E-06	2.20E-13
I-129	1.57E+07	4.41E-08	1.40E-15
Ba-133	1.07E+01	6.48E-02	2.05E-09
Cs-134	2.06E+00	3.36E-01	1.07E-08
Cs-135	2.30E+06	3.01E-07	9.55E-15
Cs-137	3.00E+01	2.31E-02	7.32E-10
Ce-144	7.78E-01	8.91E-01	2.82E-08
Pm-147	2.62E+00	2.65E-01	8.38E-09
Sm-147	1.06E+11	6.54E-12	2.07E-19
Sm-151	9.00E+01	7.70E-03	2.44E-10
Eu-152	1.33E+01	5.21E-02	1.65E-09
Eu-154	8.80E+00	7.88E-02	2.50E-09
Eu-155	4.96E+00	1.40E-01	4.43E-09
Pb-210	2.23E+01	3.11E-02	9.85E-10
Po-210	3.79E-01	1.83E+00	5.79E-08
Ra-226	1.60E+03	4.33E-04	1.37E-11
Ac-227	2.18E+01	3.18E-02	1.01E-09
Ra-228	5.75E+00	1.21E-01	3.82E-09
Th-228	1.91E+00	3.63E-01	1.15E-08
Th-229	7.34E+03	9.44E-05	2.99E-12
Th-230	7.70E+04	9.00E-06	2.85E-13

Radionuclide	**Half-life (years)**	**Decay constant (year^{-1})**	**Decay constant (s^{-1})**
Pa-231	3.27E+04	2.12E-05	6.72E-13
Th-232	1.40E+10	4.95E-11	1.57E-18
U-233	1.58E+05	4.39E-06	1.39E-13
U-234	2.44E+05	2.84E-06	9.00E-14
U-235	7.04E+08	9.84E-10	3.12E-17
U-236	2.34E+07	2.96E-08	9.38E-16
Np-237	2.14E+06	3.24E-07	1.03E-14
Pu-238	8.77E+01	7.90E-03	2.50E-10
U-238	4.47E+09	1.55E-10	4.91E-18
Pu-239	2.41E+04	2.88E-05	9.11E-13
Pu-240	6.54E+03	1.06E-04	3.36E-12
Am-241	4.32E+02	1.60E-03	5.08E-11
Pu-241	1.44E+01	4.81E-02	1.52E-09
Am-242m	1.52E+02	4.56E-03	1.44E-10
Cm-242	4.46E-01	1.55E+00	4.92E-08
Pu-242	3.76E+05	1.84E-06	5.84E-14
Am-243	7.38E+03	9.39E-05	2.98E-12
Cm-243	2.85E+01	2.43E-02	7.71E-10
Cm-244	1.81E+01	3.83E-02	1.21E-09
Cm-245	8.50E+03	8.15E-05	2.58E-12
Cm-246	4.73E+03	1.47E-04	4.64E-12

Table B.3: Dose coefficients for radionuclides included in the baseline data set of the Assessment Model. Unless indicated otherwise, inhalation and ingestion dose coefficients are from EC (1996) [using adult public values with worst-case clearance rates for inhalation dose]; irradiation cloudshine and groundshine coefficients are from Eckerman and Legett (1996); irradiation slab coefficients are from Eckerman and Ryman (1993) - see text for further details. Suggested values for attenuation coefficients are derived from Hung (2000), based on data by Eckerman and Ryman (1993).

Radionuclide	Inhalation (Sv Bq^{-1})	Ingestion (Sv Bq^{-1})	Irradiation Cloudshine (Sv h^{-1} Bq^{-1} m^{3})	Irradiation Groundshine (Sv year^{-1} Bq^{-1} m^{2})	Irradiation Slab (Sv year^{-1} Bq^{-1} kg)	Attenuation Coefficient
H-3	2.60E-10	1.80E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Be-10	3.50E-08	1.10E-09	4.97E-13	1.08E-10	2.91E-10	2.77E+01
C-14	5.80E-09	5.80E-10	9.36E-15	4.01E-13	3.63E-12	5.59E+01
Na-22	1.30E-09	3.20E-09	3.67E-10	6.47E-08	3.70E-06	1.32E+01
Cl-36	7.30E-09	9.30E-10	5.98E-13	3.53E-10	6.46E-10	2.04E+01
Ca-41	1.80E-10	1.90E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mn-54	1.50E-09	7.10E-10	1.38E-10	2.50E-08	1.39E-06	1.36E+01
Fe-55	7.70E-10	3.30E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Co-57	1.00E-09	2.10E-10	1.79E-11	3.41E-09	1.35E-07	2.71E+01
Ni-59	4.40E-10	6.30E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Co-60	3.10E-08	3.40E-09	4.28E-10	7.26E-08	4.38E-06	1.20E+01
Ni-63	4.80E-10	1.50E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zn-65	2.20E-09	3.90E-09	9.79E-11	1.71E-08	1.00E-06	1.26E+01
Se-79	6.80E-09	2.90E-09	1.42E-14	5.18E-13	5.03E-12	5.40E+01
Sr-90	1.60E-07	2.80E-08	3.54E-13	5.18E-11	1.90E-10	2.88E+01
Zr-93	2.50E-08	1.10E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nb-94	4.90E-08	1.70E-09	2.59E-10	4.70E-08	2.62E-06	1.38E+01
Zr-95	5.90E-09	9.50E-10	1.21E-10	2.22E-08	1.22E-06	1.41E+01
Tc-99	1.30E-08	6.40E-10	1.03E-13	2.04E-12	3.39E-11	3.85E+01
Ru-106	6.60E-08	7.00E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pd-107	5.90E-10	3.70E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108m	3.70E-08	2.30E-09	2.61E-10	4.89E-08	2.61E-06	1.49E+01
Ag-110m	1.20E-08	2.80E-09	4.57E-10	8.14E-08	4.64E-06	1.32E+01
Sb-125	1.20E-08	1.10E-09	6.73E-11	1.29E-08	6.61E-07	1.54E+01
Te-125m	4.20E-09	8.70E-10	1.21E-12	8.39E-10	4.09E-09	4.47E+01
Sn-126	2.80E-08	4.70E-09	6.62E-12	1.52E-09	3.98E-08	3.59E+01
I-129	3.60E-08	1.10E-07	1.01E-12	6.15E-10	3.50E-09	1.31E+02
Ba-133	1.00E-08	1.50E-09	5.83E-11	1.18E-08	5.35E-07	1.79E+01
Cs-134	2.00E-08	1.90E-08	2.54E-10	4.67E-08	2.56E-06	1.42E+01
Cs-135	8.60E-09	2.00E-09	3.42E-14	8.49E-13	1.04E-11	4.65E+01
Cs-137	3.90E-08	1.30E-08	3.34E-13	9.44E-11	2.03E-10	2.61E+01
Ce-144	5.30E-08	5.20E-09	2.75E-12	5.81E-10	1.94E-08	2.77E+01
Pm-147	5.00E-09	2.60E-10	3.12E-14	8.84E-13	1.35E-11	3.73E+01
Sm-147	9.60E-06	4.90E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	4.00E-09	9.80E-11	8.86E-17	1.12E-13	2.66E-13	4.66E+02
Eu-152	4.20E-08	1.40E-09	1.90E-10	3.41E-08	1.89E-06	1.30E+01
Eu-154	5.30E-08	2.00E-09	2.07E-10	3.69E-08	2.07E-06	1.29E+01
Eu-155	6.90E-09	3.20E-10	7.70E-12	1.69E-09	4.92E-08	3.37E+01
Pb-210	5.60E-06	6.90E-07	1.61E-13	6.72E-11	6.61E-10	8.36E+01
Po-210	4.30E-06	1.20E-06	1.40E-15	2.55E-13	1.41E-11	1.39E+01
Ra-226	9.50E-06	2.80E-07	1.02E-12	1.93E-10	8.58E-09	2.29E+01
Ac-227	5.50E-04	1.10E-06	1.84E-14	4.45E-12	1.34E-10	2.75E+01

Radionuclide	**Inhalation (Sv Bq^{-1})**	**Ingestion (Sv Bq^{-1})**	**Irradiation Cloudshine (Sv h^{-1} Bq^{-1} m^{3})**	**Irradiation Groundshine (Sv year^{-1} Bq^{-1} m^{2})**	**Irradiation Slab (Sv year^{-1} Bq^{-1} kg)**	**Attenuation Coefficient**
Ra-228	1.60E-05	6.90E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Th-228	4.00E-05	7.20E-08	2.92E-13	6.72E-11	2.15E-09	2.65E+01
Th-229	2.40E-04	4.90E-07	1.21E-11	2.49E-09	8.68E-08	2.82E+01
Th-230	1.00E-04	2.10E-07	5.33E-14	2.01E-11	3.27E-10	2.93E+01
Pa-231	1.40E-04	7.10E-07	5.65E-12	1.19E-09	5.15E-08	1.91E+01
Th-232	1.10E-04	2.30E-07	2.61E-14	1.44E-11	1.40E-10	3.74E+01
U-233	9.60E-06	5.10E-08	5.11E-14	1.89E-11	3.77E-10	2.29E+01
U-234	9.40E-06	4.90E-08	2.20E-14	1.85E-11	1.09E-10	3.58E+01
U-235	8.50E-06	4.70E-08	2.33E-11	4.42E-09	1.95E-07	2.32E+01
U-236	8.70E-06	4.70E-08	1.39E-14	1.59E-11	5.81E-11	3.16E+01
Np-237	5.00E-05	1.10E-07	3.19E-12	7.95E-10	2.11E-08	3.16E+01
Pu-238	1.10E-04	2.30E-07	1.26E-14	1.98E-11	4.09E-11	3.73E+01
U-238	8.00E-06	4.50E-08	9.00E-15	1.33E-11	2.79E-11	8.74E+01
Pu-239	1.20E-04	2.50E-07	1.25E-14	8.96E-12	7.98E-11	2.18E+01
Pu-240	1.20E-04	2.50E-07	1.23E-14	1.90E-11	3.96E-11	4.44E+01
Am-241	9.60E-05	2.00E-07	2.43E-12	7.35E-10	1.19E-08	5.37E+01
Pu-241	2.30E-06	4.80E-09	2.28E-16	5.43E-14	1.60E-12	2.96E+01
Am-242m	9.20E-05	1.90E-07	8.96E-14	7.13E-11	4.56E-10	3.59E+01
Cm-242	5.90E-06	1.20E-08	1.45E-14	2.22E-11	4.62E-11	3.16E+01
Pu-242	1.10E-04	2.40E-07	1.04E-14	1.57E-11	3.46E-11	5.58E+01
Am-243	9.60E-05	2.00E-07	6.66E-12	1.51E-09	3.84E-08	4.04E+01
Cm-243	6.90E-05	1.50E-07	1.91E-11	3.72E-09	1.57E-07	2.29E+01
Cm-244	5.70E-05	1.20E-07	1.22E-14	2.03E-11	3.41E-11	3.52E+02
Cm-245	9.90E-05	2.10E-07	1.26E-11	2.54E-09	9.19E-08	2.79E+01
Cm-246	9.80E-05	2.10E-07	1.12E-14	1.82E-11	3.14E-11	1.29E+02

Table B.4: Radionuclide-specific factors for calculating the dose to skin from contaminated material on the face and hands. Data from CEC (1993).

Radionuclide	**Skin gamma D_{gamma7} (Sv h^{-1} per Bq cm^{-2})**	**Skin beta D_{beta4} (Sv h^{-1} per Bq cm^{-2})**	**Skin beta D_{beta40} (Sv h^{-1} per Bq cm^{-2})**
H-3	0.00E+00	0.00E+00	0.00E+00
Be-10	0.00E+00	2.51E-06	3.65E-07
C-14	0.00E+00	9.02E-07	0.00E+00
Na-22	1.20E-07	2.40E-06	3.77E-07
Cl-36	1.10E-11	2.51E-06	5.37E-07
Ca-41	0.00E+00		
Mn-54	6.10E-08	0.00E+00	0.00E+00
Fe-55	1.60E-08	0.00E+00	0.00E+00
Co-57	4.00E-08	1.10E-07	0.00E+00
Ni-59	6.39E-08	0.00E+00	0.00E+00
Co-60	1.30E-07	1.83E-06	2.85E-08
Ni-63	0.00E+00	1.83E-08	0.00E+00
Zn-65	5.00E-08	3.77E-08	1.14E-09
Se-79	0.00E+00	1.14E-06	0.00E+00
Sr-90	2.40E-12	5.14E-06	1.76E-06
Zr-93	0.00E+00	2.40E-08	0.00E+00
Nb-94	1.00E-07	2.17E-06	1.83E-07
Zr-95	8.50E-08	2.68E-06	8.72E-08
Tc-99	3.49E-14	1.60E-06	1.37E-08
Ru-106	1.20E-08	2.85E-06	1.60E-06
Pd-107	0.00E+00	0.00E+00	0.00E+00
Ag-108m	1.28E-07	2.76E-07	1.15E-07
Ag-110m	1.50E-07	8.23E-07	1.02E-07
Sb-125	3.51E-08	1.73E-06	6.61E-08
Te-125m			
Sn-126	1.33E-07	4.54E-06	1.43E-06
I-129	9.70E-09	6.51E-07	0.00E+00
Ba-133			
Cs-134	8.80E-08	1.83E-06	3.08E-07
Cs-135	0.00E+00	1.10E-06	5.71E-11
Cs-137	3.30E-08	2.54E-06	3.90E-07
Ce-144	4.10E-09	4.45E-06	1.50E-06
Pm-147	4.90E-13	1.26E-06	4.11E-10
Sm-147			
Sm-151	6.40E-12	2.85E-08	0.00E+00
Eu-152	1.18E-07	1.60E-06	1.71E-07
Eu-154	9.02E-08	3.42E-06	3.77E-07
Eu-155	1.77E-08	8.68E-07	3.20E-10
Pb-210	8.30E-09	2.63E-06	8.45E-07
Po-210	8.80E-13	0.00E+00	0.00E+00
Ra-226	1.64E-07	5.89E-06	1.64E-06

Radionuclide	Skin gamma D_{gamma7} (Sv h^{-1} per Bq cm^{-2})	Skin beta D_{beta4} (Sv h^{-1} per Bq cm^{-2})	Skin beta D_{beta40} (Sv h^{-1} per Bq cm^{-2})
Ac-227	3.81E-08	6.59E-06	2.00E-06
Ra-228	5.26E-08	3.08E-06	7.19E-07
Th-228	1.27E-07	6.34E-06	1.22E-06
Th-229	7.31E-08	8.56E-06	1.36E-06
Th-230	3.83E-09	1.04E-07	0.00E+00
Pa-231	6.27E-08	1.48E-07	5.14E-09
Th-232	2.20E-09	3.08E-08	0.00E+00
U-233	1.70E-09	5.25E-07	0.00E+00
U-234	2.70E-09	7.42E-09	0.00E+00
U-235	5.31E-08	2.52E-06	1.09E-08
U-236	3.55E-09	4.57E-09	0.00E+00
Np-237	3.20E-08	3.46E-06	9.93E-08
Pu-238	2.70E-09	1.06E-07	0.00E+00
U-238	9.23E-09	3.82E-06	1.26E-06
Pu-239	1.00E-09	4.34E-10	0.00E+00
Pu-240	2.60E-09	0.00E+00	0.00E+00
Am-241	1.70E-08	5.48E-08	0.00E+00
Pu-241	3.30E-12	0.00E+00	0.00E+00
Am-242m	1.95E-08	3.65E-09	0.00E+00
Cm-242	2.40E-09	0.00E+00	0.00E+00
Pu-242	3.07E-09	0.00E+00	0.00E+00
Am-243	4.60E-08	4.24E-06	1.37E-07
Cm-243	2.75E-08	1.94E-06	3.42E-08
Cm-244	2.20E-09	0.00E+00	0.00E+00
Cm-245	2.58E-08	9.82E-07	0.00E+00
Cm-246	2.52E-09	0.00E+00	0.00E+00

B.2 Radioactive Gas Pathway

The following parameters are used in equations A.1 to A.7:

f_{gas}	Fraction of the activity associated with radionuclide: H-3 = 0.039 (Yim *et al.*, 1993). C-14 = 0.2 (Yim *et al.*, 1993).
τ_{gas}	Average timescale of generation of radionuclide: H-3 = 50 years (representative value). C-14 = 50 years (representative value).
P_{waste}	Bulk density of the material in the disposal unit = 700 kg m^{-3} (see Table B.6).
τ	Emanation factor for radon = 0.1 (NEA, 1987).
H_1	Effective diffusion relaxation length for the waste = 0.2 m (NEA, 1987).
h_2	Thickness of the cover = 1.5 m (minimum burial depth for SPB).
H_2	Effective relaxation length of the cover = 0.2 m (NEA, 1987).
W	Width of the source perpendicular to the wind direction = 10 m (minimum width of landfill profile).
u	Mean wind speed = 6.2 m s^{-1} (representative value).
h	Height for vertical mixing = 2 m (approximate height of adult human).
O_{out}	Time spent in the gas plume: • Site worker = 0.2 years $year^{-1}$ (8 hours per day, 220 working days per year). • Member of the public = 0.25 years $year^{-1}$ (6 hours per day, 365.25 days per year).
B	Breathing rate: • Worker = 2.1 × 103 m3 year-1. This is based on the time spent in the gas plume by the worker (1760 hours year-1; 8 hours per day, 220 working days per year) and the breathing rate of the worker (1.2 m3 h-1). • Public (indoors) = 4.9 × 103 m3 year-1. This is based on an average time a member of the public spends indoors (6575 hours year-1; 18 hours per day, 365.25 days per year) indoor and the indoor breathing rate of the member of the public (0.75 m3 h-1). • Public (outdoors) = 2.2 × 103 m3 year-1. This is based on an average time a member of the public spends outdoors (2192 hours $year^{-1}$; 6 hours per day, 365.25 days per year) indoor and the outdoor breathing rate of the member of the public (1.0 m^3 h^{-1}).
O_{in}	Occupancy of house by public = 0.75 years $year^{-1}$ (18 hours per day, 365.25 days per year).
K_1	Effective dose equivalent corresponding to an absorbed energy of 1 joule = 2 Sv J^{-1} (IAEA, 2003).
ψ	Equilibrium factor = 0.8 (IAEA, 2003).
K_2	Potential α-energy of Rn-222 in equilibrium with its daughters = 5.54 × 10^{-9} J Bq^{-1} (IAEA, 2003).
a_H	Horizontal area of a dwelling = 50 m^2 (representative value).
V	Volume of the house = 125 m^3 (representative value).
k	Turnover rate = 8766 $year^{-1}$ (1 per hour; UNSCEAR, 1977).

In addition to the above, the user has to specify the site-specific parameters of *a*, the surface area of the landfill, and *t*, the duration of operation of the landfill.

B.3 Groundwater Pathway

B.3.1 Transport Calculations

The materials that radionuclide-bearing water/leachate will come into contact with along the groundwater pathway are assumed to be the waste, the geological barrier, and the rock bearing the groundwater. Sealing materials, such as liners, are assumed to not interact with the leachate. If the groundwater is used for irrigation, the radionuclides will also come into contact with soil.

For the purposes of the Assessment Framework, any artificial mineral barrier and the natural geological barrier are assumed to be composed of the same material, whose properties may be approximated by those of natural clay. The rock bearing the groundwater, and any unsaturated rock above it, is assumed to be homogeneous and can be approximated to one of five major lithological types – sandstone, silt/slate, clay, granite (crystalline rock), and limestone/chalk.

Therefore, for the groundwater pathway, the hydrogeological and geochemical properties are provided in the Assessment Model baseline data set for seven materials (Tables B.5 and B.6).

Table B.5: Illustrative distribution coefficients (K_d, m^3 kg^{-1}) for the radioelements considered in the baseline data set of the Assessment Model. Sources of data include Bailey *et al.* (2000), McKinley and Scholtis (1992) and Vandergraaf and Ticknor (1994).

Element	Waste	Soil	Clay	Sandstone	Lst/Chalk	Granite	Silt/Slate
H	0	1.00E-04	0	0		1.00E-06	0
Be	0	2.40E-01		1.4E-01			
C	0	1.00E-01	1.00E-03	0		1.00E-06	1.00E-03
Na	0						
Cl	0	1.50E-02	0	0		1.00E-06	0
Ca	0	9.00E-03	5.0E-02	1.4E-01			5.0E-02
Mn	0	4.90E-02		5.0E-02			
Fe	0	2.20E-01		5.0E-02			
Co	0	6.00E-02	4.9E+00	5.0E-02		1.0E-02	1.0E+01
Ni	0	4.00E-01	5.0E-02	5.0E-02		1.0E-02	5.0E-02
Zn	0	2.00E-01	2.9E+00	5.0E-02			2.9E+00
Se	0	1.50E-01	3.0E-02	1.0E-03		5.0E-03	3.0E-02
Sr	0	1.30E-02	1.00E-01	1.4E-01		1.00E-06	1.00E-01
Mo	0	7.40E-03		1.0E-02		5.0E-03	
Nb	0	1.60E-01	2.0E+00	5.0E-01		4.0E+00	2.0E+00
Zr	0	6.00E-01	2.0E-01	1.0E+00		5.0E-01	2.0E-01
Tc	0	1.40E-04	0	0		1.90E-01	0
Ru	0	5.50E-02					
Pd	0	5.50E-02	3.0E-01	5.0E-02	6.0E-04	1.0E-02	3.0E-01
Ag	0	9.00E-02	1.0E-01	5.0E-03		9.00E-02	0
Cd	0		2.9E+00				2.9E+00
Sn	0	1.30E-01	3.0E-01			1.0E-01	3.0E-01
Sb	0	4.50E-02	2.0E-02			1.0E-02	2.0E-02
Te	0	1.30E-01					
I	0	1.00E-03	0	0		1.00E-06	0
Ba	0	9.00E+00					
Cs	0	2.70E-01	3.0E-01	1.6E+00		1.0E-01	1.0E+01
Ce	0	4.90E-01	4.3E+01	2.0E+00		1.3E+01	4.3E+01
Pm	0	2.40E-01		2.0E+00			
Sm	0	2.40E-01	7.0E-01	2.0E+00		2.5E+01	7.0E-01
Eu	0	2.40E-01	1.0E+00	2.0E+00		7.8E+00	1.0E+00
Pb	0	2.70E-01	4.9E+00	1.0E+00		3.20E+00	4.9E+00
Po	0	1.50E-01		1.0E+00			
Ra	0	4.90E-01	9.00E+00	1.0E-02	6.0E-04	1.00E-03	9.00E+00
Ac	0	4.50E-01	2.9E+00	4.0E+00		5.0E+00	2.9E+00
Th	0	3.00E+00	1.43E+01	1.0E+00	8.0E-01	5.0E-01	1.43E+01
Pa	0	5.40E-01	5.7E+00	4.0E+00		1.0E+01	5.7E+00
U	0	3.30E-02	3.0E-01	1.5E-02	6.0E-04	1.0E-02	3.0E-01
Np	0	4.10E-03	3.0E-02	3.0E-03	6.0E-04	1.0E-02	3.0E-02
Pu	0	5.40E-01	1.0E+00	5.0E-01	8.0E-01	1.0E-01	1.0E-01
Am	0	2.00E+00	2.9E+00	2.0E+00	1.1E-01	3.20E+00	2.9E+00
Cm	0	4.00E+00	2.9E+00	2.0E+00	1.0E+01	2.0E-02	2.9E+00

Table B.6: Hydrogeological properties for the materials considered in the baseline data set of the Assessment Model.

Property	Waste	Soil	Clay / barrier	Sandstone	Lst/Chalk	Granite	Silt/Slate
Porosity (-)	0.5	0.3	0.5	0.2	0.1	0.4	0.3
Hydraulic Conductivity (m s^{-1})	not needed	not needed	1.0E-9	1.0E-07	1.0E-06	1.0E-05	1.0E-09
Saturation (-)	0.5	0.5	1	1	1	1	1
Density (kg m^{-3})	700	1,300	2,000	2,100	2,200	2,300	2,000

The distribution coefficients (Table B.5) are assumed to be constant over time. Similarly, the hydrogeological properties of the geological barrier and rock are assumed to remain constant. The potential for enhancement of radionuclide mobility though complexation with other components of the leachate (e.g., colloids, dissolved organic molecules) has been considered in the derivation of the distribution coefficients.

In identifying the nature of the rock containing the groundwater, it is important for the user to consider the potential for preferential flowpaths. The user has also to define site-specific properties, including:

- Hydraulic gradient.
- Thickness of the unsaturated zone.
- Thickness of the effective geological barrier.
- Distance to any groundwater abstraction point and/or surface waters which are in hydraulic connection with the groundwater.
- Infiltration rates.
- Effectiveness of the landfill cap after closure.

Infiltration

$P_{total} - AE$ - *runoff*:
Net water infiltration rate through soil = 0.155 m $year^{-1}$, based on the following estimations: annual rainfall of the order of 1.1 m, evapotranspiration of the order of 0.45 m, and runoff at 45%.
E_0 initial cap efficiency (a dimensionless fraction of the infiltration water initially deflected by the cap) = 0.95 (representative value).
t_f time of cap failure = 100 years (typical value).

Seepage through sealing liner

c Contact between the liner and the material beneath = 0.5 (dimensionless) for average contact (DOE, 1996).
a_{holes} Average area of the holes = 3.75×10^{-4} m^2 (DOE, 1996).
h Head of leachate = 1 m (DOE, 1996).

Seepage through the geological barrier to the groundwater

D Depth of barrier = 3 m (sum of thickness of unsaturated zone – taken as 2 m – and thickness of geological barrier – taken as 1 m).

Transport in the groundwater

K_{gw}	Hydraulic conductivity of the groundwater-bearing rock = 1.0×10^{-5} m s^{-1} (default value – granite).
ΔH	Hydraulic gradient = 0.05 (representative value).
φ_{gw}	Porosity of groundwater-bearing rock = 0.4 (default value – granite).
ρ_{gw}	Bulk density of groundwater-bearing rock = 2.3×10^{3} kg/m^{3} (default value – granite).

River/Sea

q_{flow}	Volume of the water flowing through the river or sea compartment per year = 1.0×10^{7} m^{3} year^{-1} (representative value).
V_{water}	Volume of water being modelled = 2.0×10^{4} m^{3} (IAEA, 2003).

Irrigation

$Irrig_{rate}$	Irrigation rate = 0.3 m year^{-1} (no irrigation of pasture; IAEA, 2003).
d_{soil}	Depth of soil layer being irrigated = 0.25 m (IAEA, 2003).
$\lambda_{erosion}$	erosion rate = 2×10^{-4} year^{-1} (temperate; IAEA, 2003).
P_{total}	Total precipitation = 1.1 m year^{-1} (representative value).
AE	Amount of precipitation lost by evapotranspiration = 0.45 m year^{-1} (representative value).
$runoff$	Runoff = 0.495 m year^{-1} (estimated at 45% of total precipitation).
$Yield_{plant}$	Plant yield (kg m^{-2} year^{-1}) – see Section B.3.2.
TF_{plant}	Soil to plant transfer factor for radionuclide, *Rn* (Bq kg^{-1} fresh weight of crop per Bq kg^{-1} of soil) – see Section B.3.2.

B.3.2 Dose Calculations

The human individuals receiving the dose are assumed to be in a small group who farm land irrigated with contaminated water, drink contaminated water, and/or fish in contaminated water. For simplicity, only fish are assumed to be harvested from contaminated surface water. Livestock raised by the farmers is assumed to be composed of cattle only, and only meat and milk products from the livestock are consumed. The livestock are assumed to be raised on pasture only, and the pasture is assumed not to be irrigated directly. The pasture is assumed to be grown on soil previously used for growing crops and contaminated by irrigation. The crops assumed to be consumed by the farmers are root vegetables, green vegetables, and grain.

The following parameters are used in equations A.24 to A.31:

Q_{water}	Intake rate of drinking water = 0.73 m^{3} year^{-1} (IAEA, 2003).
Q_{fish}	Consumption rate of fish (freshwater or marine) = 2 kg year^{-1}.
Q_{soil}	Inadvertent consumption rate of soil = 0.03 kg year^{-1} (IAEA, 2003).
Q_{crop}	Consumption rate: • Grain = 148 kg year^{-1} (IAEA, 2003). • Root vegetables = 235 kg year^{-1} (IAEA, 2003). • Green vegetables = 62 kg year^{-1} (IAEA, 2003).
$Irrig_{rate}$	Irrigation rate per crop = 0.3 m year^{-1} (temperate, no irrigation of pasture; IAEA, 2003).
Int_{crop}	Interception factor (all crops) = 0.33 (IAEA, 2003).

F_{crop}	Preparation loss factor for surface contamination: • Grain = 1 (i.e., no loss; representative value). • Root vegetables = 1 (i.e., no loss; representative value). • Green vegetables = 0.3 (representative value).
$Yield_{crop}$	Yield: • Grain = 0.4 kg m^{-2} kg $year^{-1}$ (wet weight; IAEA, 2003). • Root vegetables = 3.5 kg m^{-2} kg $year^{-1}$ (wet weight; IAEA, 2003). • Green vegetables = 3 kg m^{-2} kg $year^{-1}$ (wet weight; IAEA, 2003). • Pasture = 1.7 kg m^{-2} kg $year^{-1}$ (wet weight; IAEA, 2003).
Q_{animal}	Consumption rate: • Cow milk = 330 kg $year^{-1}$ (IAEA, 2003). • Cow meat = 95 kg $year^{-1}$ (IAEA, 2003).
q_{water}	Cattle daily water consumption = 0.06 m^3 day^{-1} (IAEA, 2003).
q_{soil}	Cattle daily soil consumption = 0.6 kg day^{-1} (IAEA, 2003).
q_{crop}	Cattle daily pasture intake (wet) = 55 kg day^{-1} (IAEA, 2003).
O_{out}	Time spent outside exposed to the soil = 0.25 years $year^{-1}$ (6 hours per day, 365.25 days per year).
O_{in}	Time spent inside = 0.75 years $year^{-1}$ (18 hours per day, 365.25 days per year).
sf	Shielding factor from the ground when indoors = 0.1 (IAEA, 2003).
O_{dust}	Time spent exposed to dust outside = 0.25 years $year^{-1}$ (6 hours per day, 365.25 days per year).
B	Breathing rate = = 2.2×10^3 m^3 $year^{-1}$. This is based on an average time a member of the public spends outdoors (2192 hours $year^{-1}$; 6 hours per day, 365.25 days per year) indoor and the outdoor breathing rate of the member of the public (1.0 m^3 h^{-1}).
$dustload$	Dust load = 1.0×10^{-7} kg m^{-3} (IAEA, 2003).

Tables B.7 and B.8 give the uptake factors, transfer factors, and weathering factors to calculate radioactivity in food from radioactivity in soil and water.

Table B.7: Uptake factors (TF_{fish}, $m^3\ kg^{-1}$) for aquatic foodstuffs and transfer factors (TF_{animal}, $d\ kg^{-1}$) for livestock for the radioelements considered in the baseline data set of the Assessment Model. Data from IAEA (2003) and Smith *et al.* (1988).

Element	Freshwater Fish ($m^3\ kg^{-1}$)	Sea Fish ($m^3\ kg^{-1}$)	Cow Meat ($d\ kg^{-1}$ fresh weight)	Cow Milk ($d\ kg^{-1}$)
H	1.00E-03	1.00E-03	2.90E-02	1.00E-02
Be	2.00E-01	2.00E-03	6.60E-04	2.60E-06
C	9.00E+00	2.00E+01	1.20E-01	1.00E-02
Na	2.00E-02	2.00E-02	8.00E-02	1.60E-02
Cl	5.00E-02	1.00E-03	4.30E-02	1.70E-02
Ca	2.00E-01	2.00E-03	2.00E-03	3.00E-03
Mn	4.00E-01	4.00E-01	5.00E-04	3.00E-05
Fe	1.00E-01	3.00E+00	2.00E-02	3.00E-05
Co	3.00E-01	1.00E+00	1.00E-02	3.00E-04
Ni	1.00E-01	5.00E-01	5.00E-03	1.60E-02
Zn	1.00E+00	1.00E+00	1.00E-01	1.00E-02
Se	8.00E-01	6.00E+00	7.00E-03	4.50E-04
Sr	6.00E-02	2.00E-03	8.00E-03	3.00E-03
Mo	1.00E-02	5.00E-02	1.00E-02	1.00E-03
Nb	3.00E-01	1.00E-02	3.00E-07	4.10E-07
Zr	3.00E-01	2.00E-01	1.00E-06	5.50E-07
Tc	2.00E-02	3.00E-02	1.00E-04	2.30E-05
Ru	1.00E-02	2.00E-03	5.00E-02	3.30E-06
Pd	2.00E-02	3.00E-01	3.00E-03	5.00E-05
Ag	5.00E-03	5.00E-03	3.00E-05	5.00E-05
Sn	5.00E-02	5.00E-02	1.90E-03	1.00E-03
Sb	1.00E-01	4.00E-01	4.00E-05	2.50E-05
Te	2.00E-01	6.00E+00	7.00E-03	4.50E-04
I	3.00E-02	1.00E-02	4.00E-02	1.00E-02
Ba	4.00E-03	1.00E-02	5.00E-04	2.80E-04
Cs	2.00E+00	1.00E-01	5.00E-02	7.90E-03
Ce	3.00E-02	5.00E-02	2.00E-05	3.00E-05
Pm	3.00E-02	5.00E-01	5.00E-03	2.00E-05
Sm	3.00E-02	5.00E-01	5.10E-04	2.00E-05
Eu	3.00E-02	3.00E-01	4.70E-04	5.00E-05
Pb	3.00E-01	2.00E-01	4.00E-04	3.00E-04
Po	5.00E-02	2.00E+00	5.00E-03	3.40E-04
Ra	5.00E-02	5.00E-01	9.00E-04	1.30E-03
Ac	8.00E-01	5.00E-02	1.60E-04	4.00E-07
Th	3.00E-02	6.00E-01	2.70E-03	5.00E-06
Pa	1.00E-02	5.00E-02	5.00E-05	5.00E-06
U	1.00E-02	1.00E-03	3.00E-04	4.00E-04
Np	1.00E-02	1.00E-02	1.00E-03	5.00E-06
Pu	4.00E-03	4.00E-02	1.00E-05	1.10E-06
Am	3.00E-02	5.00E-02	4.00E-04	1.50E-06
Cm	8.00E-01	5.00E-02	4.00E-05	1.50E-06

Table B.8: Uptake factors (TF_{crop}, Bq kg^{-1} Bq^{-1} kg) for crops and pasture and weathering rate for green vegetables for the radioelements considered in the baseline data set of the Assessment Model. Data from IAEA (2003) and Smith *et al.* (1988).

Element	Green Vegetables (Bq kg^{-1}Bq^{-1} kg)	Green Vegetables Weathering Rate (year^{-1})	Root Vegetables (Bq kg^{-1}Bq^{-1} kg)	Grain (Bq kg^{-1}Bq^{-1} kg)	Grass (Bq kg^{-1}Bq^{-1} kg)
H	5.00E+00	1.83E+01	5.00E+00	1.00E-02	5.00E+00
Be	2.00E-03	1.83E+01	1.00E-03	7.80E-07	2.00E-03
C	1.00E-01	1.83E+01	1.00E-01	1.60E-01	1.00E-01
Na	3.00E-02	5.00E-02	3.00E-02	2.00E-02	3.00E-02
Cl	5.00E+00		5.00E+00	8.80E-02	5.00E+00
Ca	5.00E-01	1.83E+01	5.00E-01	8.00E-02	5.00E-01
Mn	5.00E-01	1.83E+01	5.00E-01	*5.00E-01*	3.00E-01
Fe	2.00E-04	1.83E+01	3.00E-04	1.00E-01	4.00E-04
Co	3.00E-02	1.83E+01	3.00E-02	8.00E-02	6.00E-03
Ni	3.00E-02	1.83E+01	3.00E-02	1.60E-01	2.00E-02
Zn	3.30E+00	1.83E+01	3.00E-02	5.00E-02	3.00E-02
Se	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Sr	3.00E+00	1.83E+01	9.00E+02	1.20E-01	3.00E+00
Nb	1.00E-02	1.83E+01	1.00E-02	1.00E-02	1.00E-02
Zr	5.00E-03	1.83E+01	5.00E-03	5.00E-03	5.00E-03
Tc	1.00E+01	1.83E+01	1.00E+01	1.00E+01	1.00E+01
Ru	4.00E-03	1.83E+01	1.00E-02	1.00E-01	4.00E-02
Pd	2.00E-01		6.00E-02	2.00E-01	2.00E-01
Ag	2.70E-04	1.83E+01	1.30E-03	8.80E-02	1.50E-01
Sn	1.00E-01	5.00E-02	7.00E+00	7.00E+00	7.00E+00
Sb	1.00E-02	1.83E+01	1.00E-02	1.50E-01	1.00E-02
Te	2.50E-03	1.83E+01	6.00E-04	*3.60E-03*	8.00E+00
I	1.00E-01	1.83E+01	1.00E-01	2.80E-01	1.00E-01
Ba	5.00E-03		5.00E-03	8.00E-02	2.00E-02
Cs	3.00E-02	1.83E+01	3.00E-02	2.00E-02	3.00E-02
Ce	1.00E-03	1.83E+01	6.00E-04	4.80E-02	2.00E-02
Pm	3.00E-03	1.83E+01	3.00E-03	4.80E-02	3.00E-03
Sm	2.00E-03	1.83E+01	2.00E-03	4.80E-02	2.00E-03
Eu	3.00E-03	1.83E+01	3.00E-03	4.80E-02	3.00E-03
Pb	1.00E-02	1.83E+01	1.00E-02	1.00E-02	1.00E-02
Po	2.00E-04	1.83E+01	2.00E-04	2.00E-04	2.00E-04
Ra	4.00E-02	1.83E+01	4.00E-02	4.00E-02	4.00E-02
Ac	1.00E-03	1.83E+01	1.00E-03	1.00E-03	1.00E-03
Th	5.00E-04	1.83E+01	5.00E-04	5.00E-04	5.00E-04
Pa	4.00E-02	1.83E+01	4.00E-02	4.00E-02	4.00E-02
U	1.00E-03	5.11E+01	1.00E-03	1.00E-04	1.00E-03
Np	1.00E-02	5.11E+01	1.00E-03	3.00E-04	5.00E-03
Pu	1.00E-04	5.11E+01	1.00E-03	3.00E-05	1.00E-03
Am	1.00E-03	1.83E+01	1.00E-03	1.00E-05	5.00E-03
Cm	1.00E-03		1.00E-03	1.00E-05	5.00E-03

B.4 Aerosol Pathway

The following parameters are used in equations A.32 to A.37:

aerosol	Aerosol concentration = 1.0×10^{-3} kg m^{-3} of air (representative value).
$t_{dep,aero}$	Time over which deposition occurs = 3600 s (illustrative value).
$V_{dep,aero}$	Aerosol deposition velocity = 0.002 m s^{-1} (IAEA 1982).
$W_{out,aero}$	Washout coefficient = 3×10^{-4} s^{-1} (Simmonds *et al.*, 1995).
h_{aero}	Height of the contaminated plume = 10 m (Clarke, 1979).
O_{plume}	Time spent exposed to the aerosol: • Worker = 1 hour $year^{-1}$ (representative value). • Member of public = 1 hour $year^{-1}$ (representative value).
B	Breathing rate: • Worker = 1.2 m^3 $hour^{-1}$ (representative value). • Member of public = 1 m^3 $hour^{-1}$ (representative value).
D_{inh}	Dose coefficient for inhalation of radionuclide – see Table B.3.
$D_{irr,cloud}$	Dose coefficient for irradiation from cloudshine – see Table B.3.
O_{out}	Time spent outdoors = 0.25 years $year^{-1}$ (6 hours per day, 365.25 days per year).
O_{in}	Time spent indoors = 0.75 years $year^{-1}$ (18 hours per day, 365.25 days per year).
sf	Shielding factor from the surface concentration while indoors = 0.1 (IAEA, 2003).
t_{exp}	Time since deposition on the surface = 1 year (representative value).
$D_{irr,ground}$	dose coefficient for irradiation from groundshine – see Table B.3.
Q_{veg}	Vegetable consumption rate = 62 kg $year^{-1}$ (BIOMOVS II, 1996).
Int_{veg}	Effective interception factor = 0.33 (BIOMOVS II, 1996).
F_{veg}	Fraction remaining after processing = 0.3 (CEC, 1990).
$Yield_{veg}$	Vegetable yield = 3 kg m^{-2} (BIOMOVS II, 1996).
λ_{Rn}	Half-life of radionuclide *Rn* – see Table B.2.
λ_w	Weathering rate of the radionuclide from the vegetable – see Table B.8.
t_r	Time following release over which the vegetables are consumed = 1 year (representative value).
N_{aero}	Number of aerosol releases per year = 1 (representative value).
D_{ing}	Dose coefficient for ingestion – see Table B.3.

B.5 External Irradiation Pathway

The following parameters are used in equation A.38:

O_{out}	Time spent outside exposed to the waste: • Worker = 0.2 years $year^{-1}$ (8 hours per day, 220 working days per year). • Public = 0.25 years $year^{-1}$ (6 hours per day, 365.25 days per year).
O_{in}	Time spent inside = 0.75 years $year^{-1}$ (18 hours per day, 365.25 days per year).
sf	Shielding factor from the ground when indoors = 0.1 (IAEA, 2003).
$D_{irr,slab}$	Dose conversion factor for irradiation – see Table B.3.
ρ_{waste}	Bulk density of the waste (kg m^{-3}) – see Table B.6.
V_{waste}	Volume used for SPB disposals = 10 m^3 (representative value).

In addition to the above, the user has to specify the site-specific parameter of $V_{landfill}$, the volume of the landfill, in order to calculate the general activity level in the irradiating material at closure.

B.6 Fire Scenario

The following parameters are used in equations A.39 to A.44:

$C_{iac,fire}$	Time-integrated air concentration at ground level at 250 m for the prevalent atmospheric conditions = 2.5×10^{-7} Bq hour m^{-3} Bq^{-1} (similar to values by Clarke, 1979).
$f_{Rn,fire}$	Release fraction for the radionuclide (Asselineau *et al.*, 1995): • H, C, and I: 1.0. • Pb: 0.5. • Zn, Ru, Sb, and Cs: 0.1 • Na and Ag: 0.01. • All other elements: 0.001.
V_{fire}	Volume of the waste consumed in the fire = 1000 m^3 (large, 1000 m^3; medium, 100 m^3; or small, 10 m^3).
$V_{landfill}$	Volume of the landfill (m^3) – user-specified.
t_{fire}	Duration of the fire = 1 hour (representative value).
$t_{dep,fire}$	Time over which deposition occurs = 3600 s (same duration as that of fire).
$v_{dep,fire}$	Dry deposition velocity = 2×10^{-3} m s^{-1} (IAEA, 1982).
$W_{out,fire}$	Washout coefficient = 3×10^{-4} s^{-1} (Simmonds *et al.*, 1995).
h_{fire}	Height of the smoke plume = 10 m (Clarke, 1979).
O_{fire}	Time spent exposed to the smoke: • Worker = 1 hour (representative value). • Member of public = 1 hour (representative value).
B	Breathing rate: • Worker = 1.2 m^3 hour^{-1} (representative value). • Member of public = 1 m^3 hour^{-1} (representative value).
D_{inh}	Dose coefficient for inhalation of radionuclide – see Table B.3.
N_{fire}	Number of fires per year = 2 year^{-1} (representative value).
$D_{irr,cloud}$	Dose coefficient for irradiation from cloudshine – see Table B.3.
O_{out}	Time spent outdoors = 0.25 years year^{-1} (6 hours per day, 365.25 days per year).
O_{in}	Time spent indoors = 0.75 years year^{-1} (18 hours per day, 365.25 days per year).
sf	Shielding factor from the surface concentration while indoors = 0.1 (IAEA, 2003).
λ_{Rn}	Half-life of radionuclide *Rn* – see Table B.2.
t_{exp}	Time since deposition on the surface = 1 year (representative value).
$D_{irr,ground}$	dose coefficient for irradiation from groundshine – see Table B.3.
Q_{veg}	Vegetable consumption rate = 62 kg year^{-1} (BIOMOVS II, 1996).
Int_{veg}	Effective interception factor = 0.33 (BIOMOVS II, 1996).
F_{veg}	Fraction remaining after processing = 0.3 (CEC, 1990).
$Yield_{veg}$	Vegetable yield = 3 kg m^{-2} (BIOMOVS II, 1996).
λ_w	Weathering rate of the radionuclide from the vegetable – see Table B.8.
t_r	Time following release over which the vegetables are consumed = 1 year (representative value).
D_{ing}	Dose coefficient for ingestion – see Table B.3.

B.7 Barrier Failure Scenario

Same as groundwater scenario – see Section B.3.

B.8 Leachate Spillage Scenario

The following parameters are used in equations A.45 and A.46:

V_{spill}	Volume of leachate in the spill = 1000 m^3 (large, 10000 m^3; medium, 1000 m^3; or small, 100 m^3).
V_{water}	Volume of the surface water body = 1000 m^3 (representative value).
$Irrig_{rate}$	Amount of irrigation in one year = 0.3 m (representative value in the case where water body is used for irrigation; IAEA, 2003).
d_{soil}	Depth of the soil layer being irrigated = 0.25 m (IAEA, 2003).
ρ_{soil}	Density of the soil = 1300 kg m^{-3} (see Table B.6).

B.9 Site Re-Engineering Scenario

Same as for a worker inadvertently excavating into the site after site closure (equations A.47 to A.50) – see Section B.10. This scenario also considers short-lived radionuclides that may be present during the operational period. The same set of radionuclides as considered for the fire scenario (Section A.2) is modelled.

B.10 Inadvertent Excavation Scenario

The following parameters are used in equations A.47 to A.51:

M_{inh}	Dust load of contaminated waste inhaled by the excavator = 1×10^{-6} kg m^{-3} (IAEA, 1995).
M_{ing}	Rate of ingestion of dust from the material = 3.4×10^{-5} kg hour^{-1} (IAEA, 1995).
T	Time the excavator is exposed to the material = 88 hours year^{-1} (representative value; IAEA, 1995).
B	Breathing rate of excavator = 1.2 m^3 hour^{-1} (representative value).
$V_{excavate}$	Volume of the excavated waste in which the activity is assumed to be contained = 10 m^3 (see Section 2.2).
ρ_{waste}	Density of the waste = 700 kg m^{-3} (see Table B.6).
D_{gamma7}	Skin equivalent dose rate for radionuclide *Rn* – see Table B.4.
D_{beta40}	Skin equivalent dose rate for radionuclide *Rn* – see Table B.4.
d_{hands}	Thickness of the contaminated layer on the hands = 1.0×10^{-4} m (CEC, 2002).
W_{skin}	Tissue weighting factor for skin = 0.01 (ICRP, 1991).
$Area_{hands}$	Area of skin in contact with the contaminated dust = 200 cm^2 (Harvey *et al.*, 1998).
$Area_{body}$	Total exposed skin area of the adult body = 3000 cm^2 (NRPB, 1997).
D_{beta4}	Skin equivalent dose rate for radionuclide *Rn* – see Table B.4.
d_{face}	Thickness of the contaminated layer on the face = 5.0×10^{-5} m (CEC, 2002).
$Area_{face}$	Area of skin in contact with the contaminated dust = 100 cm^2 (Harvey *et al.*, 1998)
Dil	Dilution factor = 0.3 (IAEA, 2003).
$V_{landfill}$	Volume of the landfill (m^3) – user-defined.

B.11 Bathtubbing Scenario

The following parameters are used in equation A.52:

$V_{bathtub}$	Volume of leachate that overflows into the growing area through the bathtub event = 1000 m^3 (illustrative value).
G_{area}	Growing area of soil required to raise crops / livestock = 1.0×10^5 m^2 (representative value).
d_{soil}	Depth of the soil layer = 0.25 m (IAEA, 2003).
ρ_{soil}	Density of the soil = 1300 kg m^{-3} (see Table B.6).

B.12 References

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