Safety Assessment Methodologies for Near Surface Disposal Facilities

Results of a co-ordinated research project

Volume 2

Test cases

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FOREWORD

For several decades, countries have made use of near surface facilities for the disposal of low and intermediate level radioactive waste. In line with the internationally agreed principles of radioactive waste management, the safety of these facilities needs to be ensured during all stages of their lifetimes, including the post-closure period. By the mid 1990s, formal methodologies for evaluating the long term safety of such facilities had been developed, but intercomparison of these methodologies had revealed a number of discrepancies between them.

Consequently, in 1997, the International Atomic Energy Agency launched a Co-ordinated Research Project (CRP) on *I*mprovement of *S*afety *A*ssessment *M*ethodologies for Near Surface Disposal Facilities (ISAM). The particular objectives of the CRP were to:

— provide a critical evaluation of the approaches and tools used in post-closure safety assessment for proposed and existing near-surface radioactive waste disposal facilities;

— enhance the approaches and tools used;

— build confidence in the approaches and tools used.

The CRP ran until 2000 and resulted in the development of a harmonized assessment methodology (the ISAM project methodology), which was applied to a number of test cases. Over seventy participants from twenty-two Member States played an active role in the project and it attracted interest from around seven hundred persons involved with safety assessment in seventy-two Member States.

The results of the CRP have contributed to the Action Plan on the Safety of Radioactive Waste Management which was approved by the Board of Governors and endorsed by the General Conference in September 2001. Specifically, they contribute to Action 5, which requests the IAEA Secretariat to "develop a structured and systematic programme to ensure adequate application of the Agency's waste safety standards", by elaborating on the Safety Requirements on "Near Surface Disposal of Radioactive Waste" (Safety Standards Series No. WS-R-1) and the Safety Guide on "Safety Assessment for Near Surface Disposal of Radioactive Waste" (Safety Standards Series No. WS-G-1.1).

The report of this CRP is presented in two volumes; Volume 1 contains a summary and a complete description of the ISAM project methodology and Volume 2 presents the application of the methodology to three hypothetical test cases.

The IAEA expresses its appreciation to all ISAM participants who contributed to the success of the project and to the preparation of the associated documentation, and to R. Little (UK) for technical review of the report. The IAEA officers responsible for the ISAM project were C. Torres-Vidal and B. Batandjieva of the Division of Radiation, Transport and Waste Safety.

EDITORIAL NOTE

CONTENTS (VOLUME II)

1. VAULT TEST CASE

1.1 SPECIFICATION OF ASSESSMENT CONTEXT

The scope and content of a safety assessment are determined by the assessment context. The assessment context is expressed in terms of the assumptions and constraints set by the regulatory framework and the purpose and focus of the assessment.

1.1.1. Purpose

The development of a disposal facility passes through several distinct phases including site selection, design facility construction, disposal operations and final site closure. The safety assessment is normally required to support regulatory decisions throughout these various phases and the scope and content and site-specific nature of the assessment normally increases with each phase. The regulatory-safety assessment cycle is therefore an ongoing iterative process.

The safety assessment undertaken for the Vault Test Case is assumed to be that developed following the site selection process. It is assumed, for the purposes of the test case, that previous assessments have been relatively simple and have not used all of the available data. Furthermore, past assessments were for a different facility design and inventory so past results are not very useful to help guide and prioritize this iteration of the safety assessment. It is recognized that additional iterations of the safety assessment process are very likely to be required in the future.

The purpose of the current assessment is:

- To assess the level of safety using currently available information;
- To identify the most important uncertainties;
- To identify areas requiring further data collection and/or alternative conceptual models that may be the subject of future safety assessment iterations; and
- To develop confidence that the site and facility design will be suitable for waste disposal and that further investment in site characterisation and other activities will be worthwhile. This would prepare the way for an application for facility construction and ultimately permission to commence disposal operations.

The safety assessment aims to illustrate progress towards demonstrating an adequate level of safety (particularly compliance with the regulatory requirements) but it is considered too early in the assessment cycle to demonstrate complete compliance with the set of regulatory requirements for authorization of disposals as set out in Section 1.1.3.

Only post-closure safety is to be assessed, the operational safety case will not be considered. The assessment is to consider impacts on humans only; other biota are not to be considered. In addition, the assessment only considers radiological impacts; chemical or biological toxicity are not to be assessed. It is recognized that this issue may be important, but it is assumed that it will be dealt with in a separate safety assessment aimed at compliance with different environmental regulations.

1.1.2. Target audience

The target audience (stakeholders) for the assessment context is assumed to be composed of hypothetical regulators and staff involved in producing the safety assessment. The assessment context provides the means by which the target audience is informed on what is to be included in the assessment and the reasons for these choices. Other possible stakeholders such as the public are not considered at this stage. However, it is noted that for many safety assessments it might be beneficial to involve a broad range of stakeholders as early as possible in the assessment process.

1.1.3. Regulatory framework

The regulatory framework has been developed for the specific purposes of the ISAM Test Cases. It is not based on the regulations for any particular country but is based on broadly accepted international principles (e.g. IAEA WS-R-1 [4], ICRP 60 [5], 77 [6] and 81 [7]). The regulatory framework is founded on four basic objectives set out below. Some additional requirements are assumed to be provided by the regulator.

(a) *Requirement No. 1 – Independence of safety from controls.*

Following the closure of the disposal facility, the continued isolation of the waste from the accessible environment should not depend on actions by future generations to maintain the integrity of the disposal system.

(b) *Requirement No. 2 – Effects in the future.*

Radioactive wastes shall be managed in such a way that estimated impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today. Following closure of the disposal facility, estimated impacts should be constrained to a fraction of the dose limit.

(c) *Requirement No.3 – Optimization.*

The radiological detriment to members of the public from the disposal of radioactive waste shall be *a*s *l*ow *a*s *r*easonably *a*chievable (ALARA), economic and social factors being taken into account.

(d) *Requirement No. 4 – Radiological protection criteria.*

The assessed radiological impact of disposal to members of the public shall be consistent with dose constraint. The protection of the public from the long term impacts of radioactive waste disposal should aim to provide confidence that doses do not exceed a constraint of 0.3 mSv y^{-1} for 'normal' exposures. It is assumed that human intrusion exposures lower than 10 mSv y^{-1} shall not warrant further consideration.

(e) *Additional Regulatory Requirements*

No more than 100 years of active institutional control of the site can be assumed after the end of disposal operations. The operator will need to document any assumptions regarding passive institutional control (e.g. societal memory) after the end of active control.

The regulatory requirements stipulate that there is no cut-off beyond which impacts need not be considered. Therefore, it is recognized that the safety assessment developers need to define and document the approach to time dependence.

The regulators recognize that the performance of a disposal system in the far future is less amenable to quantification than during the period of control. The regulators are not expected, therefore, to determine the safety of the facility exclusively on estimates of dose but to consider other factors, including some of a more qualitative nature, in arriving at their judgement.

Consistent with IAEA [4], the radiological dose to the public shall be assessed by reference to the exposed group of individuals in the population receiving the highest dose (the critical group which is assumed to be homogeneous with respect to its diet and those aspects of behaviour that affect dose). Because human habits can change significantly, even over a short period of time, this group should be seen as hypothetical. Consistent with ICRP 81 [7], critical groups should be defined, which are conservative but plausible, based on current lifestyles and site-specific information.

1.1.4. Assessment end-points

The assessment end-points need to correspond with the regulatory requirements, hence the individual effective dose to a member of the critical group is to be calculated to demonstrate progress towards compliance with regulatory requirements No. 2, 3 and 4 given in Section 1.1.3.

Other useful performance indicators such as radionuclide fluxes from each component of the system (e.g. base of the disposal facility, base of the unsaturated zone), radionuclide concentrations in the geosphere and biosphere, etc. may be calculated to compare with background radiation levels.

With regard to optimization, reference [8] notes that a very broad interpretation can be taken of the meaning of optimization, encompassing good decision-making throughout the disposal facility programme, including qualitative judgements. In particular, reference [8] notes that the post-closure safety case should: identify the options to be evaluated, especially the design options; present appropriate qualitative and quantitative evidence that safety and resource issues have been considered; and show that a reasonable decision has been reached. Reference [9] notes that two main options can be considered: optimization of facility design and optimization of waste to be disposed and its radiological inventory.

Given the resource constraints associated with the Vault Test Case, some consideration is to be given to the impact of the assumed inventory and the potential need to develop more restrictive waste acceptance criteria and/or a more heavily engineered design. The facility is not yet operational and the inventory is based on predictions of future waste arising. The assessment process can be used to determine if facility design is adequate to enable acceptance of all the waste requiring disposal. This process can lead to the production of waste acceptance criteria related to the long term performance of the disposal facility, e.g. total facility and annual limits on total radioactivity, specific radionuclides and waste material composition (e.g. levels of organics, complexing agents, etc.).

As stated in Section 1.1.1, an objective of the test case is to develop confidence that the site will be suitable for a waste disposal facility and that future investment in the site will be worthwhile. A full cost-benefit analysis will not be conducted, however it is recognized that some consideration of economic issues should be included in most safety assessments.

1.1.5. Assessment philosophy

The following relevant points have been considered:

- A transparent approach to safety assessment is to be used, specifically, the ISAM project methodology will be used;
- The assessment should be able to provide a reasonable degree of assurance of compliance with safety objectives;
- An approach that balances simplicity, conservatism and realism is to be applied to the assessment; and
- Where possible, site specific data is to be used.

Various techniques are to be used to address the main sources of uncertainty. The uncertainty in the future evolution of the site is to be treated using a transparent scenario development and justification methodology. Data and parameter uncertainty that exists are to be treated using deterministic sensitivity analysis, while model uncertainties are to be treated using alternative conceptualisations and mathematical representations of the system. Subjective uncertainties are to be managed by using a systematic and transparent assessment approach, which allows all subjective judgements to be document, justified and quantified (as far as possible).

1.1.6. Assessment timeframes

The regulatory requirements stipulate that there is no cut-off time beyond which impacts need not be considered. Therefore, it is recognized that the safety assessment developers need to define and document the approach to time dependence. It should be noted that this does not mean that there is a regulatory requirement for time-dependent modelling, only that the approach taken needs to be adequately justified. The timescales used for quantitative assessment will be justified on the basis of scientific credibility.

Regulatory requirements state that the operator should not assume more than 100 years of active institutional control of the site following the end of disposal operations. Active control measures include site security fences, environmental monitoring, repair work, etc. An active institutional control period of 100 years is considered to be reasonable, where it refers to control by the operating company or its successor organizations. The withdrawal of controls by the operating company may be termed ‘site closure’ and marks the start of the post-closure period. It is assumed that passive institutional control over the site will last for a longer period, e.g. an additional 200 years. Passive institutional control refers to societal memory of the disposal site. This could include institutional memory and controls (e.g. local/national government records, planning authority restrictions, site marked on official maps, etc.) as well as local, informal knowledge about the whereabouts of the site. These assumptions are summarized in Table 1. For the purposes of the Vault Test Case, it is assumed that the assessment of post-closure impacts will start from the time of the final disposal to the facility.

TABLE 1. TIMEFRAMES AND ASSUMED ACTIVITIES FOR THE VAULT TEST CASE

Activity	Timeframe (years)
Waste disposal operations	30
Active institutional control by the operator – to include final capping and subsequent monitoring	Up to 100
Withdrawal of active controls	100
Passive institutional control, e.g. by local/national government and local knowledge	100 to 300
No control – all records/knowledge assumed to be lost	> 300

1.1.7. Disposal system characteristics

The Vault Test Case is being developed for a proposed, hypothetical near surface disposal facility. The facility design has been extracted from public domain documents about a proposed disposal facility in the United States of America (USA) and modified for the purposes of the Vault Test Case. A description of the facility is provided in Section 1.2.

The facility design is based on projected low level radioactive waste arising from a group of nuclear power plants, medical and research institutions, industrial applications, and other miscellaneous waste producers over a 30-year period. The inventory information (Section 1.2.1.) is based on expert judgement and is considered to be realistic. The hypothetical location of the site has been chosen as Vaalputs in north-western South Africa (Fig. 1.). Information for the Vaalputs geosphere and biosphere is provided in Sections 1.2.2 and 1.2.3 respectively.

FIG. 1. Location of Vaalputs.

The post-closure assessment is based on current human behaviour, habits and actions at the site and, if necessary, analogue sites. Analogue sites allow consideration of environmental change, e.g. climate becoming wetter. However, this is bounded in that only natural, agriculture and leisure land uses are considered. Urban and industrial land uses are deemed unlikely due to the geographical location of the site.

No attempt is made to evaluate the impact of technological development as any assumptions would be difficult to justify. Changes in social and institutional factors are considered but those are related to society as it exists today or past societies (see analogue sites above). No attempt will be made to predict advances in society and institutions as such predictions would be difficult to justify.

In line with regulatory requirement No.1 (Section 1.1.), the test case assumes that the continued isolation of the waste from the accessible environment will not depend on actions by future generations to maintain the integrity of the disposal system. Therefore, issues such as retrievability, remedial actions and monitoring after site closure will not be considered.

The test case only considers inadvertent human intrusion. The impact of deliberate human intrusion is primarily the responsible of those intruding and is beyond the control of current generations. To clarify, deliberate human intrusion applies when the intruder knows it is a radioactive waste disposal facility. In contrast, an archaeologist may dig up the site because they recognize it as a man-made structure. But if they do not know it is a radioactive waste disposal facility, this is inadvertent human intrusion.

1.2. DESCRIPTION OF DISPOSAL SYSTEM

1.2.1. Near field

Waste inventory

A broad set of radionuclides is assumed to be disposed of at the facility. Radionuclides with a half-life of less than 10 years are not included in the assessment. This is justified on the basis of the length of the active and passive control periods (~300 years) during which time it is assumed these radionuclides will have decayed to insignificant levels compared to the other long lived radionuclides. The identified set of radionuclides is shown in Table 2.

TABLE 2. INVENTORY FOR THE VAULT TEST CASE

Radionuclide	**Inventory disposed [Bq]**
^{3}H	1E+15
^{14}C	1E+13
^{59}Ni	2E+10
^{63}Ni	1E+15
^{90}Sr	1E+14
^{99}Tc	3E+10
^{129}I	6E+9
^{137}Cs	8E+15
^{234}U	5E+10
^{238}U	5E+10
^{238}Pu	2E+10
^{239}Pu	3E+10
^{241}Pu	6E+11
^{241}Am	2E+10

Facility design

The facility design has been extracted from public domain documents describing a proposed disposal facility in the USA and modified for the purposes of the Vault Test Case. The disposal facility is a set of 20 concrete vaults located above ground level for the disposal of low-activity waste. The spatial layout of the disposal site is shown in Fig. 2. The waste disposal area contains two sets of 10 vaults with an on-site road running down the middle. Approximate dimensions of the disposal area are 170 m by 210 m giving a surface area of 35,700 m^2. There is a buffer zone in all directions of at least 200 m between the disposal area and the site perimeter fence where no disposals are allowed. The operational period of the disposal facility is planned for 30 years.

Low activity waste is received in standard 200 litre drums. Grout is added into the drums to fill the void space and make a blend of grout and waste. These drums are then placed into concrete cubes, and grout is filled in between the drums. The resulting waste form is therefore expected to be a monolith of concrete with embedded steel drums and waste. The cubes are then stacked in the vaults.

For assessment purposes the following assumptions have been made:

— The facility is designed to accept 150 000 m^3 of waste. This volume is assumed to refer to the total volume of 200 litre drums, containing waste and grout. Therefore, the facility will accept a total of 750 000 drums, which is equivalent to 37 500 per vault; and

— It has been assumed that the waste drums represent 50% of the total disposal facility volume, i.e. the concrete cubes and grout between the drums also occupy 150 000 m^3 and the total vault capacity will be ~ 300 000 m^3.

— Assumed dimensions (see Fig. 3):

- Each 200 litre drum has a diameter of ~50 cm and height ~1 m.
- Each concrete box will hold 8 drums (two layers of 4 drums). Internal dimensions: 1m x 1m x 2m high = 2000 litres. External dimensions: 1.2 m x 1.2 m x 2.25 high = 3 240 litres. Assumed concrete wall thickness ~ 10cm. Therefore each concrete box represents 1 600 litres of waste, 400 litres of infill grout and 1 240 litres of concrete, i.e. around 50% waste and 50% grout/concrete.
- Each vault has internal dimensions of 9 m high by 20.5 m wide by 83 m long. This allows concrete cubes to be stacked 4 high x 17 x 69. This corresponds to a capacity of 4 692 concrete cubes, containing 37 536 drums. Each vault has an internal volume of 15 300 m^3.
- Assumed vault wall and base thickness would be 0.3 to 0.5 m.

It is assumed that the facility will be built above ground with foundations below ground. The facility will be built on top of a sand bed engineered on top of the local geology to provide seismic stability. A drainage system will be maintained underneath the facility during the operational phase but prior to site closure this will be decommissioned and unfilled and will be indistinguishable from the engineered sand bed. It will be assumed that the lifetime of all parts of the engineered barriers will not vary significantly and so bathtubbing will not occur.

Current closure plans for the disposal facility propose covering the vaults with a multiple layer cover to form a low gradient mound. This will include a waterproof cover on the vault roof, a layer of compacted clay, a soil cover and finally a thick erosion-resistant rock/gravel layer.

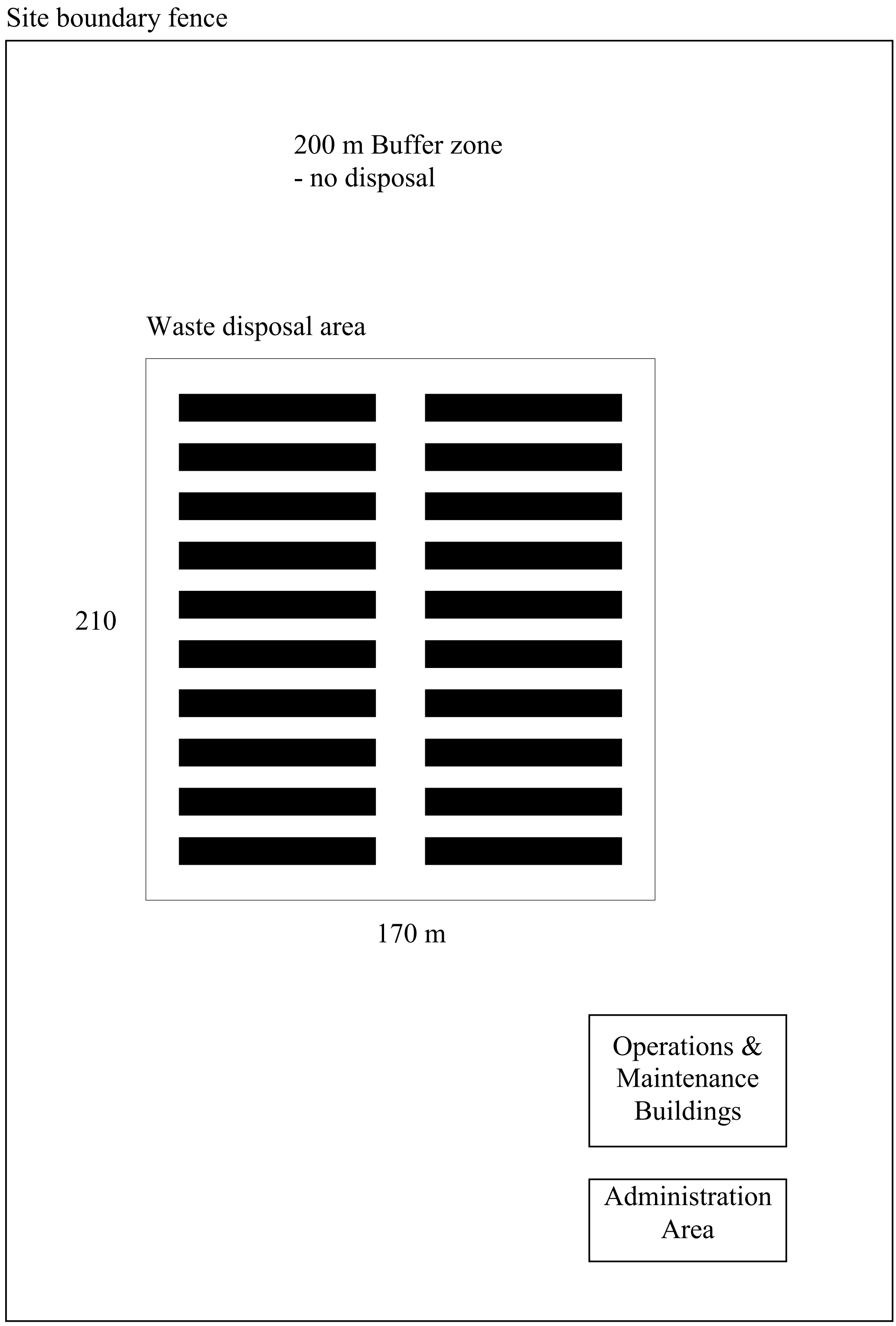


FIG. 2. Planned Site Layout for the Vault Test Case.

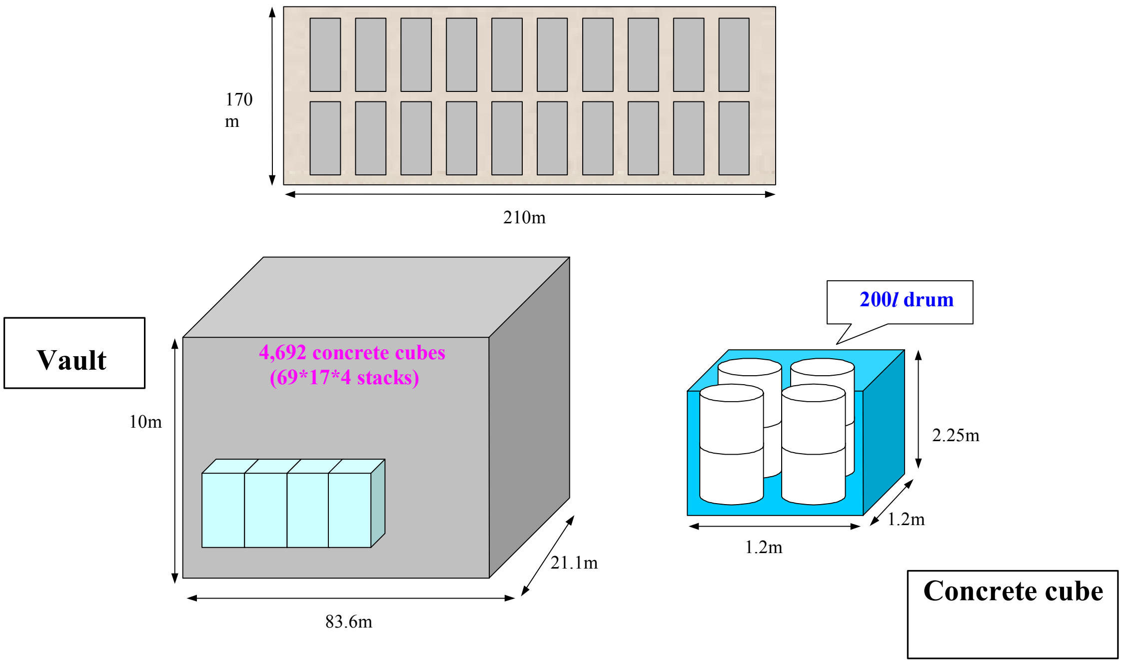


FIG. 3. Proposed Waste System Dimensions for the Vault Test Case.

1.2.2. Geosphere

The geology and hydrogeology of Vaalputs is summarized below. A more detailed description is provided in the Borehole Test Case (Section 3).

Vaalputs is situated on fractured precambrian crystalline basement rocks, which are covered by younger sedimentary rocks. Metamorphism transformed the original sedimentary and volcanic rocks to granite-gneisses and metavolcanics. Near surface sediments include red sand, aeolian sand, calcretised sandy, gritty clay and red/greyish fluvial, gritty, sandy clay containing gravel and quartz pebbles (Figs 4 and 5). The structural geology is very complex (Fig. 6 and Fig. 7). Five deformational events have been identified.

Seismic activity takes place throughout South Africa. Since the existence of the Vaalputs seismic station, a number of small seismic events have been recorded (up to 3.4 on the Richter scale). Earthquakes of magnitude 6-7 have been recorded in the north-west region in the last 50 years. The possibility therefore exists that fracture zones (faults) may be rejuvenated or new fractures could be initiated.

At Vaalputs, the unsaturated zone extends between 50 – 70 m below the surface and consists of the weathered overburden and fractured bedrock. The unsaturated zone is followed by the saturated, fractured bedrock. The aquifer is structurally controlled by fault zones. Hydraulic characteristics of the unsaturated and saturated zones are summarized in Figs 4 and 5.

Lithology		Saturated Hydraulic conductivity (md^{-1})	Bulk density kg m^{-3}	Porosity
	Red sand	2.5×10^{-3}		0.30 - 0.35
	Red sandy Gritty clay	6.5×10^{-3}		0.37 - 0.45
	White Kaolintic clay	51×10^{-3}		
	Weathered Granite	6.5×10^{-3}		0.36

FIG. 4. Hydraulic Parameters of the Unsaturated Zone.

Lithology		Hydraulic conductivity (md^{-1})	Specific storativity
	Weathered Granite	2.0 - 5.0	$10^{-4} – 10^{-3}$
	Fractured Granite	1.0×10^{-3} - 3.0	$10^{-6} – 10^{-3}$

FIG. 5. Hydraulic Parameters of the Saturated Aquifer Zones.

Formation	Lithology	Age (Ma)	Geological Process	Geological Period
Kalahari Gordonia	Red sand	20-5	Aeolian dunes	Tertiary to Recent
Vaalputs	Calcrete and silcrete ferruginised sandy gritty clay. Brown sandy gritty clay. Grey sandy gritty clay with interbedded pebble bands	35-20	Fluvial	
Dasdap	Siliceous sandstone. Cross-bedded arkosic grit Conglomerate	38-20	Alluvial fan	
Unconformity	Kaolinised and silicified surface			Late Cretaceous
Karoo (Dwyka)	Diamictite	300	Glacial	Jurassic-late Carboniferous
Namaqualand Metamorphic Complex O'Okiep Garies	Basment granitoids Metamorphic rocks	1050	Tectonism, intrusion	Precambrian

FIG. 6. Geological Succession at Vaalputs.

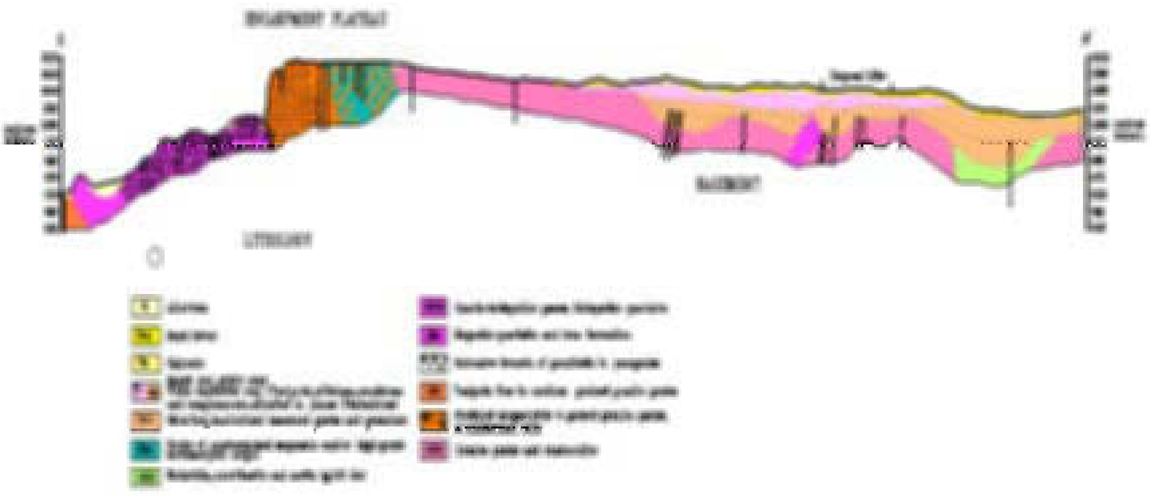


FIG. 7. East-west Cross-section through the Vault Test Case Disposal Site.

The Vaalputs aquifer system consists of large and smaller scale fracture zones, separated by matrix blocks. The fracture zones have much higher hydraulic conductivity values than the aquifer matrix. Some of the fractures are, however, annealed and could form groundwater flow boundaries. The Vaalputs aquifer is bounded in the west by a topographical and groundwater divide. To the north and south, it is bounded by major shear zones. In the east, a physical boundary is formed by the Koa River Valley drainage system, although some of the flow terminates in a large depression formed by a pan. The regional fault zones influence the piezometric head elevation, groundwater chemistry and flow. The aquifer is divided by fractures into zones or compartments. Hydraulic properties change and lead to changes in piezometric head elevation and groundwater chemistry take place. High permeability zones have been determined in the unsaturated zone. Recharge takes place through these fracture zones. The regional piezometric gradient is gentle towards the northeast. Locally, it is however influenced by fracture zones. At the disposal site, several fracture zones occur that form conduits in the subsurface. These zones may be important for groundwater flow and radionuclide transport.

1.2.3. Biosphere

Vaalputs is situated in a semi-arid region, approximately 90 km from the nearest town. The site is located on a flat plateau on the edge of an escarpment that has a north-south trend. To the west the relief is mountainous and to the east there are extensive flat plains. The long term average rainfall is 80 mm per annum and rainfall events are normally short lived summer thunderstorms; the annual rainfall might occur in a few hours. Potential evaporation is very high (~2 100 mm per annum). The drainage system in the area is not well developed and most streamlets terminate in local pans.

The natural background radiation dose is 2.25 mSv y^{-1}.

The plant and animal life of the area is characteristic of a semi-desert environment. The plant life is a major determinant of the animals it supports. Six ecological zones have been identified. The common harvester termite posse the greatest intrusion threat as it constructs extensive and deep tunnel systems (~ 4 m depth) and is capable of excavating large quantities of soil (~1 kg m^{-2} per day). The termites can tunnel through the very hard calcrete layer by way of fractures. They are likely to invade the disposal facility cover, making rehabilitation difficult. The termites also occupy a pivotal position in the food chain and could be eaten by tribal communities.

The Vaalputs area is sparsely populated. Agriculture is the main activity, specifically sheep farming. The sheep diet is natural vegetation supplemented by imported fodder and borehole water. The average capacity of the land is one animal per 9 ha. Some cows, goats and hens are also kept for domestic use. Farmers tend to migrate to other areas in the winter and return in the summer. The main potential exposure pathways are likely to be drinking borehole water and consumption of animal products contaminated via borehole water.

1.3. DEVELOPMENT AND JUSTIFICATION OF SCENARIOS

1.3.1. Vault test case approach

The basis of the approach adopted was developed at the first meeting of the group and is illustrated in Fig. 8.

The basic approach is comprised of the following elements (see also Appendix A):

— Carry out an initial screening of the ISAM FEPs list on the basis of the assessment context and system description (Section 1.2). Record the justification for excluding any FEPs from further consideration;

— Focus initially on one reference scenario termed the 'Design Scenario' (Section 1.3.3), which represents how the system might be expected to evolve assuming the design functions as planned. This design scenario approach was adopted because the facility assessed was still in the planning stage. If the Design Scenario were not to yield acceptable results, it would be unlikely that development of the disposal facility would proceed with the current design and the investigation of alternative, more conservative scenarios would be unnecessary;

— Decide on the external FEPs (scenario generating FEPs) for the Design Scenario (Section 1.3.3.);

— Identify the safety-relevant features and associated safety functions for the Design Scenario (Section 1.3.3.);

— Develop a description for the Design Scenario (Section 1.3.3.). This includes estimates of the expected lifetime/performance of the identified safety-relevant features and their safety functions;

— Identify alternative scenarios at a high level by revisiting the screened ISAM FEPs list, especially focusing on the external FEPs, and select which alternative scenarios should be assessed in detail (Section 1.3.4);

— Decide on the status of external FEPs for each alternative scenario to be assessed (Section 1.3.5.);

— Identify safety-relevant features and associated safety functions for each alternative Scenario to be assessed (Section 1.3.5.); and

— Develop a description of each alternative scenario (Section 1.3.5.). This includes estimates of the expected lifetime/performance of the identified safety-relevant features and their safety functions.

Once the Design Scenario and alternatives have been described, their FEPs and FEPs interactions can be analysed in more detail to allow the development of associated conceptual models (see Fig. 9). This is described in Section 1.4.

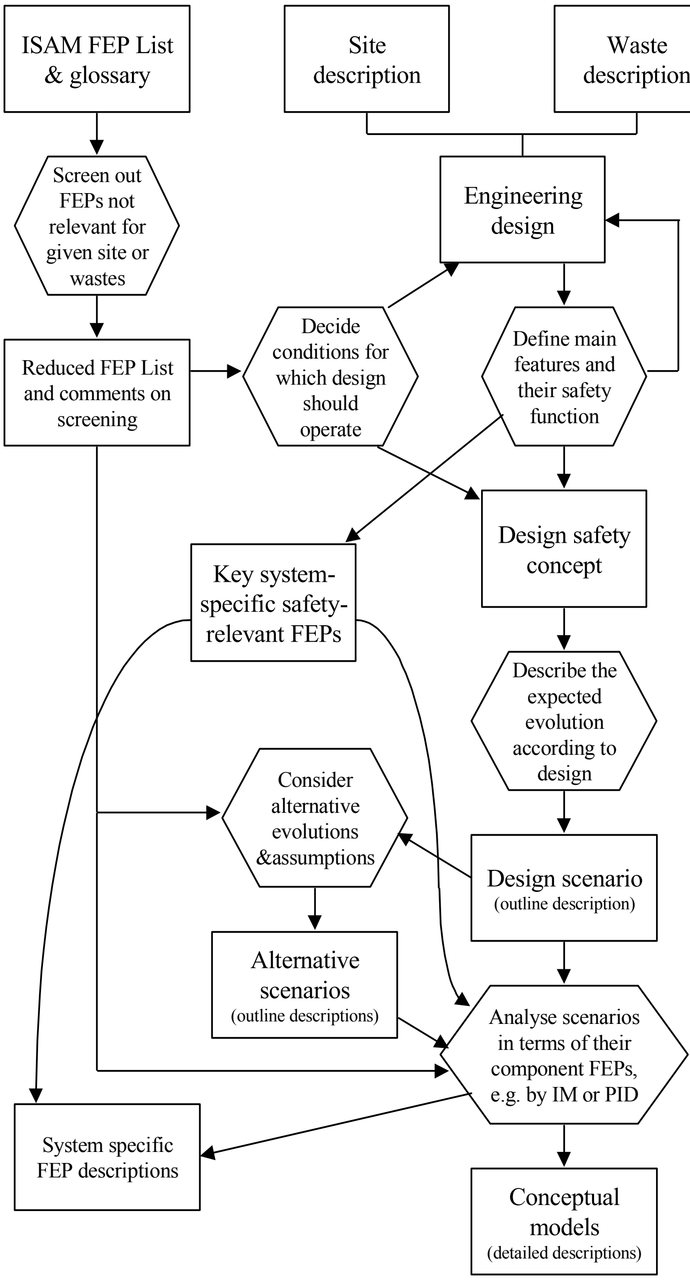


FIG. 8. Vault Test Case Scenario Generation Approach.

1.3.2. Initial FEPs screening

Prior to the ISAM FEPs list being screened to unify hose relevant to the test case facility, the assessment context and system description documentation were reviewed to identify points for further clarification and increase participants' understanding of the disposal system. It was agreed at this early stage that it was only necessary to record a simple 'yes' if a FEP should be included. For excluded FEPs, the justification for the decision was recorded. The results of this initial screening process are recorded in Table 3.

TABLE 3. ISAM FEP LIST SCREENED FOR THE VAULT TEST CASE

0	**ASSESSMENT CONTEXT**
0.01	Impacts of concern – yes
0.02	Timescales of concern- yes
0.03	Spatial domain of concern – yes
0.04	Repository assumptions- yes
0.05	Future human action assumptions- yes
0.06	Future human behaviour (target group) assumptions- yes
0.07	Dose response assumptions- yes
0.08	Aims of the assessment- yes
0.09	Regulatory requirements and exclusions- yes
0.10	Model and data issues- yes

1	**EXTERNAL FACTORS**
1.1	REPOSITORY ISSUES
1.1.01	Site investigation – Yes, noted that already have large number of investigation boreholes at the site
1.1.02	Excavation/construction – Yes, if you consider that construction includes the implementation of the design
1.1.03	Emplacement of wastes and backfilling – Yes, issues of heterogeneity
1.1.04	Closure e.g. capping – Yes
1.1.05	Records and markers, repository – Yes
1.1.06	Waste allocation – Yes – fixed as LLW
1.1.07	Repository design – Yes
1.1.08	Quality control – Yes, e.g. could have poor quality concrete which effects performance of the facility
1.1.09	Schedule and planning – Yes, need to consider 30 year operational period
1.1.10	Administrative control, repository site – Yes
1.1.11	Monitoring of repository – No, assume no monitoring, or if monitoring no impact on performance
1.1.12	Accidents and unplanned events – Yes, could have waste packaged dropped and impact on performance of concrete barrier.
1.1.13	Retrievability – No, assumed not to be required
1.2	GEOLOGICAL PROCESSES AND EFFECTS
1.2.01	Tectonic movements and orogeny – no, given the location of the site, especially over 10,000 or even 1 million years
1.2.02	Deformation, elastic, plastic or brittle – no, as 1.2.01
1.2.03	Seismicity – Yes, see description of the site, note recent activity

1.2.04	Volcanic and magmatic activity – no, as 1.201
1.2.05	Metamorphism – no, as 1.201
1.2.06	Hydrothermal activity – no, as 1.201
1.2.07	Erosion and sedimentation – yes
1.2.08	Diagenesis – no, not relevant
1.2.09	Salt diapirism and dissolution – no, not relevant
1.2.10	Hydrological/hydrogeological response to geological changes – yes, could have seismically driven groundwater flow
1.3	CLIMATIC PROCESSES AND EFFECTS
1.3.01	Climate change, global – yes
1.3.02	Climate change, regional and local –yes
1.3.03	Sea level change – no, too far from sea
1.3.04	Periglacial effects – no, not even after 10,000 years given the location of the site
1.3.05	Glacial and ice sheet effects, local – no, see 1.3.04
1.3.06	Warm climate effects (tropical and desert) – yes
1.3.07	Hydrological/hydrogeological response to climate changes –yes
1.3.08	Ecological response to climate changes –yes
1.3.09	Human response to climate changes –yes
1.3.10	Other geomorphological changes – yes, FEP needs clarification with definition and more examples
1.4	FUTURE HUMAN ACTIONS
1.4.01	Human influences on climate – yes, could include global warming
1.4.02	Motivation and knowledge issues (inadvertent/deliberate human actions) – yes, need to discuss to decide on which intrusion scenarios to consider.
1.4.03	Un-intrusive site investigation – no, related to geophysical investigations for deep facilities
1.4.04	Drilling activities (human intrusion) – yes
1.4.05	Mining and other underground activities (human intrusion) – yes
1.4.06	Surface environment, human activities – yes
1.4.06.01	Surface Excavations – to be considered later
1.4.06.02	Pollution - – to be considered later
1.4.06.03	Site Development – to be considered later
1.4.06.04	Archaeology – to be considered later
1.4.07	Water management (wells, reservoirs, dams) – yes
1.4.08	Social and institutional developments – yes
1.4.09	Technological developments – no, need to distinguish social and institutional developments from technological developments on the basis of the assessment context

1.4.10	Remedial actions – no, consistent with assumption that have no monitoring. Some discussion about this point. No, to rule out endless speculation for this stage of the assessment
1.4.11	Explosions and crashes – yes
1.5	OTHER
1.5.01	Meteorite impact – no, very low probability, non-radiological consequences significantly greater. No difference between meteorite impact on store and disposal facility
1.5.02	Miscellaneous and FEPs of uncertain relevance – no, nothing thought of at present.
2	**DISPOSAL SYSTEM DOMAIN: ENVIRONMENTAL FACTORS**
2.1	WASTES AND ENGINEERED FEATURES
2.1.01	Inventory, radionuclide and other material – yes
2.1.02	Waste form materials and characteristics – yes
2.1.03	Container materials and characteristics – yes
2.1.04	Buffer/backfill materials and characteristics – yes
2.1.05	Engineered barriers system e.g. caps – yes
2.1.06	Other engineered features materials and characteristics – yes, although nothing specific in the system description
2.1.07	Mechanical processes and conditions (in wastes and EBS) – yes
2.1.08	Hydraulic/hydrogeological processes and conditions (in wastes and EBS) – yes
2.1.09	Chemical/geochemical processes and conditions (in wastes and EBS) – yes
2.1.10	Biological/biochemical processes and conditions (in wastes and EBS) – yes
2.1.11	Thermal processes and conditions (in wastes and EBS) – yes, due to diurnal temperate variation
2.1.12	Gas sources and effects (in wastes and EBS) – yes
2.1.13	Radiation effects (in wastes and EBS) – maybe, but probably radiation levels not sufficiently high – will need to do some hand calculations to check
2.1.14	Nuclear criticality – as 2.1.13
2.1.15	Extraneous materials – need to explain this FEP in the generic list. No, given the current stage of the assessment.
2.2	GEOLOGICAL ENVIRONMENT
2.2.01	Excavation disturbed zone, host lithology – no, facility is on the surface. There could be a need to consider impacts of foundations but this could be included in construction (1.1.02)
2.2.02	Unsaturated lithology – yes
2.2.03	Saturated lithology –yes
2.2.04	Discontinuities, large scale (in geosphere) – yes
2.2.05	Contaminant transport path characteristics (in geosphere) – yes
2.2.06	Mechanical processes and conditions (in geosphere) – yes, note that this is considered to be post construction

2.2.07	Hydraulic/hydrogeological processes and conditions (in geosphere) –yes
2.2.08	Chemical/geochemical processes and conditions (in geosphere) – yes
2.2.09	Biological/biochemical processes and conditions (in geosphere) – yes
2.2.10	Thermal processes and conditions (in geosphere) – no, not considered to be relevant for the geosphere (note that we are considering it in the near field)
2.2.11	Gas sources and effects (in geosphere) – yes, because cover might force the gas from the repository down
2.2.12	Undetected features (in geosphere) – yes, could have undetected faults and fractures
2.2.13	Geological resources – yes
2.3	SURFACE ENVIRONMENT
2.3.01	Topography and morphology – yes
2.3.02	Soil and sediment – yes
2.3.03	Aquifers and water-bearing features, near surface – yes
2.3.04	Lakes, rivers, streams and springs – yes
2.3.05	Coastal features – no, given inland location of site
2.3.06	Marine features – no, given inland location of site
2.3.07	Atmosphere – yes
2.3.08	Vegetation – yes
2.3.09	Animal populations – yes
2.3.10	Meteorology – yes
2.3.11	Hydrological regime and water balance (near-surface) – yes
2.3.12	Erosion and deposition – yes (note overlap with the EFEP with the same title, although this is more local)
2.3.13	Ecological/biological/microbial systems – yes
2.3.14	Animal/plant intrusion – yes
2.4	HUMAN BEHAVIOUR
2.4.01	Human characteristics (physiology, metabolism) – yes
2.4.02	Adults, children, infants and other variations – yes
2.4.03	Diet and fluid intake – yes
2.4.04	Habits (non-diet-related behaviour) – yes
2.4.05	Community characteristics – yes
2.4.06	Food and water processing and preparation – yes
2.4.07	Dwellings – yes
2.4.08	Wild and natural land and water use – yes
2.4.09	Rural and agricultural land and water use (incl. Fisheries) – yes
2.4.10	Urban and industrial land and water use – no, rule out on the basis of the stage of the assessment and the assessment context

2.4.11	Leisure and other uses of environment – maybe (bounded by site dweller scenario)
3	**RADIONUCLIDE/CONTAMINANT FACTORS**
3.1	CONTAMINANT CHARACTERISTICS
3.1.01	Radioactive decay and in-growth – yes
3.1.02	Chemical/organic toxin stability – no, this is stated in the assessment context
3.1.03	Inorganic solids/solutes – yes
3.1.04	Volatiles and potential for volatility – yes
3.1.05	Organics and potential for organic forms – yes
3.1.06	Noble gases – yes
3.2	CONTAMINANT RELEASE/MIGRATION FACTORS
3.2.01	Dissolution, precipitation and crystallisation, contaminant – yes
3.2.02	Speciation and solubility, contaminant – yes
3.2.03	Sorption/desorption processes, contaminant –yes
3.2.04	Colloids, contaminant interactions and transport with –yes
3.2.05	Chemical/complexing agents, effects on contaminant speciation/transport –yes
3.2.06	Microbial/biological/plant-mediated processes, contaminant –yes
3.2.07	Transport of contaminants through water pathway–yes
3.2.08	Transport of contaminants through solid releases–yes
3.2.09	Transport of contaminants through gas releases–yes
3.2.10	Atmospheric transport of contaminants –yes
3.2.11	Animal, plant and microbe mediated transport of contaminants – yes
3.2.12	Human-action-mediated transport of contaminants – yes
3.2.13	Foodchains, uptake of contaminants in – yes
3.3	EXPOSURE FACTORS
3.3.01	Drinking water, foodstuffs and drugs, contaminant concentrations in –yes
3.3.02	Environmental media, contaminant concentrations in –yes
3.3.03	Non-food products, contaminant concentrations in – maybe but consider in bounding scenario
3.3.04	Exposure modes – yes
3.3.05	Dosimetry –yes
3.3.06	Radiological toxicity/effects – yes
3.3.07	Non-radiological toxicity/effects – no, not considering on the basis of the assessment context
3.3.08	Radon and radon daughter exposure – yes

1.3.3. Design scenario

Development of the design scenario

Two options for the next stage in the process were considered:

(1) Review the screened FEPs list in Section 1.3.2 and break down into more detailed, lower level FEPs; and

(2) Generate scenarios down to an appropriate level of detail and then feed lower level FEPs into the ISAM FEPs list.

Given the resource constraints, it was decided to focus on a limited number of illustrative reference scenarios rather than developing a more comprehensive approach that identified all possible scenarios in a systematic manner. A functional analysis approach was used to develop the Design Scenario.

Specification of external FEPs status

For the purposes of the Vault Test Case, the Design Scenario was developed with constant present day external FEPs, although it is noted that the approach does not necessarily require external FEPs to be constant, e.g. climate change may be included in the scenario if this is very likely to happen at some point. The list of external factors in the ISAM FEP list was reviewed to decide the conditions to be fixed for the purpose of defining the safety functions. These decisions are recorded in Table 4. Note those FEPs screened out in the initial screening process (see Section 1.3.2) are excluded from Table 4.

Safety related features and associated safety functions

The main safety-related features and their safety functions are presented in Table 5. It is important to remember single features may have several safety functions. For example, the site cover may serve to minimize rainwater infiltration to prevent radionuclide release by the groundwater pathway and it may also act as a physical barrier reducing the risk of human intrusion. The design of the cover may include different components/properties to accomplish these different functions. Furthermore, these different functions may operate over different time scales. For example the cover over the disposal facility can act as a barrier to intrusion as well as an infiltration barrier. Its role as a physical barrier to intrusion may exist long after its role as an infiltration barrier has failed.

TABLE 4. STATUS OF EXTERNAL FEPS FOR THE DESIGN SCENARIO FOR THE VAULT TEST CASE

1 EXTERNAL FACTORS – for Design Scenario

1.1 REPOSITORY ISSUES

1.1.01 Site investigation – Assumed not to be important in terms of the long term performance of the disposal system.

1.1.02 Excavation/construction – Site is engineered to take benefit from the presence of the sand that can be load bearing. We might want to highlight that we could have a variant that will allow for removal of the sand.

1.1.03 Emplacement of wastes and backfilling – As planned

1.1.04 Closure e.g. capping – As planned

1.1.05 Records and markers, repository – Discussion as to whether to have markers and/or records. Thought that for 100 years there is control, for a further 200 years there is some memory/record.

1.1.06 Waste allocation – As planned

1.1.07 Repository design – As planned

1.1.08 Quality control – As planned

1.1.09 Schedule and planning – As planned

1.1.10 Administrative control, repository site – As planned

1.1.12 Accidents and unplanned events – No accidents and unplanned events assumed

1.2 GEOLOGICAL PROCESSES AND EFFECTS

1.2.03 Seismicity – Designed to withstand event up to a given magnitude for a 1 000 year period within a set radius. Could use 2.4 G as design target (or whatever the most appropriate figure is). Assume above 2.4 G events do not occur. Effect of hydraulic pump induced by earthquake is assumed at this stage not to matter. Beyond 1000 year the effect of earthquake is assumed to be no more significant than effect of general (non earthquake induced) degradation

1.2.07 Erosion and sedimentation – On a regional scale we assume no significant net erosion and sedimentation (can have sand dunes moving around) – note there is another FEP (2.3.12) for which we can consider local erosion/sedimentation.

1.2.10 Hydrological/hydrogeological response to geological changes – See discussion concerning seismicity above

1.3 CLIMATIC PROCESSES AND EFFECTS

1.3.01 Climate change, global – No change, assume as present day but allow for variability

1.3.02 Climate change, regional and local – No change, assume as present day but allow for variability

1.3.06 Warm climate effects (tropical and desert) – No change, assume as present day but allow for variability e.g. flash floods, etc.

1.3.07 Hydrological/hydrogeological response to climate changes – Not applicable since no change assumed no change assumed

1.3.08 Ecological response to climate changes – Not applicable since no change assumed

1.3.09 Human response to climate changes – Not applicable since no change assumed

1.3.10 Other geomorphological changes – Not applicable since no change assumed

1.4 FUTURE HUMAN ACTIONS

1.4.01 Human influences on climate – Not applicable since no change assumed

1.4.02 Motivation and knowledge issues (inadvertent/deliberate human actions) – No intrusion assumed because no valuable resources in or near site, records kept, use concrete, shallow slopes, long institutional control period. In design need to try to design against intrusion, i.e. need to make intrusion unattractive. Intrusion impacts can be limited if adopt quantitative acceptance criteria that are based on intrusion pathway.

1.4.04 Drilling activities (human intrusion) – Not considered, see above

1.4.05 Mining and other underground activities (human intrusion) – Not considered, see above

1.4.06 Surface environment, human activities – See below

1.4.06.01 Surface Excavations – Not considered, see 1.4.02

1.4.06.02 Pollution – Not considered, on basis of present site location and no activities resulting in significant pollution at present in the vicinity of the site

1.4.06.03 Site Development – Not considered, see 1.4.02, plus argument relating to consideration of present day activities in the vicinity of the site

1.4.06.04 Archaeology – Not considered, see 1.4.02.

1.4.07 Water management (wells, reservoirs, dams) – No large scale water management, but local wells are included in the human behaviour FEPs (2.4).

1.4.08 Social and institutional developments – Assume that society remains as present day and that memory/records are kept for 300 years

1.4.11 Explosions and crashes – Would design the facility to withstand the impact of a light aircraft, so that this FEP does not need to be considered.

TABLE 5. SAFETY RELEVANT FEATURES AND ASSOCIATED SAFETY FUNCTIONS FOR THE VAULT TEST CASE

Safety relevant features	Safety function
Waste/waste treatment	Waste acceptance criteria (No valuable material, no oxidising/complexing agents, no putrescibles, flammables, etc)
Waste form/grout	Minimize voids (mechanical, biological) Chemical control (e.g. sorption, microbiology) limits radionuclide release Reduces water flow contact with waste Mechanical stability (both operational and post-closure) Solidify and stabilise Non-flammable Reduce dose in handling
Containers (200 l steel drums)	Management of waste during operation Chemical control (corrosion) limits radionuclide release Reduces water flow contact with waste (at early times)
Concrete cubes/boxes & grout	Chemical protection of drums (reduce corrosion) Chemical control (e.g. sorption, microbiology) limits radionuclide release Reduces water flow contact with waste Mechanical stability (both operational and post-closure) Non-flammable Reduce dose in handling
Vault base, walls, grout (membrane & roof slabs)	Protection of humans and from water ingress Chemical control (e.g. sorption, microbiology) limits radionuclide release Reduce water flow contact with waste Mechanical stability (supports cover) but need to consider seismicity and settlement Non-flammable Reduces releases during operation and post-closure periods
Sand bed (below disposal facility), sand cap/cover/infill	Mechanical stability/mechanical buffering reduces local stress e.g. vs. seismicity Drainage (base and sides) Chemical properties (clay fraction) retarding release of contaminants Colloid filtration
Cover/multi-layer cap (clay, concrete, soil, geotextiles, vegetation)	Protection (infiltration of water; erosion (gully and denudation); intrusion of human, animals, plants, planes; gas escape)
Unsaturated zone (50-70m thick, average 55m) – sand (re-worked), calcrete, sandy clay, white kaolinitic clay, weathered granite	Physical separation from groundwater Migration path for percolation (retardation, sorption) Colloid filtration Dispersion (negative feature – preferential flow paths)
Saturated zone (average depth of 55m) – aquifer (weathered granite, fractured granite)	Natural discharge zone(s) Dilution/dispersion Attenuation Salinity (potability/non-potable) (negative feature – preferential flow paths, wells)
Location	Selected for geological stability Favourable topography (no rivers; flat) Remote area (from humans population centres) Limited climate change expected (negative feature – climate variability)

Description of the design scenario

By considering the lifetime/performance of the safety related features and their safety functions the Design Scenario description can be developed. At this stage only a largely qualitative, high level description of the temporal evolution of the system is required based on questions such as 'how', 'why' and 'when' need to be asked when considering the failure of the safety features. In the development of the Design Scenario, it is important to have a good description for the design. If the design is well specified, the design scenario and alternative scenarios can be relatively easily defined. If the design is poorly defined, then the scenarios are more difficult to specify and there needs to be greater iteration between the scenario and design work.

In the text below a brief outline summary of the Design Scenario is given, describing the expected temporal evolution of the system and its safety-related features, i.e. a high-level description of the evolution of the system. This summary has been checked to ensure consistency with the external FEPs discussed in Section 1.3.3.

Top level assumptions:

— Design Scenario will not consider any human intrusion events (FEPs 1.4.02, 1.4.04, 1.4.05, 1.4.06, 1.4.07 screened out); and
— Climate remains as present day conditions (FEPs 1.3.01, 1.3.02, 1.3.07, 1.3.08, 1.3.09, 1.3.10, 1.4.01 screened out).

Total institutional control period of 300 years (FEPs 1.1.05 and 1.1.10):

- 100 years of active institutional controls (e.g. to maintain the cover, monitor environmental performance, restrict access, etc.);
- A further 200 years of passive institutional control (e.g. site location on official maps, land use restrictions); and
- Biosphere practices will be as present day, in particular it is assumed that farming will be practised in the vicinity of the site.

Variants on these assumptions can be considered as alternate scenarios.

Operational period

The Vault Test Case will only assess post-closure safety. This section is included to clarify the status of the facility at the end of the operational period and hence rule out possible 'what if?' questions. The site is built and operated as planned (FEPs 1.1.02, 1.1.03, 1.1.06, 1.1.07, 1.1.08 and 1.1.09 assumed to be as planned). Although, there may be minor handling accidents these do not damage the vault structure or underlying materials, or any damage is made good (FEP 1.1.12). Any badly damaged packages are placed in overpacks.

During operations, the vaults are covered by temporary roofs to minimize entry of rainfall and vault floors are designed to shed any water into drainage sumps. Completely filled vaults are covered by a temporary cover which limits infiltration and prevents animal intrusion. Hence there is no excess water left in the vaults at closure. The whole site area is controlled to prevent animal and unauthorized human access (FEP 1.1.10). After closure of the last vault, the temporary covers over each vault are built up to form the final cover given in the design (FEP 1.1.04 closure as planned). All site investigation activities are managed to ensure no effect on post-closure performance, e.g. boreholes sealed and correctly closed (FEP 1.1.01).

At closure, the facility appears as a mound with low gradient sides in an otherwise extremely flat area. The engineered drainage system under the waste drainage will be filled in at closure.

Active institutional control period

Active site control is maintained for a period of 100 years after the end of disposal operations. In this period, the site area is fenced and patrolled to prevent animal and unauthorized human access. Occasional unauthorized access may occur, but this is not significant. Any burrowing animals would be controlled. It is assumed that termite activity has no significant effect on cover performance. The condition of the cover will be monitoring and will be repaired as necessary. Some radiological monitoring may also may be carried out for re-assurance purposes.

The design of the cover will be effective in reducing infiltration water reaching the vaults to an insignificant level. There will be pore water in the materials contained in the vaults (e.g. waste, grout, concrete, etc). The saturation level will depend upon water retention coefficients. Some moisture will enter and leave the vaults as unsaturated water flux and water vapour.

Some corrosion of the steel waste drums will have begun even before they were emplaced and likewise there will be some small amount of degradation of the wastes within the drums. The cement matrix will limit internal and external corrosion due to prevailing alkaline conditions. The drums are not designed to be gas tight; thus there may be releases of gaseous species in this period, e.g. tritiated water vapour, radon, ^{14}C gases. Gases from the vault will travel to the cover surface, any gas will be dispersed in the air.

Passive institutional control period

After active control ends, local damage to the cover (e.g. due to animal intrusion, human activities, wind erosion and water erosion) will not be repaired. Infiltration through the cover will increase as it degrades. However, degradation of the concrete and waste during this time period is similar to the active period.

As noted earlier, during this passive control period there will still be institutional controls on land use (site usage and occupancy). This will prevent people living on the site and building houses and/or constructing roads.

Post institutional control period

At some point the degradation of the cover, which began in the passive control period, will lead to exposure of the concrete vaults. For the purposes of the Design Scenario, the first exposure event is assumed to be at 500 years after closure (i.e. 200 years after the end of passive controls). Between 500 and 3000 years, a significant fraction of the concrete vaults will be exposed due to further cover degradation.

Infiltration of water will increase as the cover fails and the vaults are exposed. Even if there will be cracks and joints in the concrete walls and roofs so that water can contact the waste form, the near field is assumed to form a porous flow medium. Thus corrosion of the drums and degradation of the wastes in affected sections of the vault will proceed more rapidly and radionuclides will be leached from the waste. Note as the vault is made of concrete, chemical control (e.g. alkaline conditions) will influence radionuclide behaviour. Some downward migration occurs below the vaults. During rain storm events, small pools may be formed at the site. The water flows through the unsaturated zone and ends up in the underlying aquifer.

It is assumed that groundwater discharges occur to a salt pan.

The waste, drums and concrete gradually become exposed and degrade. It is assumed that they will mix with cover materials and the surrounding near surface geosphere forming a heterogeneous mix.

The site could be used for a residential and agriculture buildings. Water could be extracted from wells drilled nearby and used for agriculture.

1.3.4. Alternative scenarios

Given that the Design Scenario has been developed, there is a need to go through the key assumptions and decide if there is a need to develop alternative scenarios. The need to develop alternative scenarios can be assessed by comparing each category of external FEP in the ISAM FEPs list against the Design Scenario. These external FEPs can be considered to be scenario generating FEPs – changes in their status were considered to result in the generation of additional scenarios. In contrast, differences in the internal FEPs were considered to result in different conceptual models associated with the same scenario, rather than different scenarios.

The following external FEP categories can be identified from the ISAM FEPs list:

— Repository issues;
— Geological processes and effects;
— Climate processes and effects;
— Future human actions; and
— Other.

If the range of possible conditions for external FEPs in a category is not satisfactorily covered by the Design Scenario, then an alternative scenario may be developed. This process is iterative.

To help screen the resulting scenarios, probability, uncertainty and consequence can be used as screening criteria (Table 6). It was agreed that initially the focus should be on the high consequence FEPs. It was recognized that, ideally, initial results from the Design Scenario analysis could be used to help identify key FEPs that should be varied in alternative scenarios. However, at the time of selecting alternative scenarios, results from the Design Scenario were not available so the Vault Test Case Group relied on analysis of the FEPs alone and their expert knowledge gained from similar assessments.

TABLE 6. SCREENING CRITERIA FOR POSSIBLE ALTERNATIVE SCENARIOS FOR THE VAULT TEST CASE

Importance of consequence	**Probability**	**Knowledge**		
		Certain	**Uncertain**	**None**
Important	High	Consider	Investigate	Investigate
	Low	Further investigation needed	Further investigation needed	Further investigation needed
Not important	High	Screen out	Check	Check
	Low	Screen out	Screen out	Check

Repository issues FEPs. The review highlighted the fact that it is hard to consider each repository issue on its own due to a lack of detailed design information. It was decided to adopt a high level statement concerning repository issues – assume the disposal facility is not constructed/operated to the standards/requirements of the Design Scenario. Therefore, it was identified that there was a need to investigate a poor design/performance scenario.

Geological processes and effects FEPs. The review suggested that there was a need to consider an earthquake scenario and its effect on the disposal facility and the geosphere. It was noted that regional erosion is not significant and therefore no alternative scenario concerning this FEP was required.

Climatic processes and effects FEPs. It was noted that, in light of the site context, future climate change should not be significant, and that variations in climate may be taken into account by varying parameter values in the Design Scenario. Thus it was considered unnecessary to develop a climate change scenario.

Future human actions FEPs. Deliberate intrusion was screened out for the Vault Test Case in the assessment context and so it did not need to be considered further. For the Design Scenario, inadvertent intrusion into the waste was also ruled out and so there was a need to considered a human intrusion scenario that could be broken down into variants or sub-scenarios as necessary. The impact of intrusion could be investigated at different times (even before 300 years) as a form of sensitivity analysis for doses against the duration of the institutional control period. It was also recognized that intrusion may affect not only the intruder and/or site dweller. Also the performance of the system (e.g. damage to cover) could be affected.

There might also be a need to consider an alternative human activities scenario to account for the fact that human activities, different to those currently found at the site, might develop in the future. Various sub-scenarios might need to be developed under this high level scenario heading.

Other FEPs – none were considered significant.

Thus four alternative scenarios were identified. In light of resource constraints, it was decided to select only one alternative scenario for development. The screening criteria given in Table 6 were applied to the four scenarios. Given the potentially high consequences of human intrusion (demonstrated in previous assessments of near surface disposal facilities – and the relatively high probability of human intrusion over the timescales of concern, it was decided to develop the Human Intrusion Scenario.

1.3.5. Human intrusion scenario

Development of the human intrusion scenario

Specification of external FEP

The external FEPs for the human intrusion scenario were reviewed (see Table 7). The external FEPs for disposal facility issues remained the same as for the Design Scenario (see Table 4), geological processes and effects, and climate processes and effects. However, those relating to future human actions were modified to account for human intrusion.

TABLE 7. STATUS OF EXTERNAL FEPS FOR THE HUMAN INTRUSION SCENARIO FOR THE VAULT TEST CASE

1	**EXTERNAL FACTORS – for Human Intrusion Scenario**
1.1	REPOSITORY ISSUES
1.1.01	Site investigation – Assumed not to be important in terms of the long term performance of the disposal system.
1.1.02	Excavation/construction – Site is engineered to take benefit from the presence of the sand that can be load bearing. We might want to highlight that we could have a variant that will allow for removal of the sand.
1.1.03	Emplacement of wastes and backfilling – As planned
1.1.04	Closure e.g. capping – As planned
1.1.05	Records and markers, repository – Discussion as to whether to have markers and/or records. Control assumed for 100 years, for a further 200 years there is some memory/record.
1.1.06	Waste allocation – As planned
1.1.07	Repository design – As planned
1.1.08	Quality control – As planned
1.1.09	Schedule and planning – As planned
1.1.10	Administrative control, repository site – As planned
1.1.12	Accidents and unplanned events – No accidents and unplanned events assumed
1.2	GEOLOGICAL PROCESSES AND EFFECTS
1.2.03	Seismicity – Designed to withstand event up to a given magnitude for a 1 000 year period within a set radius. Could use 2.4 G as design target (or whatever the most appropriate figure is). Assume above 2.4 G events do not occur. Effect of hydraulic pump induced by earthquake is assumed at this stage not to matter. Beyond 1 000 year the effect of earthquake is assumed to be no more significant than effect of general (non earthquake induced) degradation
1.2.07	Erosion and sedimentation – On a regional scale we assume no significant net erosion and sedimentation (can have sand dunes moving around) – note there is another FEP (2.3.12) for which we can consider local erosion /sediment.
1.2.10	Hydrological/hydrogeological response to geological changes – See discussion concerning seismicity above
1.3	CLIMATIC PROCESSES AND EFFECTS
1.3.01	Climate change, global – No change, assume as present day but allow for variability
1.3.02	Climate change, regional and local – No change, assume as present day but allow for variability
1.3.06	Warm climate effects (tropical and desert) – No change, assume as present day but allow for variability e.g. flash floods, etc.
1.3.07	Hydrological/hydrogeological response to climate changes – Not applicable since no change assumed
1.3.08	Ecological response to climate changes – Not applicable since no change assumed
1.3.09	Human response to climate changes – Not applicable since no change assumed
1.3.10	Other geomorphological changes – Not applicable since no change assumed
1.4	FUTURE HUMAN ACTIONS

1.4.01	Human influences on climate – Not applicable since no change assumed
1.4.02	Motivation and knowledge issues (inadvertent/deliberate human actions) – Yes, intrusion assumed, but only after loss of institutional control and memory. Assume some degradation of slopes and concrete. But do not consider deliberate intrusion
1.4.04	Drilling activities (human intrusion) – Might be drilling for water but intrusion through the repository is unlikely because would not drill from the top of the cover. Furthermore dose consequences for intruder are expected to be lower than for excavation.
1.4.05	Mining and other underground activities (human intrusion) – No valuable resources in the area except for water.
1.4.06	Surface environment, human activities – See below
1.4.06.01	Surface Excavations – Combine with 1.4.06.03. Could assume a dwelling is built rather than a road because might have higher probability than road or well intrusion through the waste, or archaeology. Dwelling could give rise to highest doses (Propose that at the present stage there is no need to choose between road construction and dwelling intrusion.
1.4.06.02	Pollution – Not considered, on basis of present site location and no activities resulting in significant pollution at present in the vicinity of the site
1.4.06.03	Site Development – Combine with 1.4.06.01
1.4.06.04	Archaeology – Not considered, see 1.4.02. Can rule this out on the grounds of low probability
1.4.07	Water management (wells, reservoirs, dams) – It is assumed that direct intrusion of well through cover does not occur – see 1.4.04. Use of well at site boundary is considered as part of the design scenario.
1.4.08	Social and institutional developments – Assume that society remains as present day and that memory/records are kept for 300 years. Different times of intrusion could be considered following loss of institutional control.
1.4.11	Explosions and crashes – ruled out on the grounds of low probability

Safety related features and associated safety functions

It was initially thought that it would be useful to review the main safety related features and their functions that are relevant to the human intrusion scenario and to assign quantitative values for performance (for example, give times of barrier failure). Therefore, Table 5 was reviewed. However, it was decided that it would be too prescriptive to assign quantitative performance values and it would be more useful to progress directly on to revise the design scenario description to produce a high level, qualitative description of the human intrusion scenario.

Description of the human intrusion scenario

The text below gives a brief outline summary of the Human Intrusion Scenario. It describes the expected temporal evolution of the system and its safety-related features, i.e. a high level description of the evolution of the system. This summary has been checked to ensure consistency with the status of external FEPs discussed in Section 1.3.5.

The top level assumptions are the same as those adopted for the Design Scenario (see Section 1.3.3.) with the following exceptions:

— The scenario considers human intrusion events (see FEPs 1.4.02, 1.4.04, 1.4.05, 1.4.06, 1.4.07 in Table 7) but only once passive institutional control has been lost; and

— The scenario considers dwelling construction, dwelling residence and road construction. Well construction is not considered (see FEP 1.4.04 and 1.4.07 in Table 7).

In addition, it is cautiously assumed that the total inventory in the disposal facility is reduced by radioactive decay alone.

Operational period

Assumed to be the same as for the Design Scenario (see Section 1.3.3.).

Active institutional control period

Assumed to be the same as for the Design Scenario (see Section 1.3.3.).

Passive institutional control period

Assumed to be the same as for the Design Scenario (see Section 1.3.3.).

Post institutional control period

It is assumed that the intrusion (road and dwelling) can occur at any time from the loss of the institutional control period (300 years). It is cautiously assumed that by 300 years all engineered safety features (i.e. the multi-layer cover, waste grout, waste containers, concrete boxes, and vault walls, base roof, and grout) are in a state that does not deter or prevent human intrusion. The site is used for the construction of residential and agriculture buildings. The excavated material is spread on the surface surrounding the building and used in agricultural production activities.

The potential for radiological impacts due to the intrusion leads to consideration of three different hypothetical critical groups:

— Builders of the residence and agriculture buildings on the disposal site;
— Workers building the road crossing the disposal site; and
— Site dwellers living permanently on the site.

1.4. FORMULATION AND IMPLEMENTATION OF MODELS

1.4.1. Development of conceptual models

Figure 8 shows that once the design and alternative scenarios have been described, they can be analysed in terms of their component FEPs to allow associated conceptual models to be developed. A conceptual model should be comprised of a description of: the basic FEPs; the relationships between these FEPs; and the scope of application of the model in spatial and temporal terms. In effect it is a development of the scenario at a more detailed but still largely qualitative level. The conceptual model allows the assessment team to produce an appropriate mathematical model and computer code to represent the disposal system for the scenario being considered.

The level of detail to which the conceptual models are developed should be determined by the assessment context, e.g. the status of disposal facility development and the purpose of the assessment. This will support any decisions on what is the appropriate level of detail. The process can be iterative and more detail can be included in subsequent iterations of a safety assessment if required.

A number of tools are available for developing conceptual models including Interaction Matrices (IMs), Process Influence Diagrams (PIDs), the PROSA methodology (used in the EU EVEREST project) and the ANDRA approach based on functional analysis. These alternatives are discussed in more detail in Volume II of this report.

From the point of view of the Vault Test Case Group, the interaction matrix was found to be the most convenient tool to represent FEP interactions but this should not be taken as a recommendation for IMs over other, equally valid approaches. Furthermore certain limitations associated with IMs should be noted. External FEPs are generally not included in IMs and are normally fixed for a particular IM representation of the disposal system. Hence IMs have a tendency to represent the system as being static rather than dynamic. Therefore, for scenarios with changing external FEPs, it will be necessary to capture this effect, for example, by a series of IMs for distinctly different timeframes (e.g. different climate states). For complete transparency, it is best practice to document and justify ‘no interaction’ decisions as well as documenting the interactions that do take place.

The basic theory of IMs and the rules for their construction are briefly summarized in Appendix B.

Conceptual model for the design scenario: liquid release

Initial work was undertaken by Inmaculada Simón and then reviewed by the Vault Test Case Group and audited against the ISAM FEP list by Peter Lietava. Appendix B provides details of the initial work and the associated review and audit. In light of the review and audit, a finalized IM was developed for the liquid release pathway (Fig. 9).

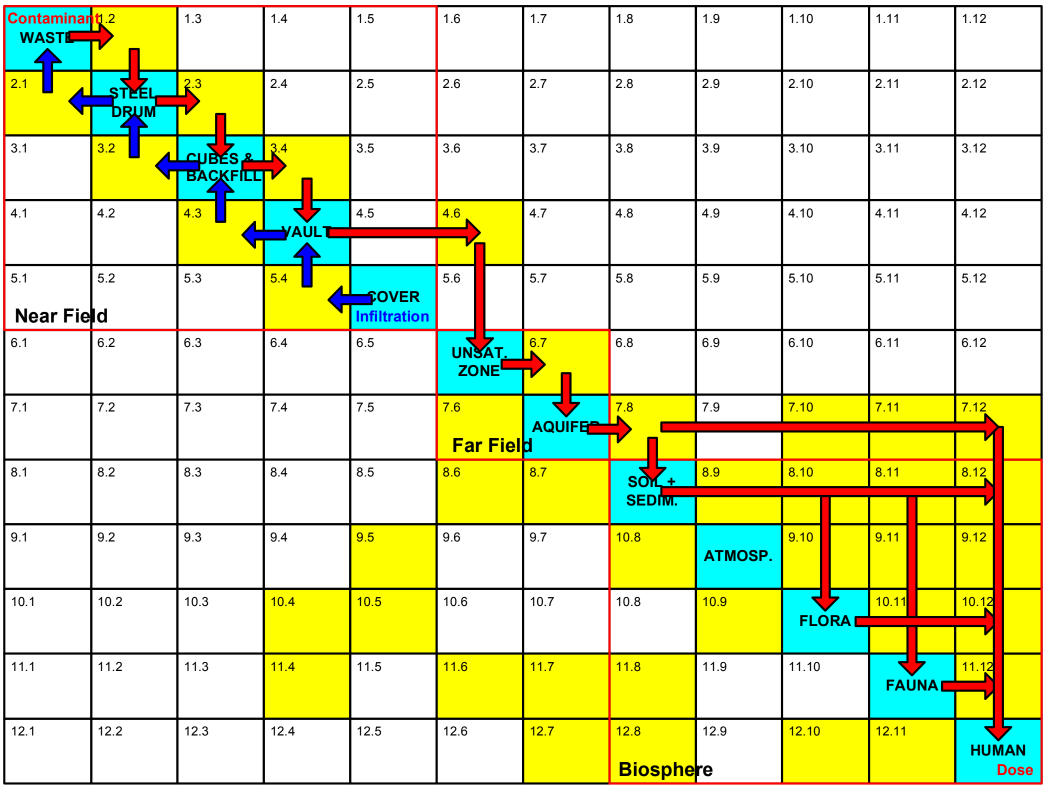


FIG. 9. Interaction Matrix for the Vault Test Case Design Scenario: Liquid Release.

The starting point on Fig. 9 for the tracking of water and contaminant transport is the cover (diagonal element 5.5), which is directly exposed to the infiltrating water. Due to the water flow through the engineered structure of the vault disposal system (marked by the arrows connecting cover through vault, cubes and backfill, and steel drums with waste leading diagonal element (LDE)), the waste is leached out of the waste matrix and contaminates the transport medium – water. The timeframe of this process, depending on the degradation of the cover, is defined by the Design Scenario. The drums are assumed to remain intact for 100 years and then fail, whilst the concrete is assumed to physically degrade gradually over a 500 year period and chemically degrade over a 1 000 year period from site closure. The cover is assumed to be maintained during the 100 year active institutional control period but then starts to degrade so that it no longer limits the rate of water infiltration after 500 years.

The contaminated water flows downward from the waste matrix and the rest of the vault to the far field (the unsaturated layer and aquifer). The aquifer is assumed as the only source of biosphere contamination. Groundwater is abstracted from a well[1] that is located at the site boundary (i.e. 200 m from the edge of the disposal area). It is assumed that the well is sunk once institutional control of the site has been lost (i.e. 300 years after site closure) and that water is abstracted indefinitely beyond this time.

Consistent with present day site information, it is assumed that the abstracted water is used to supply a five person farm. The farm raises sheep, cows and hens. It is assumed that no crops are grown other than pasture for sheep, instead uncontaminated crops are imported. Different exposure pathways contribute to the total individual dose and these are marked by arrows in Fig. 9. In particular, it is assumed that the abstracted groundwater is used for:

— Drinking water by humans;
— Bathing water by humans;
— Drinking watering for all animals; and
— Irrigation water for the pasture (cautiously included to allow the impact of pasture and soil contamination to be assessed).

It is assumed that irrigation of pasture results in contamination of the soil. Loss terms from the surface soil are erosion and percolation.

The exposure pathways for animals are:

— Consumption of water;
— Ingestion of soil (sheep only, since it is assumed that only sheep eat contaminated fodder); and
— Consumption of pasture (sheep only, it is assumed that fodder for cows and chickens is uncontaminated since insufficient fodder can be grown for all animals given the yield of the well).

[1] The additional geosphere-biosphere interface (GBI) of a salt pan could be considered, however, given the time constraints the focus was on a well GBI. This decision can be supported by evidence from an EPRI assessment of Yucca Mountain that showed that doses for a range of radionuclides were higher for a well GBI than a salt pan GBI [11].

The exposure pathways for animals are:

— Consumption of water;
— Ingestion of soil (sheep only, since it is assumed that only sheep eat contaminated fodder); and
— Consumption of pasture (sheep only, it is assumed that fodder for cows and chickens is uncontaminated since insufficient fodder can be grown for all animals given the yield of the well).

The exposure pathways for humans are:

— Consumption of water;
— Consumption of animal produce (cow milk and meat, sheep meat, eggs);
— Ingestion of soil contaminated due to irrigation;
— Inhalation of dust (outdoor) contaminated due to irrigation of pasture;
— External irradiation from soil contaminated due to irrigation; and
— External irradiation from bathing water.

The interactions in the off-diagonal elements (ODEs) included in Fig. 9 correspond to the following processes:

(1.2) Unsaturated water flow (advection, diffusion) – infiltration/percolation;

(2.1) Unsaturated water flow (advection, diffusion) – infiltration/percolation;

(2.3) Unsaturated water flow (advection, diffusion);

(3.2) Unsaturated water flow (advection, diffusion);

(3.4) Unsaturated water flow (advection, diffusion) – infiltration/percolation;

(4.3) Unsaturated water flow (advection, diffusion) – infiltration/percolation;

(4.6) Unsaturated water flow (advection, diffusion) – infiltration/percolation;

(5.4) Unsaturated water flow (advection, diffusion) – infiltration/percolation;

Unsaturated water flow (advection, diffusion) – infiltration/percolation;

Fractured flow;

(7.6) Capillarity ;

Capillarity;

Groundwater discharge/seepage;

(7.10) Irrigation of crops (water might be too saline for irrigation. However there might be some uptake of water by plants at the salt pan);

(7.11) Ingestion via salt or via well;

(7.12) Extraction via well;

Percolation;

(8.7) Infiltration;

Percolation;

(These processes might occur via fractures);

(8.9) Evapotranspiration;

(8.10) Root uptake;

Rain splash;

(8.11) Ingestion;

(8.12) Ingestion;

(9.5) Erosion;

Deposition;

Precipitation;

(9.8) Erosion;

Deposition;

Precipitation;

(9.10) Deposition;

Precipitation;

Inhalation;

Immersion – external irradiation to atmosphere;

(9.12) Inhalation;

Immersion – external irradiation to atmosphere;

Ingestion (if someone collects and drinks the rainwater);

(10.4) Bioturbation;

(10.5) Bioturbation;

(10.9) Evapotranspiration;

(10.11) Ingestion;

(10.12) Ingestion;

(11.4) Bioturbation;

(11.5) Bioturbation;

(11.6) Bioturbation;

(11.7) Bioturbation (in case, that animals – termites can burrow up to the aquifer);

(11.8) Bioturbation;

(11.12) Ingestion;

(12.7) Extraction/recharge of water;

Water treatment;

(12.8) Draining sediments;

Irrigation;

Ploughing;

(12.10) Storage;

(12.11) Storage;

Processes to considered but not explicitly included as ODEs in the matrix are:

(i) Radionuclide decay and retardation and enhanced transport (1.1), (2.2), (3.3), (4.4), (5.5), (6.6), (7.7);

(ii) Radionuclide migration in and from the crops (translocation and weathering) (10.10); and

(iii) Internal transfer in animals (11.11).

Each FEP was then reviewed with the purpose of identifying key processes, their dependencies, and the approach to model them. Appendix B summarizes the review undertaken for the near field. Time constraints prevented a similar review being undertaken for the far field and biosphere.

Conceptual model for the design scenario: gas release

Figure 10 shows the IM for the gas release. The associated conceptual model assumes that, until the cover is fully eroded, there is no construction of a house on the disposal facility and that doses result from the inhalation of gases releases to atmosphere. Following removal of the cover due to erosion, it is assumed that a house is constructed on the disposal facility. It is cautiously assumed that there is no loss of activity from the waste except by decay and gaseous emissions, and, subsequent to the erosion of the cover, the waste is not affected by erosion. Doses arise from the inhalation of gases released into the atmosphere (when no house present) and house (when house present).

Waste	1.2 Gas generation	1.3	1.4	1.5	1.6	1.7	1.8
2.1	**Steel drums**	2.3 Gas flow	2.4	2.5	2.6	2.7	2.8
3.1	3.2	**Cubes**	3.4 Gas flow	3.5	3.6	3.7	3.8
4.1	4.2	4.3	**Vaults**	4.5 Gas flow	4.6	4.7 Gas flow	4.8
5.1	5.2	5.3	5.4	**Cover**	5.6 Gas flow	5.7	5.8
6.1	6.2	6.3	6.4	6.5	**Atmosphere**	6.7	6.8 Inhalation
7.1	7.2	7.3	7.4	7.5	7.6	**House** **(assumed to be present only once cover eroded)**	7.8 Inhalation
8.1	8.2	8.3	8.4	8.5	8.6	8.7	**Human**

FIG. 10. Interaction Matrix for the Vault Test Case Design Scenario: Gas Release.

Conceptual model for the design scenario: solid release

Figure 11 shows the IM for the solid release. The conceptual model assumes that the cover is fully degraded and eroded and so the waste is exposed. The engineered barriers (steel drums, cubes, vaults and cover) are therefore not represented in the IM. It is cautiously assumed that there is no loss of activity from the waste except by decay (even subsequent to the erosion of the cover, it is cautiously assumed that the waste is not affected by erosion). It is assumed that crops (leafy and root vegetables, grain and pasture) are grown, and sheep and hens raised on the exposed waste. Doses arise from:

— Consumption of contaminated animal produce (sheep meat, chicken and eggs);
— Consumption of contaminated crops (leafy and root vegetables);
— Ingestion of contaminated soil;
— Inhalation of contaminated dust; and
— External irradiation from contaminated soil.

Waste	1.2 Degradation and erosion of barriers	1.3	1.4	1.5	1.6
2.1	**Soil**	2.3 Resuspension	2.4 Root uptake	2.5 Ingestion	2.6 External irradiation Ingestion
3.1	3.2	**Atmosphere**	3.4 Deposition	3.5	3.6 Inhalation
4.1	4.2	4.3	**Flora**	4.5 Ingestion	4.6 Ingestion
5.1	5.2	5.3	5.4	**Fauna**	5.6 Ingestion
6.1	6.2	6.3	6.4	6.5	**Human**

FIG. 11. Interaction Matrix for the Vault Test Case Design Scenario: Solid Release.

Conceptual model for the human intrusion scenario

Prior to developing the conceptual model for human intrusion, it was decided to focus on the resulting exposure to site dwellers since other assessments, such as [10], have indicated that this is a limiting pathway for human intrusion. Again, the IM approach was used.

The IM represents the state of properties at the moment when the scenario is assumed to start, i.e. at the end of the institutional control phase (300 years from closure). The elements of the leading diagonal elements of the IM that were initially identified are: the waste form/contaminant; cubes (containers); vault; cover; soil; atmosphere; flora; fauna; and human.

(1.1) Waste form/contaminant;

(2.2) Cubes (containers) – cautiously assumed to be in a physical and chemical form that does not deter human intrusion and use of excavated material for agricultural purposes;

(3.3) Vault (base, walls, grout) behaviour is analogous to the cubes;

(4.4) Cover – assumed to be maintained during the 100 year active institutional control period but then starts to degrade so that it no longer deters human intrusion by 300 years;

(5.5) Soil;

(6.6) Atmosphere;

(7.7) Flora;

(8.8) Fauna; and

(9.9) Human.

Since it is assumed that the engineered structures have lost the mechanical properties that would deter intrusion, the elements relating to the engineered barriers (cubes, vault, cover), can be excluded. The resulting interaction matrix for the human intrusion scenario is shown in Fig. 12.

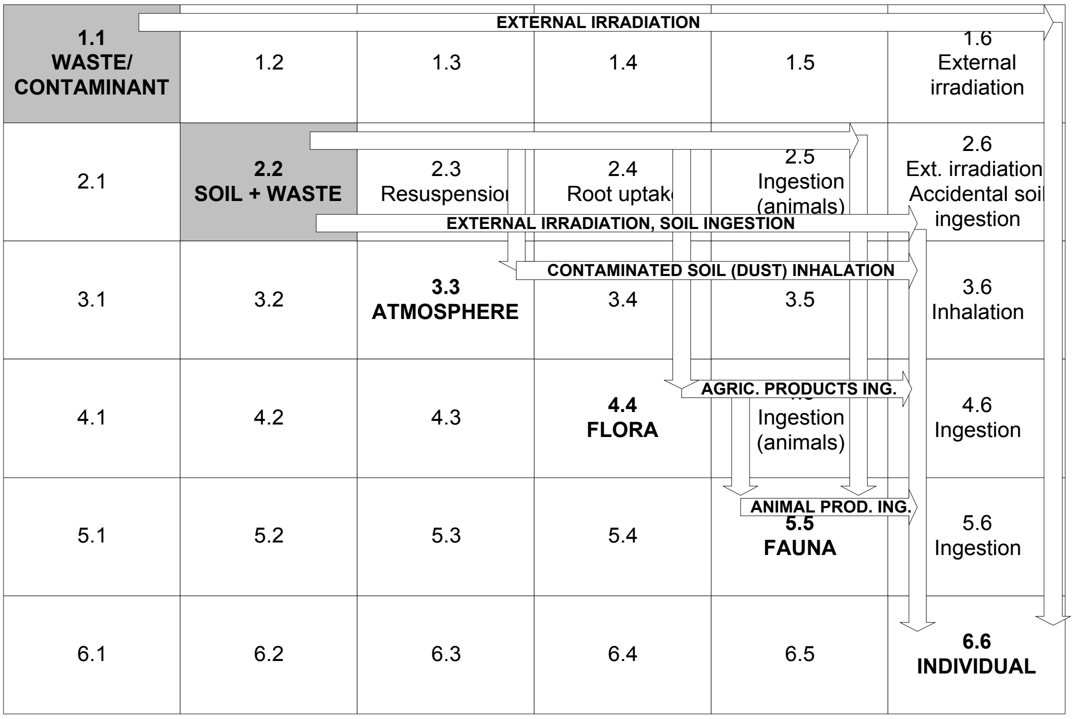


FIG. 12. Interaction Matrix for the Vault Test Case Human Intrusion Scenario.

The cell representing the "Waste" (1.1) considers the inventory that has not been removed during the excavation and remains in the disposal facility. The cell (2.2) "soil + waste" considers the radioactive material, removed by construction, mixed with soil and then used in agricultural activities. The "atmosphere" (3.3) transports the resuspended soil particles contaminated by radioactive waste to individuals living on the top of the vault cover and in its vicinity. The "flora" (4.4) and "fauna" (5.5) cells characterize the agricultural products ingested either directly by the dwellers (root and leafy vegetables), or indirectly (grain) via animal products (chicken and eggs). Given the arid nature of the site, crops need to be irrigated. It is assumed that the water is taken from an uncontaminated source, as the radiological impact due to this pathway is considered in the design scenario, where a well at the site boundary of the facility is assumed. The end-point of the human intrusion scenario calculation is the dose to "Individual" (6.6) from all assumed exposure pathways.

Three participants of the ISAM Vault Safety Case group developed and applied mathematical models for the design and human intrusion scenarios. Their models are described in Appendix C. Time constraints did not allowed an audit of each mathematical model against the corresponding conceptual model and FEPs identified in Section 1.4.1. However, it is recognized that this is an important stage in the assessment process since it can demonstrate the assessment's transparency and allow the documentation of any simplifications and additional assumptions introduced in developing the mathematical model.

1.4.2. Development of mathematical models

Mathematical model for the design scenario: liquid release

Two participants (Chang-Lak Kim and Richard Little) developed mathematical models for the design scenario liquid release pathway. Kim used the DUST-MS code [11] to represent the release of radionuclides from the disposal facility and their migration through the unsaturated zone, using the diffusive release model and finite-difference transport model in DUST-MS. GWSCREEN [12] was then used to model the migration of radionuclides through the saturated zone to a well using an analytical solution of the advection dispersion equation. The associated drinking water dose was then calculated (doses via other pathways were not calculated since there was no explicit representation of the biosphere). Little used the AMBER compartment model software application [13] to represent the entire disposal system (disposal facility, unsaturated zone, saturated zone, and biosphere) and calculated doses via all exposure pathways. Details of the models used are given in Appendix C.

Mathematical model for the design scenario: gas release

One participant (Richard Little) developed a mathematical model for the design scenario gas release and implemented it in the AMBER compartment model software application [13]. Details of the model used are given in Appendix C.1.

Mathematical model for the design scenario: solid release

One participant (Richard Little) developed a mathematical model for the design scenario gas release and implemented it in the AMBER compartment model software application [13]. Details of the model used are given in Appendix C.2.

Mathematical model for the human intrusion scenario

Two participants (Peter Lietava and Richard Little) developed mathematical models for the human intrusion scenario. Lietava implemented his model in the RESRAD code [14], whilst Little used the AMBER compartment model software application [13]. Details of the models used are given in Appendix C.3.

Assessment data

The data used for assessment of the various scenarios are given in Appendix D. Where possible these are taken from site measurements. In the absence of site-specific data, data from a range of appropriate sources have been used.

1.5. ASSESSMENT OF RESULTS

In Section 1.1.1, it is stated that the aims of the current assessment are: to assess the level of safety using currently available information; to identify the most important uncertainties and suggest further data collection and/or alternative conceptual models that may be the subject of future safety assessment iterations; and to increase confidence that the site and facility design will be suitable for waste disposal so that future investment in site characterization and other activities will be worthwhile. In light of these aims, this section:

- Presents the results of the assessment of the design and human intrusion scenarios (Section 1.5.1);
- Compares the results against the relevant assessment end points identified in Section 1.1.4 (Section 1.5.2);

— Identifies the most important uncertainties and suggests how these might be reduced in future assessments (Section 1.5.3); and
— Builds confidence in suitability of the site and facility design (Section 1.5.4).

1.5.1. Results presentation

Design scenario: liquid release calculations

As noted in Section 1.4.2., two participants undertook liquid release calculations (Chang-Lak Kim and Richard Little). The results that they obtained are presented in this section. Details of the conceptual and mathematical models used plus the associated data are provided in Appendix C and D.

In presenting the results, it is considered helpful to consider:

— The flux of radionuclides from the disposal facility to the unsaturated zone;
— The flux of radionuclides from the unsaturated zone to the saturated zone;
— The concentration of radionuclides in the groundwater; and
— The annual individual dose resulting from the use of well water.

Flux of radionuclides from the disposal facility to the unsaturated zone

Figures 13 and 14 and Table 8 show the flux of radionuclides from the disposal facility to the unsaturated zone. The figures and table show that the radionuclides fall into two broad categories. First there are those that have a peak flux during the first thousand years. These radionuclides have low distribution coefficients and/or relatively short half lives (^{3}H, ^{63}Ni, ^{90}Sr, ^{99}Tc, ^{129}I, ^{137}Cs, ^{238}Pu, ^{241}Pu and ^{241}Am) and so their peak fluxes are rapidly reached. The second category is those that have a peak flux after the first thousand years. These have higher distribution coefficients and longer half lives (^{14}C, ^{59}Ni, ^{234}U, ^{238}U and ^{239}Pu) and therefore their peak fluxes are reached less rapidly. (Distribution coefficients)

It can be seen that, in general, Little has estimated slightly earlier and lower peak fluxes than Kim, but by less than a factor of two (see for example ^{63}Ni, ^{234}U and ^{238}U fluxes). The later release times from the disposal facility for Kim means that the short lived radionuclides (^{3}H, ^{90}Sr, ^{137}Cs and ^{241}Pu) have decayed more and so their peak fluxes are lower than those of Little.

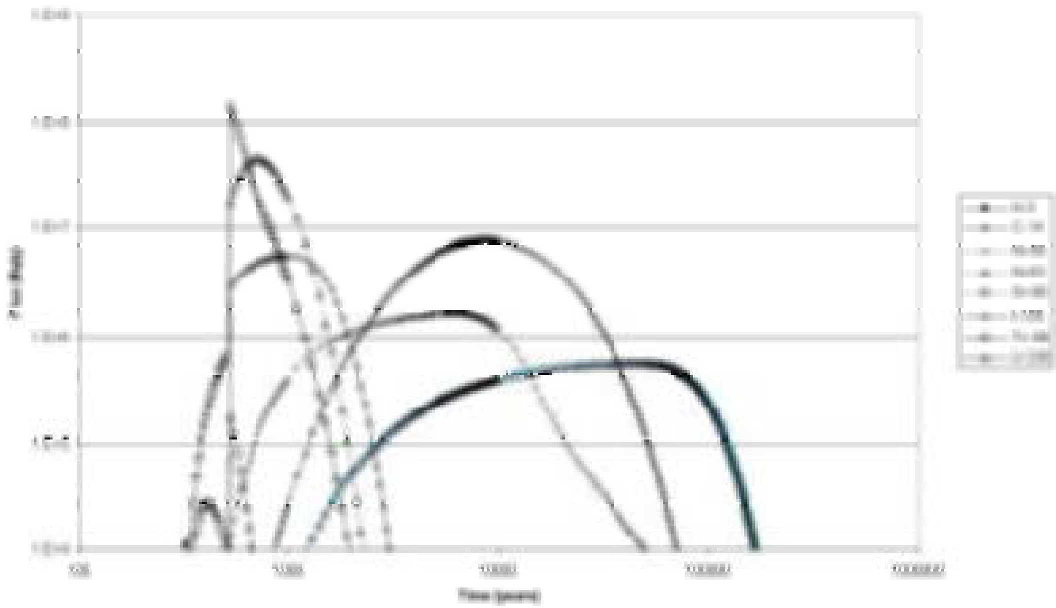


FIG. 13. Radionuclide Flux from the Disposal Facility to the Unsaturated Zone – Calculated by Kim for the Vault Test Case.

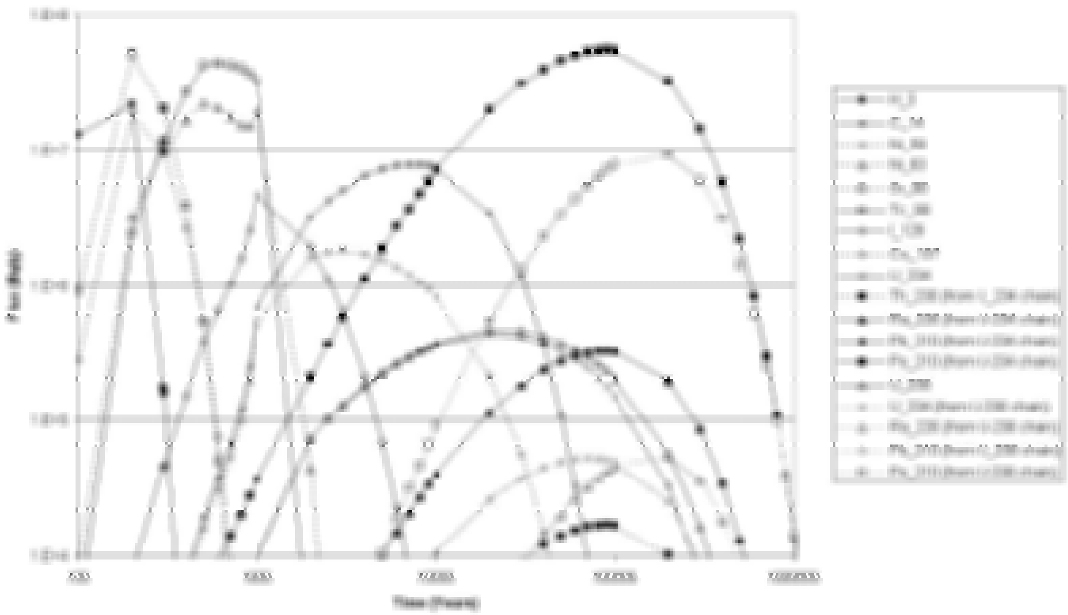


FIG. 14. Radionuclide Flux from the Disposal Facility to the Unsaturated Zone – Calculated by Little for the Vault Test Case.

TABLE 8. TIMING AND MAGNITUDE OF PEAK RADIONUCLIDE FLUXES FROM THE DISPOSAL FACILITY TO THE UNSATURATED ZONE FOR THE VAULT TEST CASE

Parent Radionuclides	**Kim**		Little	
	Time (y)	Peak Flux ($Bq\ y^{-1}$)	Time (y)	Peak Flux ($Bq\ y^{-1}$)
^{3}H	320	1.1E+4	200	2.2E+7
^{14}C	8600	7.7E+6	7000	7.7E+6
^{59}Ni	6100	1.7E+6	3000	1.8E+6
^{63}Ni	700	4.4E+7	500	2.2E+7
^{90}Sr	520	1.7E+5	200	5.1E+7
^{99}Tc	520	1.4E+8	600	4.4E+7
^{129}I	1000	5.5E+6	1000	4.7E+6
^{137}Cs	540	2.3E+3	200	1.9E+7
^{234}U	42000	5.4E+5	20000	4.5E+5
^{238}U	42000	5.4E+5	20000	4.7E+5
^{238}Pu	1100	1.1E-6	500	1.1E-1
^{239}Pu	34000	4.4E+3	30000	4.4E+3
^{241}Pu	520	6.3E-16	200	2.1E-4
^{241}Am	2400	1.3E+2	1000	4.7E+2

The difference in the fluxes results from differences in the conceptual and mathematical models used by the two participants (see Appendix C). Key differences and their effects on the fluxes from the disposal facility to the unsaturated zone are summarized below.

— Kim's model assumes that, prior to the failure of the concrete cube surrounding the waste at 300 years, no water has come into contact with the waste and so there is no release of radionuclides (even though the drums containing the waste are assumed to have failed at 100 years). In contrast, Little's model assumes that as soon as the drums fail at 100 years, water can come into contact with the waste (since the concrete cube is not impermeable) and so radionuclides can start to be released.

— Kim's model assumes that there are two step changes in the infiltration of precipitation into the disposal facility. From closure to 100 years, it is assumed that 10% of the total precipitation infiltrates, from 100 to 500 years 50% of the total precipitation infiltrates, and from 500 years 100% infiltrates. Little's model assumes that there is a linear failure starting at 100 years (10% of the total precipitation infiltrates) to 500 years (100% of the total precipitation infiltrates).

— Kim's model assumes that there is a step change at 500 years in the physical status of the concrete in the disposal facility from non-degraded to fully degraded. Little's model assumes that there is a linear failure starting at closure (non-degraded) to 1000 years (fully degraded). This affects the value adopted for the concrete distribution coefficients – the values for non-degraded concrete are generally higher. This in turn affects the flux of radionuclides from the disposal facility. This is best illustrated by the flux of ^{99}Tc. In contrast to the general trend, Kim's peak flux of ^{99}Tc is greater (1.4E+8 $Bq\ y^{-1}$ vs 4.4E+7 $Bq\ y^{-1}$) and earlier (520 years vs 600 years) than Little's. This is because at 500 years, the distribution coefficient for ^{99}Tc in Kim's model is 0 $m^3\ kg^{-1}$ (the fully degraded value), whilst in Richard's model, it is 5E-4 m^3 kg^{-1}. Thus ^{99}Tc is five times more retarded in Richard's model, resulting in a later and lower peak flux.

— Kim's model assumes that radionuclides are released from the drums containing the conditioned waste by diffusion. Once they have diffused out of the drum they are then transported by advective flow down through the disposal facility into the unsaturated zone. Kim's model assumes that radionuclides are released from the drums and transported through the disposal facility by advective flow and so are released more rapidly from the disposal facility than the diffusive/advective release model of Richard. The relatively short diffusion distance (0.01 m) for the radionuclides across the drums means that whilst there is some delay compared with an advective release, it is not too significant.

Flux of radionuclides from the unsaturated zone to the saturated zone

Figures 15 and 16 and Table 9 show the flux of radionuclides from the unsaturated zone to the saturated zone. Comparing Tables 8 and 9, it can be seen that the unsaturated zone delays and attenuates the flux of radionuclides due to sorption in the unsaturated zone and the slow infiltration rate of water (1.8E-2 m y^{-1}). Only five radionuclides (^{14}C, ^{99}Tc, ^{129}I, ^{234}U, and ^{238}U) have a peak flux in excess of 100 Bq y^{-1} (compared with the 12 radionuclides from the disposal facility to the unsaturated zone that have a peak flux in excess of 100 Bq y^{-1}). These are long-lived radionuclides and/or mobile radionuclides. Even for the most mobile (^{99}Tc), the peak flux is not reached until 2 500 years, and for the less mobile U isotopes(e.g. U-234), the peak flux is not reached until around 50 000 years.

It can be seen that there is very good agreement between the participants in terms of the timing and magnitude of the flux (always within a factor of two). This is despite the participants adopting different conceptual and mathematical models to represent the migration of radionuclides through the unsaturated zone (see Appendix C). Both participants' models explicitly represent the processes of advection, retardation and decay. However, Kim's model also explicitly considers dispersion and diffusion and so a difference in the timing and magnitude of the fluxes might be expected. Although, there is no explicit representation of dispersion and diffusion in Little's model, the compartment modelling approach will result in some additional numerical dispersion (see for example[15]) and therefore some dispersion is implicitly considered in the model.

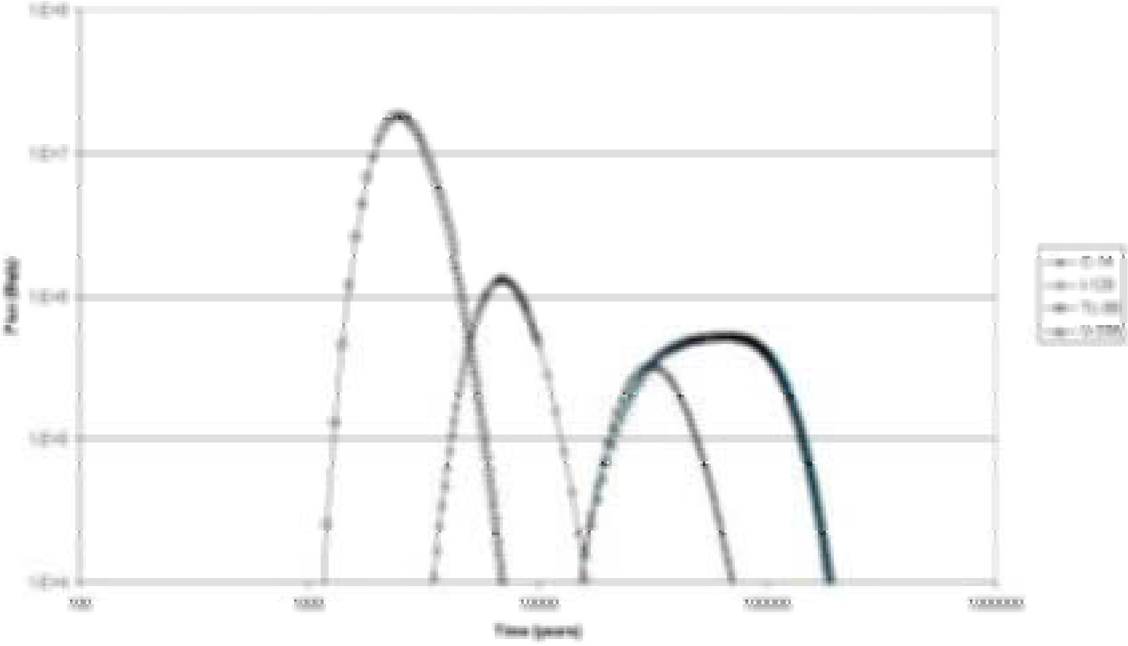


FIG. 15. Radionuclide Flux from the Unsaturated Zone to the Saturated Zone – Calculated by Kim for the Vault Test Case.

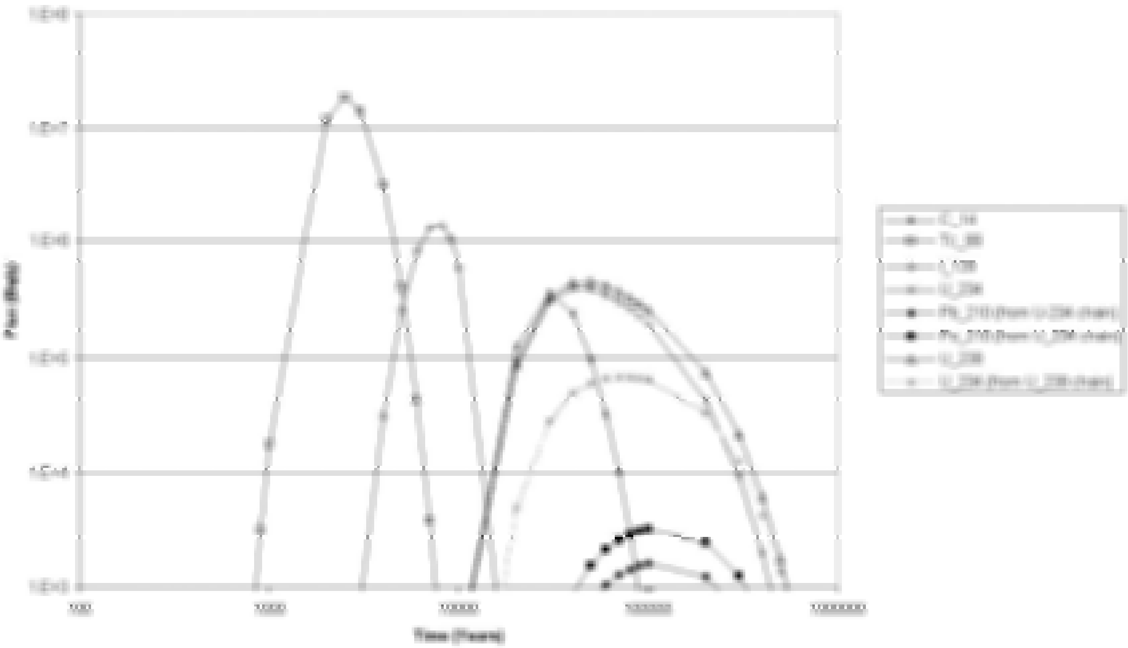


FIG. 16. Radionuclide Flux from the Unsaturated Zone to the Saturated Zone – Calculated by Little for the Vault Test Case.

TABLE 9. TIMING AND MAGNITUDE OF PEAK FLUXES OF KEY RADIONUCLIDES FROM THE UNSATURATED ZONE TO THE SATURATED ZONE FOR THE VAULT TEST CASE

Parent Radionuclides	Kim		Little	
	Time (y)	Peak Flux (Bq y^{-1})	Time (y)	Peak Flux (Bq y^{-1})
^{14}C	31000	3.3E+5	30000	3.7E+5
^{99}Tc	2500	1.8E+7	2500	1.9E+7
^{129}I	6900	1.3E+6	8000	1.4E+6
^{234}U	65000	5.2E+5	40000	4.1E+5
^{238}U	65000	5.2E+5	50000	4.6E+5

Concentration of radionuclides in the well water

Figures 17 and 18 and Table 10 show the concentration of radionuclides in the well water. From comparison of these figures and table with those for the flux from the unsaturated zone to the saturated zone, it can be seen that the saturated component of the geosphere does not significantly retard the key radionuclides (^{14}C, ^{99}Tc, ^{129}I, ^{234}U, and ^{238}U). The timing and relative magnitude of the peak fluxes to the saturated zone and the peak concentrations in the well water are broadly the same. This is because of the relatively rapid transit time of water along the fracture assumed (less than two years) and the low distribution coefficients for these radionuclides in the geosphere (see Appendix D). The peak concentrations for the ^{238}Pu, ^{238}U and ^{234}U chain decay products (^{230}Th, ^{226}Ra, ^{210}Pb, and ^{210}Po) are slightly later than their parents (by a factors of about two) due to their generally higher distribution coefficients and the time required for them to in-grow.

There is very good agreement (always within a factor of two) between the participants in terms of the timing and magnitude of the concentration of the key radionuclides (^{14}C, ^{99}Tc, ^{129}I, ^{234}U, and ^{238}U). This is because similar conceptual and mathematical models have been used to calculate flow and transport in the saturated zone, although the implementation in the calculational software is different (see Appendix C). Kim’s concentrations are consistently higher than Little’s, possibly due to the diluting effect of the numerical dispersion resulting from Little’s compartment implementation (see Appendix C and Scott [15]). There is a larger discrepancy (up to a factor of 40) in Kim’s and Little’s concentrations for the ^{238}Pu, ^{238}U and ^{234}U chain decay products (^{230}Th, ^{226}Ra, ^{210}Pb, and ^{210}Po). This could arise partly from a difference in the approach used to model the transport of the decay products. Kim models each daughter separately as a single member radionuclide, whilst Little models all chain members together.

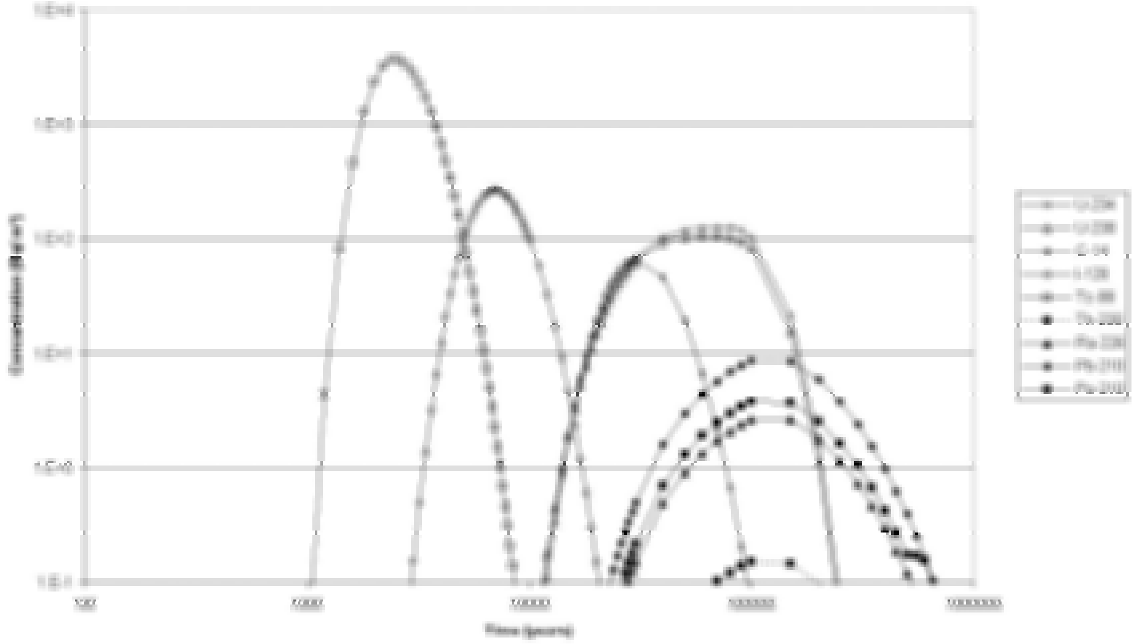


FIG. 17. Concentration of Key Radionuclides in the Well Water – Calculated by Kim for the Vault Test Case.

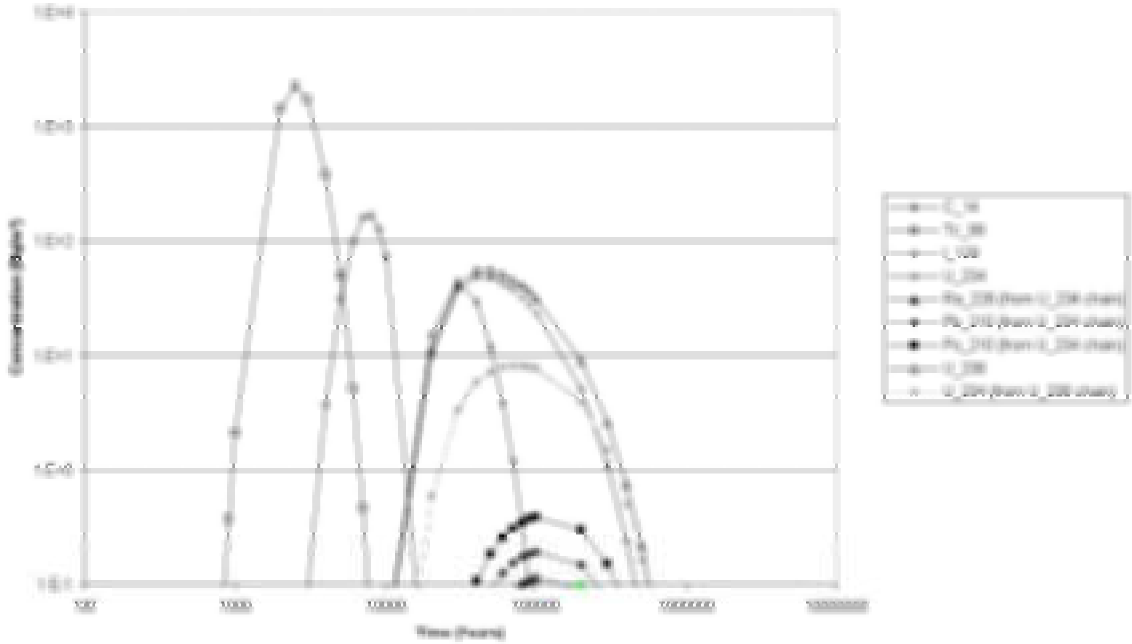


FIG. 18. Concentration of Key Radionuclides in the Well Water – Calculated by Little for the Vault Test Case.

TABLE 10. TIMING AND MAGNITUDE OF PEAK CONCENTRATIONS OF KEY RADIONUCLIDES IN THE WELL WATER FOR THE VAULT TEST CASE

Key Radionuclides	**Kim**		**Little**	
	Time (y)	Peak Concentration ($Bq\ m^{-3}$)	Time (y)	Peak Concentration ($Bq\ m^{-3}$)
^{14}C	31000	6.7E+1	30000	4.4E+1
^{99}Tc	2400	3.7E+3	2500	2.2E+3
^{129}I	7000	2.7E+2	8000	1.7E+2
$^{234}U^{*}$ (1)	73000	1.3E+2	50000	5.5E+1
^{238}U (2)	59000	1.1E+2	50000	5.5E+1
$^{230}Th^{*}$	120000	1.6E-1	100000	2.3E-2
$^{226}Ra^{*}$	120000	2.8E+0	100000	1.4E-1
$^{210}Pb^{*}$	120000	9.3E+0	100000	2.3E-1
$^{210}Po^{*}$	120000	4.0E+0	100000	4.6E-1

* Total concentration for the radionuclide including the contribution from in-growth of the radionuclide from the ^{238}Pu, ^{238}U and ^{234}U chains

(1) The peak concentration for ^{234}U in the well water is slightly later than the peak flux of ^{234}U to the saturated zone because the ^{234}U concentration includes the contribution of ^{234}U in-grown from ^{238}Pu and ^{238}U.

(2) The peak concentration for ^{238}U in the well water calculated by Kim is maintained constant for 14 000 years.

Annual individual dose from use of well water

Figures 19 and 20 and Table 11 show the annual individual dose from use of well water. Kim calculated doses for just the drinking water pathway, whilst Little calculated doses for all pathways. Since drinking water doses are directly proportional to the well water concentrations, the same time history can be seen for concentrations and doses. However, due to different dose coefficients for ingestion, the relatively importance of ^{99}Tc and ^{129}I is reversed. ^{99}Tc has the highest well water concentration (it is about an order of magnitude than ^{129}I), but the dose from the ingestion of ^{129}I (the dominant radionuclide in terms of dose) via the drinking water pathway is about an order of magnitude higher than that from ^{99}Tc.

Results from Little show that, for all radionuclides with the exception of ^{14}C, ^{230}Th and ^{226}Ra, the dose from the ingestion of drinking water for a radionuclide is within a factor of two of the total dose for that radionuclide, indicating that the ingestion of drinking water is a key exposure pathway. Indeed, the dose from the drinking water pathway accounts for 58% of the total peak dose summed over all radionuclides.

There is very good agreement (always within a factor of two) between the participants in terms of the timing and magnitude of the drinking water dose for the key radionuclides (^{14}C, ^{99}Tc, ^{129}I, ^{234}U, and ^{238}U). This reflects the good agreement in well water concentrations (see Section 1.5.1.). Kim's doses are consistently higher than Little's, reflecting his higher well water concentrations. There is a larger discrepancy (up to a factor of 40) in Kim's and Little's doses for the ^{238}Pu, ^{238}U and ^{234}U chain decay products (^{230}Th, ^{226}Ra, ^{210}Pb, and ^{210}Po), again reflecting the differences in well water concentrations.

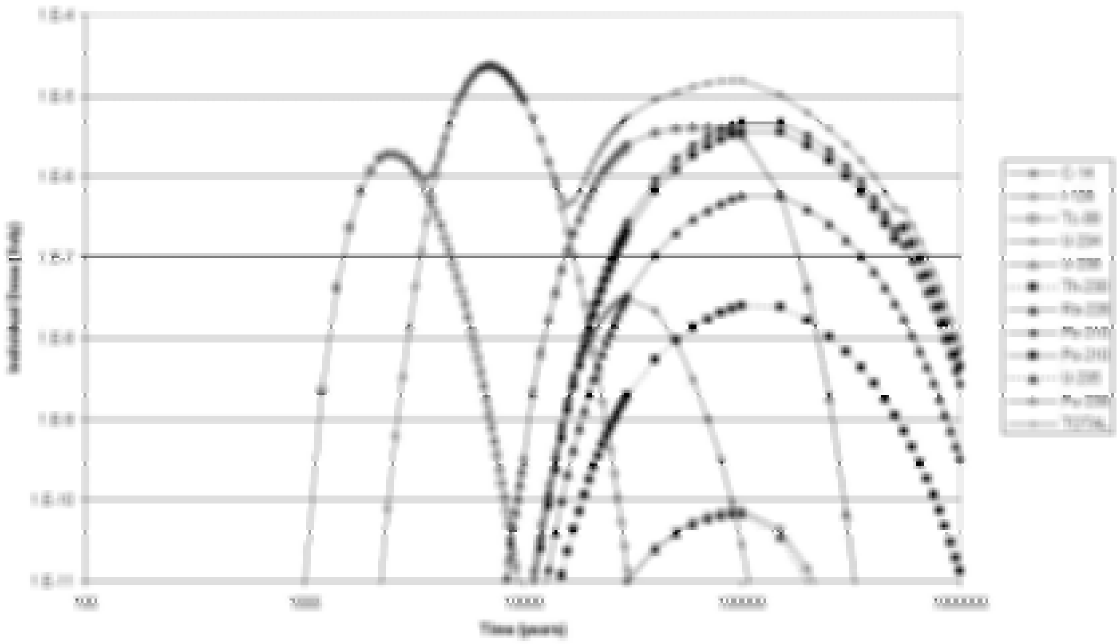


FIG. 19. Individual Doses from Key Radionuclides from Use of Well Water – Calculated by Kim for the Vault Test Case.

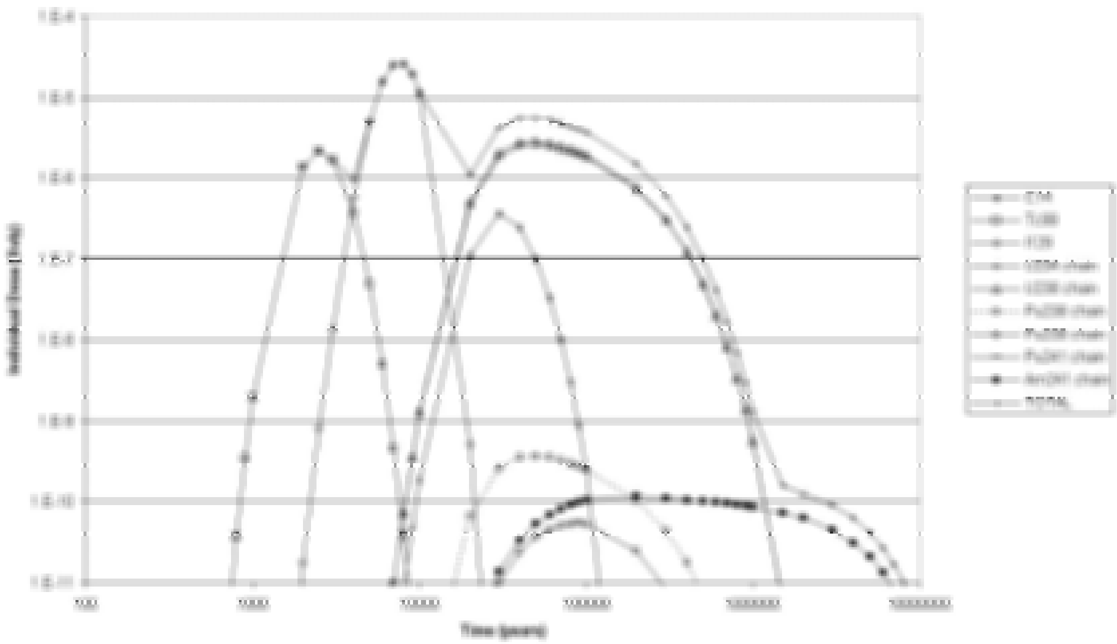


FIG. 20. Individual Doses from Key Radionuclides from Use of Well Water – Calculated by Little for the Vault Test Case.

TABLE 11. TIMING AND MAGNITUDE OF PEAK DOSES FOR KEY RADIONUCLIDES FROM USE OF WELL WATER FOR THE VAULT TEST CASE

Key Radionuclides	Kim		Little		
	Time (y)	Peak Individual Dose from Drinking Water (Sv y^{-1})	Time (y)	Peak Individual Dose from Drinking Water (Sv y^{-1})	Peak Individual Dose from All Pathways (Sv y^{-1})
^{14}C	31000	3.1E-8	30000	2.1E-8	3.6E-7
^{99}Tc	2400	1.9E-6	2500	1.2E-6	2.2E-6
^{129}I	7000	2.3E-5	8000	1.5E-5	2.6E-5
$^{234}U^{*}$	73000	4.2E-6	50000	2.2E-6	2.5E-6
^{238}U	59000	4.1E-6	50000	2.4E-6	2.9E-6
$^{230}Th^{*}$	120000	2.7E-8	100000	3.9E-9	2.3E-8 (1)
$^{226}Ra^{*}$	120000	6.4E-7	100000	3.1E-9	6.7E-8
$^{210}Pb^{*}$	120000	5.2E-6	100000	1.3E-7	1.7E-7
$^{210}Po^{*}$	120000	3.9E-6	100000	4.4E-7	5.3E-7
Total	**7000**	**2.4E-5**	**8000**	**1.5E-5**	**2.6E-5**

* Total dose for the radionuclides including the contribution from in-growth of the radionuclide from the ^{238}Pu, ^{238}U and ^{234}U chains

(1) The peak dose from all pathways for ^{230}Th is reached at 50000 years.

Design scenario: gas release calculations

As noted in Section 1.4.2., one participant undertook gas release calculations (Richard Little). The results obtained are presented below. The conceptual model is provided in Section 1.4, whilst details concerning the mathematical models used plus the associated data are given in Appendix C.1 and D-2, respectively.

Figure 21 and Table 12 show the annual individual dose from inhalation of ^{3}H, ^{14}C and ^{222}Rn from the decay of ^{226}Ra in the ^{234}U, ^{238}U and ^{238}Pu chains. Doses from ^{3}H and ^{14}C are less than 1E-7 Sv y^{-1}. Radon doses are also less than 1E-7 Sv y^{-1} up to the loss of the cover, but once the cover is lost and a house is constructed, doses increase by about two orders of magnitude due to the lower rate of dilution in houses than in the open atmosphere. Doses then continue to rise due to the in-growth of ^{226}Ra. They peak at 210 000 years for ^{222}Rn in-grown from the ^{234}U and ^{238}Pu chains with doses of 1.2E-3 Sv y^{-1} and 1.7E-7 Sv y^{-1}, respectively. Dose from ^{222}Rn in-grown from the ^{238}U chain is still slowly rising at 1 000 000 years when the dose is 1.8E-3 Sv y^{-1}.

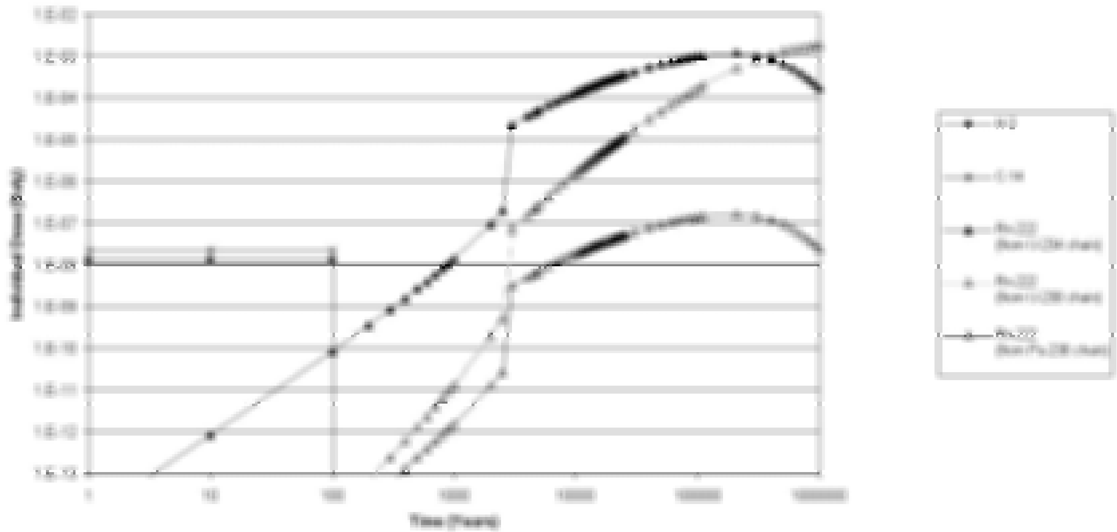


FIG. 21. Individual Doses for Gas Release for the Vault Test Case.

TABLE 12. TIMING AND MAGNITUDE OF PEAK DOSES FOR GAS RELEASE FOR THE VAULT TEST CASE

Radionuclides	**Time (y)**	**Peak Dose ($Sv\ y^{-1}$)**
^{3}H	100	1.2E-8
^{14}C	100	2.2E-8
^{222}Rn from ^{234}U chain decay	210 000	1.2E-3
^{222}Rn from ^{238}U chain decay	1 000 000	1.8E-3
^{222}Rn from ^{238}Pu chain decay	210 000	1.7E-7
Total	**1 000 000**	**2.0E-3**

Design scenario: solid release calculations

One participant undertook solid release calculations (Richard Little). The results obtained are presented below. The conceptual model is described in Section 1.4, whilst details concerning the mathematical models used, plus the associated data, are given in Appendix C-2 and D-3, respectively.

Figure 22 and Table 13 show the annual individual doses from the solid release. From the loss of cover at 3 000 years to around 10 000 years the total dose is dominated by ^{14}C. Thereafter the ^{234}U and ^{238}U chains dominated due to the in-growth of radiologically significant daughters; indeed dose from the ^{238}U chain is still slowly rising at 1 000 000 years.

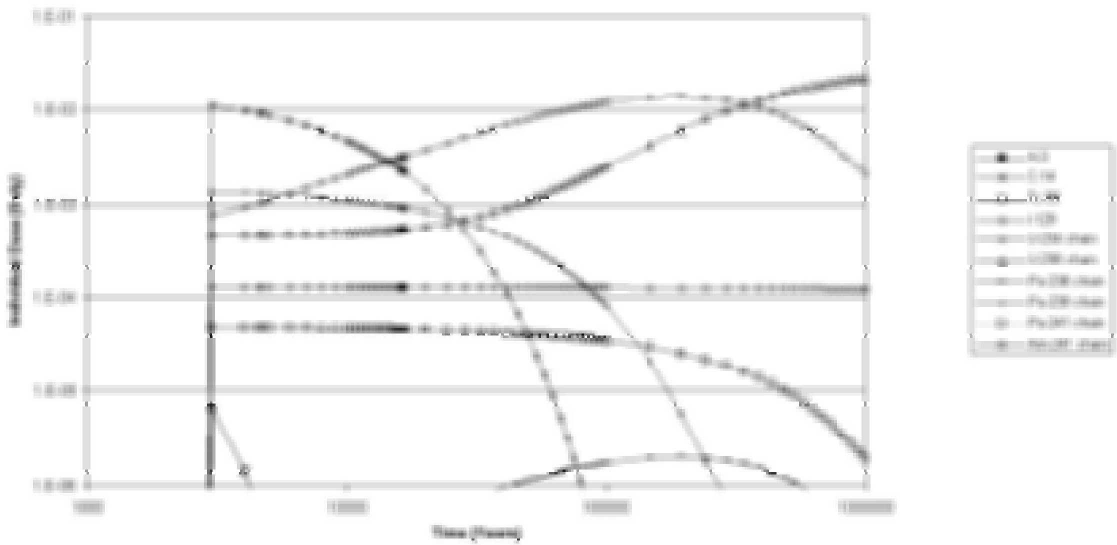


FIG. 22. Individual Doses for Solid Release for the Vault Test Case.

TABLE 13. TIMING AND MAGNITUDE OF PEAK DOSES FOR SOLID RELEASE FOR THE VAULT TEST CASE

Parent Radionuclides	**Time (y)**	**Peak Dose (Sv y^{-1})**
^{3}H	-	-
^{14}C	3 000	1.1E-2
^{59}Ni	3 000	2.5E-7
^{63}Ni	3 000	1.3E-11
^{90}Sr	-	-
^{99}Tc	3 000	4.8E-5
^{129}I	3 000	1.3E-4
^{137}Cs	-	
^{234}U	200 000	1.4E-2
^{238}U	1 000 000	2.2E-2
^{238}Pu	200 000	2.0E-6
^{239}Pu	3 000	1.0E-3
^{241}Pu	3 000	6.7E-6
^{241}Am	3 000	6.5E-6
Total	**1 000 000**	**2.4E-2**

Human Intrusion Scenario Calculations

Two participants undertook calculations for the human intrusion scenario (Peter Lietava and Richard Little). The results they obtained are presented in this section. Details of the conceptual model are given in Section 1.4.2, whilst the mathematical models used plus the associated data are provided in Appendix C-3 and D-4, respectively.

Table 14 gives the peak annual individual dose for each radionuclide disposed assuming intrusion occurs at the time institutional control is lost (300 years). Lietava's model calculates the time history of dose resulting from a single intrusion event at the time of loss of institutional control (300 years). It assumed that radionuclides in the excavated waste are lost from the soil due to leaching and erosion. Thus the peak dose from each radionuclide occurs at 300 years (see Fig. 23). In contrast, Little has developed a model that evaluates the dose consequence of a single intrusion event but assumes that this event can occur at any time after loss of institutional control. It calculates the dose received in the year of intrusion but, unlike Lietava's model, Little's model does not model the time history of doses in the years following the intrusion. Instead it assumes that the peak dose is received in the year of intrusion. The resulting time history of doses is shown in Fig. 24. From this figure, it can be seen that, for most radionuclides, the dose consequence of an intrusion decreases with time due to radioactive decay. However, for the ^{234}U and ^{238}U chains doses increase with time due to the in-growth of radiologically significant daughters. This is consistent with the findings of Kocher [16].

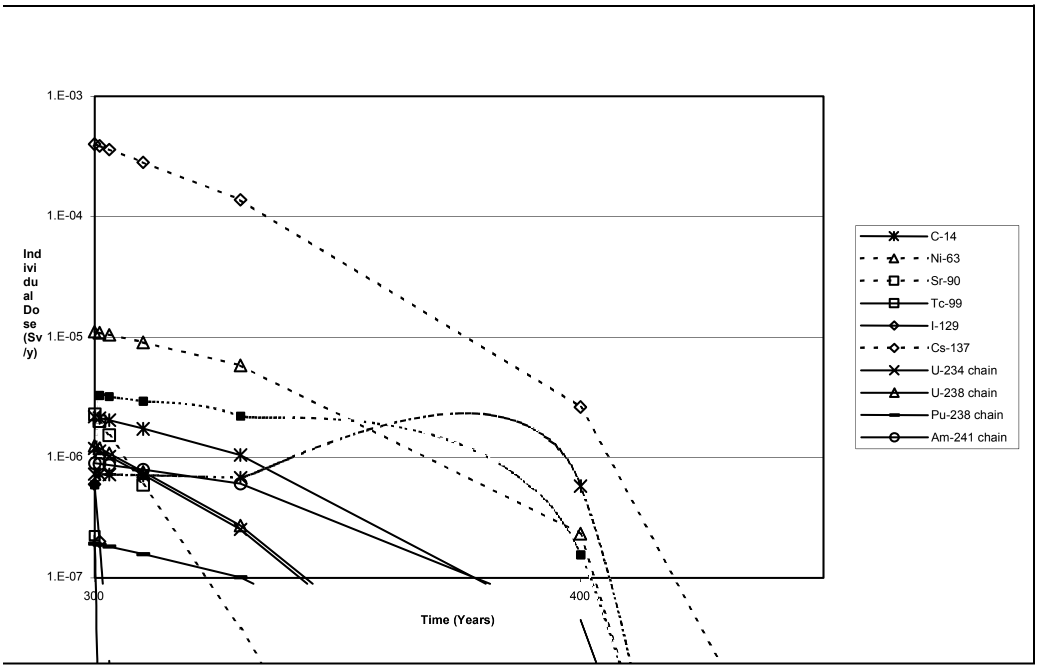


FIG. 23. Dose for Human Intrusion Scenario Assuming a Single Intrusion Event at 300 Years after Closure – Calculated by Lietava for the Vault Test Case.

The total dose calculated by Lietava and Little agrees within a factor of three, with Little's total dose being the higher. For individual radionuclides, Little's doses are generally higher but by only an order of magnitude or less. Indeed, both participants calculate that the radionuclide contributing most to the total dose is ^{137}Cs. These relatively minor differences can be explained by a number of differences in the conceptual models used by the two participants.

— Lietava assumes that radionuclides are lost from the soil by erosion and leaching, Little assumes no such loss.

— Lietava assumes that the excavated waste is spread in a 5 cm thick layer on top of the soil, Little assumes that it is uniformly mixed in the soil (which has a thickness of 30 cm).

— Lietava considers external irradiation from the buried waste that is not excavated from the disposal facility.

— Lietava and Little use different mathematical models to represent the contamination of crops due to foliar dust deposition.

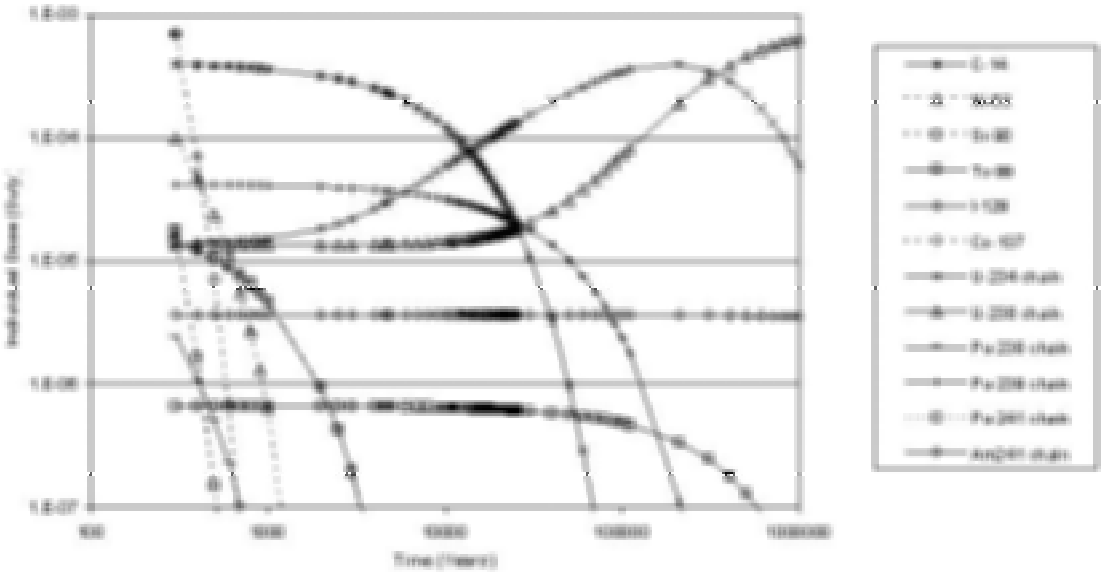


FIG. 24. Dose for Human Intrusion Scenario Assuming Intrusion Event Can Occur Any Time after 300 Years after Closure – Calculated by Little for the Vault Test Case.

More significant differences (more than an order of magnitude) exist for ^{14}C and transuranic radionuclides. Again, Little's doses are higher than those of Lietava. The differences for ^{14}C result from use of a specific ^{14}C sub-model by Lietava that assumes that 98% of carbon in plants is absorbed directly from the air (^{12}C) and only 2% from the soil (^{14}C) and so the uptake of ^{14}C from the soil is significantly restricted compared with the model used by Little. Due to the limitations of computer code RESRAD 5.91 used by Lietava, the amount of decay products created from parent radionuclides ^{238}Pu, ^{239}Pu, ^{241}Pu and ^{241}Am during the institutional control period had to be neglected and leads to an underestimation of their contribution to the doses.

TABLE 14. PEAK DOSE FOR HUMAN INTRUSION SCENARIO ASSUMING INTRUSION AT 300 YEARS AFTER CLOSURE FOR THE VAULT TEST CASE

Parent Radionuclides	**Peak Dose ($Sv\ y^{-1}$)**	
	Lietava	Little
^{3}H	3.1E-11	3.7E-11
^{14}C	2.2E-6	4.0E-4
^{59}Ni	8.1E-9	7.3E-9
^{63}Ni	1.1E-5	1.0E-4
^{90}Sr	2.3E-6	1.8E-5
^{99}Tc	2.3E-7	6.6E-7
^{129}I	6.0E-7	3.7E-6
^{137}Cs	4.0E-4	7.0E-4
^{234}U	1.2E-6	1.4E-5
^{238}U	1.3E-6	1.3E-5
^{238}Pu	1.9E-7	2.4E-6
^{239}Pu	6.0E-7	4.2E-5
^{241}Pu	7.3E-7	1.4E-5
^{241}Am	9.0E-7	1.4E-5
Total	**4.2E-4**	**1.3E-3**

1.5.2. Comparison of results against assessment end-points

Design scenario: liquid release calculations

The principal assessment end-point considered in the current study is individual effective dose (Section 1.1.4). Results presented in Table 11, indicate that, for the liquid release calculations, the peak dose summed across all pathways and radionuclides is about an order of magnitude below the dose constraint of 3E-4 Sv y^{-1}. Furthermore, it is around two orders of magnitude below the dose from background radiation.

Table 15 shows a comparison of the measured background radionuclide/element concentrations at the Vaalputs site and the estimated concentrations resulting from the liquid release of radionuclides from the disposal facility. It can be seen that all the calculated concentrations are well below the measure concentrations, usually by more than an order of magnitude.

TABLE 15. COMPARISON OF MEASURED AND CALCULATED RADIONUCLIDE / ELEMENT CONCENTRATIONS FOR THE LIQUID RELEASE FOR THE VAULT TEST CASE

Radionuclide/ Element	Units	Mean Measured Concentration (range in brackets)	Calculated Concentration	
			Kim	Little
Ra-226 in groundwater	Bq m^{-3}	4.0E+2 (1.0E+1 – 5.7E+3)	2.8E+0	1.4E-1
U in groundwater	mg m^{-3}	5.0E+1 (2.0E+0 – 2.5E+2)	8.8E+0	4.4E+0
U in soil	mg kg^{-1}	4.1E+0 (2.6E+0 – 7.6E+1)	-	1.6E-1
Th in soil	mg kg^{-1}	2.6E+1 (1.6E+1 – 4.2E+1)	-	1.7E-8

Design scenario: gas release calculations

Results presented in Table 12, indicate that, for the gas release calculations, the peak dose summed across all radionuclides is about an order of magnitude above the dose constraint of 3E-4 Sv y^{-1} and is comparable with the dose from background radiation. However, it should be recognized that this dose does not occur until 1 000 000 years. As IAEA [17] states, the reliability of dose as an indicator of safety decreases with time and over timescales such as this, dose calculations must be seen, at best, as only illustrative. Furthermore, the calculations are highly cautious in that it is assumed that there is no loss of activity from the waste except by decay and gaseous emissions, and after 3 000 years the cover over the waste is removed by erosion (and subsequent to this the waste is not affected by erosion). In practice, losses might be expected to occur due to leaching and, once the cover has been eroded, erosion. Indeed if the erosion rate of 6.7E-4 m y^{-1} is assumed all the waste will have been eroded by around 16 000 years. At this time the total dose is 2.3E-4 Sv y^{-1}, just below the dose constraint and an order of magnitude below the dose from background radiation.

There are several additional philosophical points identified by Vault Test Case participants relating to the gas release calculations that need to be considered when comparing the results against assessment endpoints.

First, the associated conceptual model assumes that humans build a house on the exposed waste. Some might argue that this is a form of human intrusion and so the release should be considered as part of a human intrusion scenario rather than the design scenario. The counter argument is that the humans do not physically intrude into the waste since it is exposed on the surface due to natural processes (erosion). Indeed, the design scenario describes the exposure of the waste and states that “the site could be used for a residence”.

Second, there is the question whether it is appropriate to apply a dose constraint of 3E-4 Sv y^{-1} to the calculations. As noted in Section 1.1.3, this dose constraint is for ‘normal’ exposures. It might be argued that exposures resulting from the building of a house on top of exposed waste are not ‘normal’ and that this is a form of human intrusion. Therefore, for comparison against calculated doses, it can be argued that it is more appropriate to adopt a dose value based on intervention levels, for example of 1E-2 Sv y^{-1}, rather than one based on the dose constraint for ‘normal’ exposures.

Third, the results for the liquid, gaseous and solid releases for the design scenario are presented for three separate exposure groups (one for each release). It could be argued that there should be a single exposure group considered for all releases for the design scenario. Thus the doses should be summed across all three release mechanisms. This would be highly cautious and some modifications to assumptions concerning human habits would have to be introduced. Even if the existing peak doses for the three releases are summed, the resulting total dose exceeds the maximum peak dose for the individual releases by less than 10%.

Time constraints did not allow this philosophical debate to be resolved. Nevertheless, for the purposes of the presentation of the illustrative results, it is assumed that:

- The gas release is part of the design scenario rather than a human intrusion scenario;
- A dose criterion of 3E-4 Sv y^{-1} is applicable; and
- Doses to a gas release exposure group are presented.

These are working assumptions and should not be seen as the recommendations of members of the Vault Test Case.

Design scenario: solid release calculations

Results presented in Table 13, indicate that, for the solid release calculations, the peak dose summed for all radionuclides is about two orders of magnitude above the dose constraint of 3E-4 Sv y^{-1} and is an order of magnitude above the dose from background radiation. It should be recognized that this peak dose does not occur until 1 000 000 years, however a dose of 1E-2 Sv y^{-1} occurs at 3 000 years.

It can be argued that the calculations are highly cautious since it is assumed that there is no loss of activity from the waste except by decay, even after 3 000 years when the cover over the waste is removed by erosion. In practice, losses might be expected to occur due to leaching and by erosion of the waste once the cover has been eroded. Indeed, if the erosion rate of 6.7E-4 m y^{-1} is assumed, all the waste will have been eroded by around 16 000 years. At this time the total dose is 7E-3 Sv y^{-1}, which is still more than an order of magnitude above the dose constraint and around a factor of three above the dose from background radiation.

Table 16 shows a comparison of the measured background U and Th element concentrations at the Vaalputs site and the estimated soil concentrations resulting from the erosion of the cover and subsequent exposure of the waste in the disposal facility. It can be seen that the calculated U concentration is within the range of measured concentrations but is five orders of magnitude below the measured Th concentration.

TABLE 16. COMPARISON OF MEASURED AND CALCULATED ELEMENT CONCENTRATIONS FOR THE SOLID RELEASE FOR THE VAULT TEST CASE

Element	**Units**	**Mean Measured Concentration (range in brackets)**	**Concentration Calculated by Little**
U in soil	mg kg^{-1}	4.1E+0 (2.6E+0 – 7.6E+1)	6.3E+0
Th in soil	mg kg^{-1}	2.6E+1 (1.6E+1 – 4.2E+1)	1.1E-4

The same three philosophical points made for the gas release calculations (see Section 1.5.2.) can also be made for the solid release calculations.

Human intrusion scenario calculations

It is stated in Section 1.1.3 that, consistent with the latest recommendations from ICRP [7], a dose of around 1E-2 Sv y^{-1} may be used as a generic reference level below which intervention is not likely to be justifiable. The total dose calculated by both participants is about an order of magnitude below this level. (Somehow contradicts the statements on natural background doses being around 2.4 mSv)

Table 17 shows a comparison of the measured background U and Th element concentrations at the Vaalputs site and the estimated soil concentrations resulting from the excavation of radionuclides from the disposal facility. Again, it can be seen that the calculated concentrations are below the measure concentrations – in case of Little's values by more than an order of magnitude for U and seven orders of magnitude for Th.

TABLE 17. COMPARISON OF MEASURED AND CALCULATED ELEMENT CONCENTRATIONS FOR THE HUMAN INTRUSION SCENARIO

Element	Units	Mean Measured Concentration (range in brackets)	Concentration Calculated by Lietava/Little
U in soil	mg kg^{-1}	4.1E+0 (2.6E+0 – 7.6E+1)	1.4E+0/1.8E-1
Th in soil	mg kg^{-1}	2.6E+1 (1.6E+1 – 4.2E+1)	4.8E-9/3.1E-6

1.5.3. Consideration of uncertainties

Uncertainties can be considered to arise from three inter-linked sources [10]:

- Scenario uncertainty – uncertainty in the evolution of the disposal system over the timescales of interest;
- Model uncertainty – uncertainty in the conceptual, mathematical models and computer codes used to simulate the evolution and behaviour of the disposal system; and
- Data/parameter uncertainty – uncertainty/variability in the data (i.e. directly measurable quantities) and parameters (i.e. quantities derived from direct measurements) used as inputs in the modelling.

Each of these sources of uncertainty is discussed in turn below.

Scenario uncertainty

Incomplete knowledge of how the disposal system will evolve is a major source of uncertainty in a post-closure safety assessment. The scenarios used to address such uncertainties, are inevitably stylized situations due to the limitations associated with predicting the disposal system evolution and human behaviour.

Two scenarios have been considered in the current assessment: the design scenario with liquid, gaseous and solid release of radionuclides; and the human intrusion scenario. The range in associated total doses is from 2E-5 to 2E-2 Sv y^{-1}, i.e. three orders of magnitude. Due to time and resource constraints, it has not been possible to assess quantitatively the additional scenarios identified in Section 1.3.4 for consideration (a poor design/performance scenario, an earthquake scenario and an alternative human activities scenario). It is therefore proposed that these should be quantitatively assessed in a future iteration of the assessment process.

Model uncertainty

Discussion in Section 1.5.1. (design scenario: liquid release, and human intrusion scenario) has already highlighted the differences caused by differences in the conceptual and mathematical models adopted by the participants who have undertaken calculations. Indeed, a range of different conceptual and mathematical models have been applied by participants. The resulting differences are often small (an order of magnitude or less), especially for the key radionuclides. Thus, based on the results from the current assessment, model uncertainties appear to result in smaller differences in doses (one order of magnitude) than scenario uncertainties (three orders of magnitude).

Two further examples are described below that illustrate the effect of model uncertainty.

Kim's groundwater flow conceptual and mathematical model used to produce the results discussed in Section 1.5.1 assumes (consist with the model used by Little) that flow occurs along a one-dimensional stream tube along which longitudinal dispersion occurs. Kim also undertook calculations for a conceptual and mathematical model that assumed three-dimensional dispersion in which it was assumed that transverse dispersion was 10% of longitudinal dispersion. The peak radionuclide concentrations in the well water estimated by the two models are given in Table 18. The greater dispersion associated with the three dimensional dispersion model results in lower concentrations by about two orders of magnitude.

TABLE 18. PEAK CONCENTRATIONS OF KEY RADIONUCLIDES IN THE WELL WATER FOR ONE AND THREE DIMENSIONAL DISPERSION MODELS FOR THE VAULT TEST CASE

Key Radionuclides	**Peak Concentration (Bq m^{-3})**	
	One dimensional dispersion	Three dimensional dispersion
^{14}C	6.7E+1	6.3E-1
^{99}Tc	3.7E+3	3.3E+1
^{129}I	2.7E+2	4.9E+0
^{234}U	1.3E+2	9.6E-1
^{238}U	1.1E+2	9.6E-1
^{230}Th	1.6E-1	1.6E-3
^{226}Ra	2.8E+0	2.5E-1
^{210}Pb	9.3E+0	8.0E-2
^{210}Po	4.0E+0	5.0E-2

Little has implemented an alternative mathematical model, to that described in Appendix C.1, to represent the flux of radon. The flux (Bq m^{-2} y^{-1}) through the floor of the house (assuming no benefit for the presence of a cover) is given by [18]:

$$\chi_{Rn} = C_{Ra}\, e_{Rn} \sqrt{\frac{\lambda_{Rn}\, d_{Rn}}{\vartheta_H}} \tag{1}$$

where

C_{Ra} is the decayed concentration of ^{226}Ra in the waste underlying the house (Bq m^{-3}),

e_{Rn} is the radon emanation power (-),

λ_{Rn} is the decay constant of radon (y^{-1}),

d_{Rn} the effective diffusion coefficient of radon (m^2 y^{-1}),

ϑ_H the porosity of the base of the house (-). (would have thought it directly not inversely proportional)

A radon diffusion coefficient for floor-slab of 1.6E+1 m^2 y^{-1}, an emanation fraction of 0.2 and a porosity of 0.25 are assumed, consistent with Penfold et al [19]. This model gives the same radon fluxes and associated doses as that described in Appendix C.1.

Data/parameter incertainty

Common data has been used by the participants who have undertaken calculations associated with the two scenarios. Where possible, site specific data have been used. Furthermore, it has not been possible to undertake deterministic sensitivity analysis and probabilistic calculations. Thus no quantitative analysis on the effect of data/parameter uncertainty on doses can be presented for the current assessment.

The gas and solid release calculations of the design scenario result in doses that exceed the dose constraint. A key parameter for the calculations is the rate of erosion for the cover over the disposal facility. The value used (6.7E-4 m y^{-1}) has been selected on the basis that it is consistent with the assumption in the design scenario that the cover is totally eroded by around 3 000 years. It is not a site specific value. It recommended that in the next iteration of the assessment, emphasis should be placed on the collection of suitable erosion data since it is clearly a key parameter.

In the case of the liquid release pathway, the role of the unsaturated zone in delaying and attenuating the flux of radionuclides is important. It would therefore be useful to collect further evidence from the site to support this finding.

1.5.4. Confidence building

One of the aims of the current assessment is to increase confidence that the site and facility design will be suitable for waste disposal so that further investment in site characterisation and other activities will be worthwhile.

A range of scenarios and associated conceptual and mathematical models have been assessed. The results indicate that doses for the design scenario liquid release calculations and the human intrusion scenario are about an order of magnitude lower than the appropriate dose criterion. However, the gas and erosive releases associated with the design scenario are one and two orders of magnitude above the dose constraint, respectively. Even if a less cautious gas scenario is considered, that allows for losses due to erosion, the peak doses are only lowered by an order of magnitude. The key issue for these two releases is erosion of the disposal facility cover resulting in subsequent erosion of the waste. As discussed below, this erosion is affected by both site and design characteristics.

From analysis of the results presented in Section 1.5.1, it might appear that the site has relatively good characteristics, especially given the low rainfall and thick unsaturated zone, that restrict the significance of the liquid release. Indeed, the low rainfall and relatively high salinity of the groundwater also restricts human activities and the density of population. However, the nature of the rainfall (low frequency but high intensity) does encourage erosion and so any disposal facility design used should aim to mitigate against erosion. Unfortunately, the above grade design considered in the current assessment is more susceptible to erosion than a below grade design. Furthermore, the 2 m cover is relatively rapidly eroded.

Therefore, in light of the results obtained from the current assessment, it appears that the site is suitable but there is scope for the design to be modified with the introduction of a thicker cover and/or below grade facility that would significantly reduced the rate of erosion and the time at which waste might become exposed. However, even with such a facility, long term isolation of the waste over timescales that would ensure acceptable doses from the ^{234}U and ^{238}U chains cannot be guaranteed. Therefore, in addition to the revision in the design, there might be a need to reduce the inventory of these long-lived radionuclides by one or two orders of magnitude. With these provisions, it is concluded that future investment in site characterization and other activities will be worthwhile.

1.6. LESSONS LEARNT AND CONCLUSIONS

Based on the experience of working on the Vault Test Case and applying the various steps of the ISAM project methodology, a number of valuable lessons have been learned. Those that are specific to the Vault Test Case are recorded in this section. More general conclusions that apply to the ISAM project methodology or are in common with the other ISAM Test Cases are collated in Section 4 of this report.

— The particular purpose of the Vault Test Case assessment was set out in the assessment context and consisted of the following: to assess the level of safety of the disposal system using currently available information; to identify the most important uncertainties; to suggest further data collection and/or alternative conceptual models that may be the subject of future safety assessment iterations; and to increase confidence that the site and facility design will be suitable for waste disposal and that future investment in site characterisation and other activities will be worthwhile. Based on the information provided in this report, it is considered that the Vault Test Case has fulfilled each of these aims. In particular, this initial assessment has indicated that the site appears to have relatively good characteristics (e.g. low rainfall, thick unsaturated zone) and is suitable for further investigation and there is potential for significant improvements in performance (e.g. through changes to the facility design, inventory, etc.).

— The Vault Test Case developed and successfully applied a scenario development and justification procedure to identify a design scenario and several alternative scenarios. It is recognized that this is one of several approaches that can be used, all of which may be equally valid and this topic is considered in more detail in the Scenario Development section (see Volume I).

— At various stages in the assessment process, it was found helpful to develop a summary flow diagram of the basic steps in particular sub-components of the overall methodology to clarify understanding and for communication purposes (for example, the process of scenario development and justification, see Fig. 8). It was also found useful to review these flow diagrams after implementation and modify them in the light of experience. This is another example of the iterative nature of the safety assessment process.

— In carrying out the safety assessment, it was found to be very helpful to have two participants with different software applications independently undertaking calculations. This had a number of benefits: the cross-checking of results; the identification of differences in conceptual and mathematical models and input data; the correction of associated errors; and the identification and understanding of key processes.

— A range of different conceptual and mathematical models were applied by participants for the design scenario liquid release and human intrusion scenario calculations. The resulting differences were often small (an order of magnitude or less), especially for the key radionuclides. Thus, based on these limited results, model uncertainties appear to result in smaller differences in doses (one order of magnitude) than uncertainties associated with the future evolution of the site (three orders of magnitude). Note this conclusion only applies to this initial iteration of the Vault Test Case and should not be taken as a more general conclusion.

— The results of this study indicate that when assessing a near surface disposal facility, it can be important to consider release mechanisms in addition to liquid release. Human intrusion, gaseous and solid release can all be important exposure pathways.

— A key aspect of the ISAM project methodology is that it should be applied in an iterative manner. Due to time constraints, only one iteration of the Vault Test Case assessment has been undertaken. Further iterations could be undertaken to investigate some of the key issues identified in this first iteration (for example, modifications to the facility design, reductions in the inventory of certain radionuclides and the investigation of further alternative scenarios).

— The Vault Test Case has also focused primarily on the scenario generation and model development aspects of the ISAM project methodology. It is recognized that further work on this case could consider in more depth the confidence building aspects of the safety assessment such as results presentation, treatment of uncertainty, quality assurance, etc. with suitable practical examples.

— Many of the assumptions and decisions made in the Vault Test Case were made for pragmatic reasons to enable progress to be made with the limited time available. It is recognized that other safety assessments might require a more detailed and thorough implementation of the tools and approaches tested by the Vault Test Case, depending upon the assessment context.

2. RADON TEST CASE

The RADON Test Case was the second case evaluated in the ISAM project. It differs from other test cases in four main ways:

- This case has been developed for an existing facility that has been operated for more than 30 years; it considers the different levels of knowledge about the site, the disposal units on the site and the wastes that have been developed in the past, as well as differing levels of quality assurance applied more than 30 years ago and modern quality assurance;
- Several different types of disposal unit are present at the site (boreholes, vaults and trenches);
- The geographical position and associated geological, hydrogeological, climate and social conditions are significantly different from other two test cases; and
- The inventory is dominated by short lived radionuclides. About 90% of the total volume and activity is Cs-137.

2.1. SPECIFICATION OF ASSESSMENT CONTEXT

2.1.1. Purpose

The Test Case has been developed for an existing site that has been in operation more than 30 years, and all but one disposal unit is now closed. Past assessments have been relatively simple and have not used all of the data that is now available. Some records on the radionuclide inventory and the material and chemical composition of the waste have been lost. The purpose of this assessment is to:

- Determine if the site is safe for present and future generations, or if additional safety measures are needed;
- Guide research and development priorities; and
- Contribute to the confidence of policy makers and the scientific community.

Only post-closure safety performance is assessed and operational safety is not considered. At the same time monitoring data from the operational phase is used for the safety assessment as well as data about the geosphere, engineered barriers and waste behaviour over time. The assessment considers impacts on humans only; other biota are not considered.

The assessment only considers radiological impacts; chemical or biological toxicity is not be assessed. It is recognized that this issue may be important, but it is assumed that it will be dealt with in a separate safety case aimed at compliance with different environmental regulations.

2.1.2. Regulatory framework and assessment end-points

The assessment is based on broadly accepted international safety requirements (e.g. IAEA WS-R-1 [4], ICRP 60, 77 and 81 [5, 6, 7]). These principles are not identical to the regulations for the Russian Federation where the facility is assumed to be located. The framework is founded on the four basic principles set out below.

(a) Requirement No. 1 – Independence of safety from controls

Following the withdrawal of active control of the disposal facility, the continued isolation of the waste from the accessible environment shall not depend on actions by future generations to maintain the integrity of the disposal system.

(b) Requirement No. 2 – Effects in the future

Radioactive wastes shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today. Following closure of the disposal facility, calculated impacts should be constrained to a fraction of the dose limit.

(c) Requirement No.3 – Optimization

The radiological detriment to members of the public that may result from the disposal of radioactive waste shall be as low as reasonably achievable (ALARA), economic and social factors being taken into account.

(d) Requirement No. 4 – Radiological protection standards

The assessed radiological impact to members of the public from the disposal facility shall be consistent with dose constraints of 0.1 mSv/y^{-1}.

The assessment endpoints need to correspond with the international agreed regulatory requirements, hence the individual effective dose will be calculated to demonstrate progress towards compliance with regulatory requirements set out above.

For some alternative scenarios with low probability events an individual risk should be evaluated if predicted dose exceeds the dose constraint.

Concentrations of radionuclides in environmental media should also be evaluated to assess whether there is an acceptable level of protection of the environment.

2.1.3. Assessment philosophy

The assessment philosophy depends on the knowledge of the disposal system and the availability of the data needed for calculations and modelling. Previous safety assessments are assumed to have been made at the design and operational stages. The information about the system is now more detailed and correct than has been available before. Therefore the overall objective is to use a realistic, not cautious approach and develop a best estimate assessment. At the same time, for some data at some steps of the assessment process, a cautious approach has been applied. The assessment approach will depend on the knowledge of the disposal system and the availability of the data needed for calculations and modeling.

Uncertainties caused by natural data variability or by lack of data can be addressed using probabilistic modelling techniques with probability density functions defined from site data or from literature. However, at this stage of the development of safety assessment approaches for these facilities, probabilistic approaches have not been used.

2.1.4. Assessment timeframes

When undertaking a safety assessment for disposal to a near surface disposal facility, four main phases should be taken into account (Table 19). The first one is facility operation. This phase is not considered for this safety assessment but its duration is considered to determine the state of the engineered barriers at the closure time. The operational period is assumed to be 30-60 years. The next phase is the active institution control including final capping. During this phase the site is not accessible for the public and various kinds of monitoring are undertaken. The ISAM RADON Test Case Group proposed 300 years as a reasonable period over which such controls may be relied upon. The third phase is one of passive institutional control, which is assumed to last an additional 100 years. Passive institutional control refers to maintaining societal memory of the disposal site. This could include institutional memory and controls (e.g. local/national government records, planning authority restrictions, site marked on official maps, etc.) as well as local, informal knowledge about the whereabouts of the site. The last phase is the absence of any control. It is assumed that records and knowledge about the site are lost and unrestricted access to the site can occur. Its duration is limited only with safety assessment time frames.

TABLE 19 TIMEFRAMES AND ASSUMED ACTIVITIES FOR THE RADON TEST CASE

Activity	**Timeframe (years)**
Waste disposal operations	30 to 60 year duration
Active institutional control by the operator – to include final capping and subsequent monitoring	0 to 300
Site closure – withdrawal of active controls	300
Passive institutional control, e.g. by local/national government and local knowledge	300 to 400
No control – all records/knowledge assumed to be lost	> 400

No time cut-off for calculations is assumed. Instead, the peak doses for each radionuclide is evaluated regardless of when it occurs.

2.1.5. Disposal system characteristics

The facility is a composite site based on information from several facilities. It is an example, intended to test and improve the safety assessment methodology within the ISAM project. The design of all disposal units is typical for “RADON”-type facilities in the former Soviet Union and countries from Eastern Europe. All disposal facilities were built below ground.

The facility design for this test case is based on the typical structure of the Russian regional RADON facilities. It has a 500 m radius Clear Zone inside which there is a Zone of 200 x 200 m, where all the disposal units are located (Fig. 25). There is a Sanitary Protective Zone of 100m radius around the Clear Zone.

A drainage system was developed during the operational phase. The time over which this drainage system can be relied upon for its function should be determined for safety assessment.

All the waste is assumed to be sorted and emplaced separately in below grade disposal units:

- Spent sealed source were disposed into a specially designed borehole.
- Liquid wastes were accepted by the facility only for interim storage and following processing they are assumed to be either solidified or removed by the time of site closure and not considered in the safety assessment.
- Solid low and intermediate wastes were emplaced in four concrete vaults of different volume and structure. This facility under consideration has three 200 m^3 near surface rectangular vaults of monolithic reinforced concrete construction. They are divided into sections by concrete or wooden partitions and filled with different waste types (one of

them is biological waste). In practice, grouts occupy from 20% to 70% of the total vault volume, depending on the waste composition and structure, and their total activity.

- One more vault of similar structure, but of 940 m^3 volume, was built about 20 years later. It is sectioned and has the same waterproofing as the 200 m^3 vaults built during the first stage. Solid wastes are packed in standard 200 litre drums. It has been assumed that waste drums represent 50% of the total disposal facility capacity.
- Beside these 4 vaults some solid waste are placed into five exposed trenches. They were developed for low level Ra-226 contaminated soil.

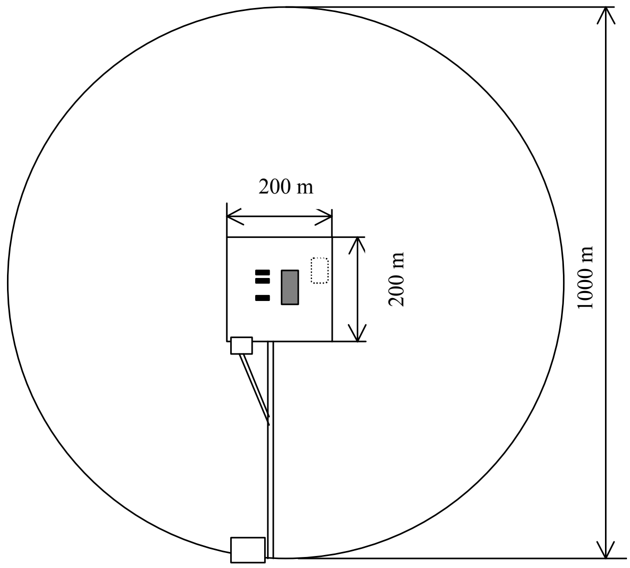


FIG. 25. Layout of the Site for the RADON Test Case.

A range of radionuclides is assumed to be present in the separate disposal units. The inventory is illustrative and described in Section 2.2.2. The inventory was developed based consideration of the information available on the RADON facilities in Bulgaria, Hungary, Lithuania, and the Russian Federation. Determining the waste inventory is known to be a rather complex procedure, especially for facilities under operation for a long period. Consequently, for the purposes of the test case the inventory should be considered illustrative rather than representative of any real site.

Total facility capacity is about 1690 m^3 including 0.3 m^3 of spent sealed sources.

The location of the hypothetical site has been chosen to be in the Volga River region in Russia (5 of 16 RADON facilities in Russia are located in the Volga region). The site is situated on the right side of the Volga River region 12 km from the regional capital town (Fig. 26). The nearest village is about 2 km from the site. It is the real site of a RADON facility, which has been in operation more than 30 years. The geological, hydrological and climate data available for the real site are used for this safety assessment.

The regional climate is temperate and continental. The long term average precipitation is 350 mm per annum but varies significantly around that value. The nearest surface water body is 2-2.5 km from the site border and about 80-100 m lower than the site level. The site is situated in the south part of Privolzhsky Heights, in the bottom of a ravine formed from quaternary sandy-clayey deposits. The unsaturated zone extends about 70 – 75 m below the level of disposal units base and consists of loamy sand, loam, and clay. Below the unsaturated zone is a confined aquifer 40-60m thick. It is overlain and underlain by clay. The nearest aquifer occurs in the intercalations of sand and sandstone into clay strata. Its width it is about 40 – 60 m. The aquifer is covered from above with a clay layer of 55-60 m thickness. The bottom of the aquifer is also clay, and is of 32-60 m thickness.

It is assumed, for that purpose of the assessment, that neither geosphere nor biosphere change within the safety assessment time frames.

FIG. 26. Location of the RADON Site.

It is assumed that discharge of contaminated perched water will take place into wells, rivers, or the land surface. Infiltration down to the aquifer is not excluded, owing to an absence of data to refute this possibility. Ground water (aquifer) discharge is assumed to be into water supply wells around the site, mainly in Kurdyum-village. Interaction of the river water and aquifer is not included in the conceptual model as it is unlikely, but cannot be definitively excluded without additional information.

Water from the eastern and western slopes of the site runs along the gully bottom, out of the site, and then through drainage under the road to the ravine near Doctorovka hamlet, and finally to the River Kurdyum. This water floods the wells and kitchen gardens in the lowlands. Some evolutionary processes and human intrusion events may lead to surface contamination, and surface run-off transport should be applied to evaluate surface water (River Kurdyum) and land contamination in thee cases.

The assessment is based on current human behaviour, habits and actions at and around the site. Present agricultural practices in the region with only natural, agriculture and leisure land uses are considered.

The site is surrounded by farmlands. The nearest settlement is 2 km north-northwest downriver (15 inhabitants) and another one is 2.5 km west-northwest upstream from the site (600 inhabitants). There is also one more hamlet 4 km east-northeast (23 inhabitants) and some dachas in the 5 km zone around the site. The nearest town is 10 km northwest and a large city (980 000 inhabitants) is about 12 km southeast from the site. Its border is assumed to become closer to the site in time.

Nevertheless, urban land use and industrial activities on the site are deemed unlikely due to the relief of the site. Village housing also seems to be unlikely on the site.

Ground water of the Aptian aquifer is assumed to be the main water source for domestic and agricultural purposes, including irrigation, animal watering, drinking, cooking washing etc. The surface water (river) use is assumed to be only an additional source for kitchen garden irrigation, animal watering and sometimes for fishing.

In accordance with regulatory requirement No.1 (Section 2.2.2), the test case assumed that the continued isolation of the waste from the accessible environment will not depend on actions by future generations to maintain the integrity of the disposal system after site closure.

2.2. DESCRIPTION OF DISPOSAL SYSTEM

2.2.1. Facility description

The site boundary is a circle with a radius of 500 m. The total area of the site is 78.5 ha, including 18.5ha of tillage, 29 ha of pasture, and 31 ha of wood. The whole site is fenced with barbed wire of 1.5 m height on reinforced concrete legs. The Restricted Zone and Clear Zone are fenced with similar fences.

The facility features include:

- A checkpoint with boiler-house and sanitary inspection room;
- Five simple (exposed) trenches for low level waste;
- A borehole for disposal of spent sealed sources;
- A tank of 200 m^3 volume for liquid radioactive waste interim storage;
- Three 200 m^3 filled and closed vaults with solid low and intermediate level waste (LILW);
- A 940m^3 vault for solid low level waste (LLW);
- A diesel power substation of 100 kW power;
- An industrial water-supply well; and
- A station for special transport decontamination and equipment processing;

The checkpoint, the diesel power station, technical water supply well are placed at the northwest entrance to the site. The well reaches a depth of 80 m.

The special transport decontamination station and all disposal and storage units are in the Restricted Zone. The station is 390 m from the checkpoint and the disposal units are located an additional 100 m from the decontamination station.

Borehole for spent sealed sources

Spent radiation sources, typically with short lived radionuclides, are disposed into a shallow ground borehole facility. The borehole is a stainless steel cylindrical vessel with a diameter of 400 mm and height of 1500 mm, which is emplaced at 4 m depth in a reinforced concrete well (Fig. 27). The thickness of the vessel walls is 5 mm. The stainless steel loading channel is a spiral tube with inside diameter 108 mm and 5 mm thickness. At the upper part of the borehole there is a carbon steel conical socket, which allows safe discharging of transport containers. This socket is covered by a carbon steel lid. The concrete wall of the borehole is surrounded by a clay-cement mixture, which fills the initial construction hole in the original soil, and acts as a seal material.

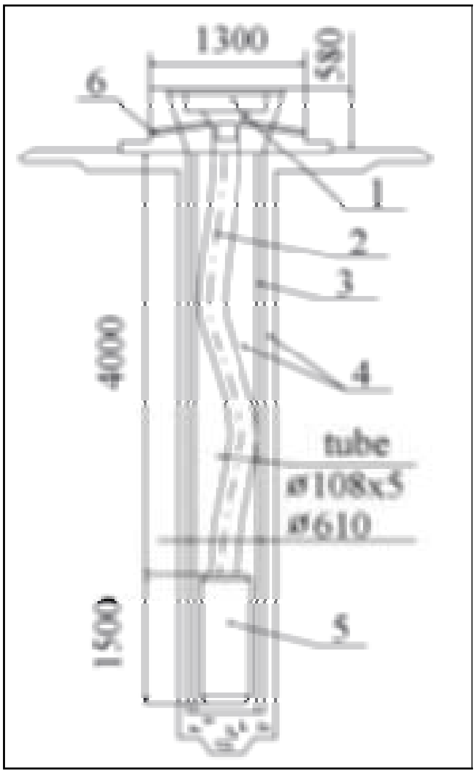


FIG. 27. The design of the borehole at the RADON Disposal Facility (dimensions in mm). 1 – carbon steel conical socket, 2 – stainless steel loading channel, 3 – steel-enforced concrete well, 4 – concrete, 5 – stainless steel cylindrical vessel, 6 – drainage channel.

The borehole has the following engineering barriers:

— Double metal cover of the sealed source itself;
— Stainless steel walls and bottom of cylindrical vessel, each of 5 mm thickness;
— Reinforced concrete surrounding the borehole of 14-20 cm thickness.

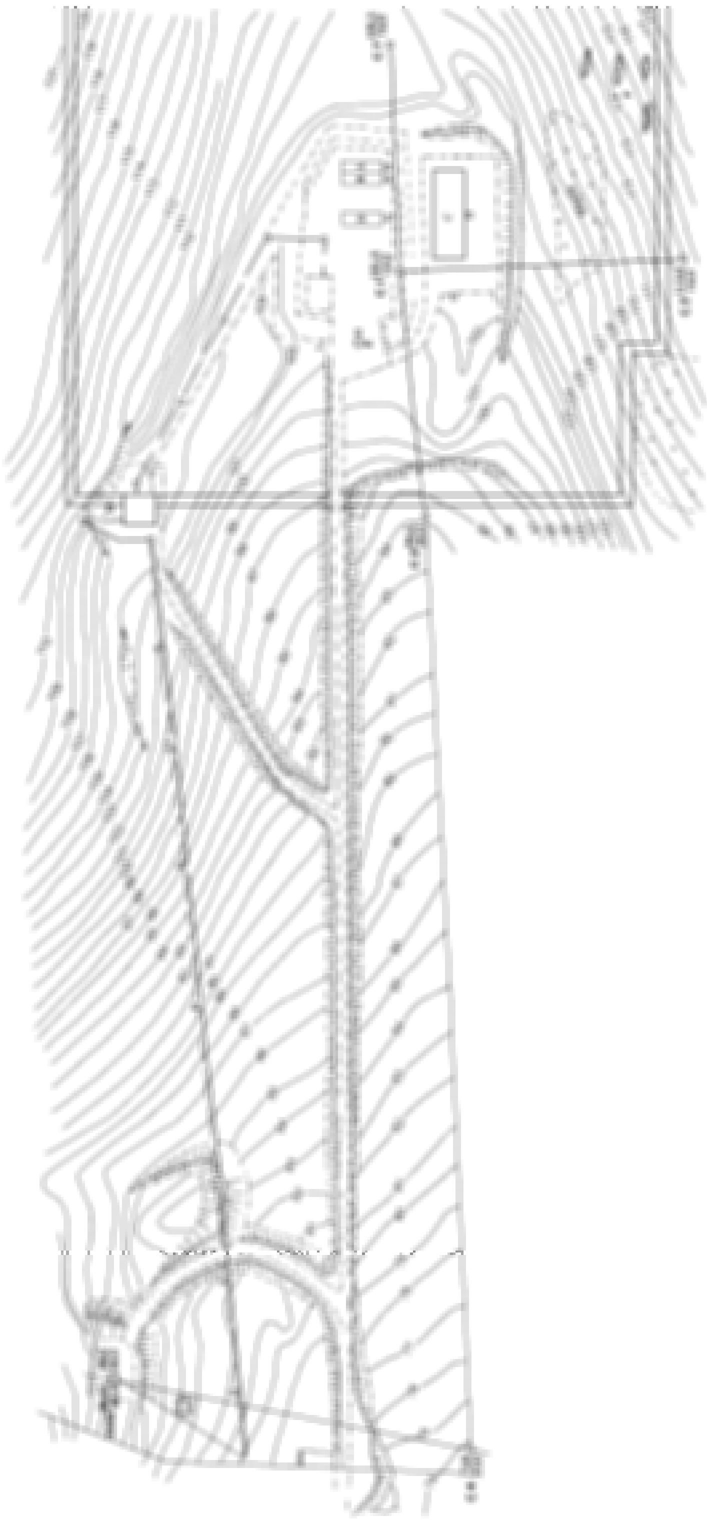


FIG. 28. Detailed Layout of the RADON Disposal Site.

Radionuclide release from sealed sources is possible only after the seal is damaged, which in turn as associated with contact with water. The form of the source itself represents an additional barrier to release, since in most cases the source is incorporated in metallic matrices, which must corrode to permit releases. For caesium sources, the activity is present as a synthetic zeolite, soluble in water. In the absence of ground-water intrusion, the most significant source of water is from cap failure and infiltration of precipitation through the unsaturated zone.

A preliminary assessment of the durability of these barriers in wet conditions is shown in Table 20.

TABLE 20. CORROSION RATE OF BARRIER MATERIALS IN WET CONDITIONS

Material	**Corrosion rate (μ/y)**	**Durability (y)**
Stainless steel (vessel, sealed source cover)	110	45 (for 5 mm wall)
Carbon steel (the cover of some sealed sources)	1120	5 (for 5 mm thickness)
Aluminium (the cover of some sealed sources)	110	46 (for 5 mm thickness)
Monolithic reinforced concrete	4000	35 (for 14 cm wall)

The following paths of radionuclide migration into the environment seem to be the most reasonable in the case of a RADON type borehole facility for spent sealed sources:

— Release as a gas or aerosol through the loading channel and cap;
— Release into accumulated water with subsequent release to water surrounding the repository; or
— Release into accumulated water, with migration to the surface by the loading channel (in the case of flooding).

Trenches for accident waste

Five simple (exposed) trenches were built at a depth of 3.5 - 4 m and 6 - 8 m away from the vaults, in which 150 m^3 of low level Ra-226 contaminated soil were placed. The location of these trenches relative to the rest of the facility can be seen in the lower right corner of Fig. 28. The trenches are located in the southern part of the Restricted Zone, near its boundary. After filling the trenches with the waste, they were covered with boards, which were covered with 1.5 m of excavated native soil.

These trenches have only one engineered barrier – the cap. However, the origin of the waste also should be taken into account. The waste soil was contaminated with radium during World War II and excavated only after more than 15 years. Consequently, all the radium on the soil is likely to be strongly sorbed. Laboratory tests on washing radium from the soil by water showed leachate with radium levels below detectable limits. There has been no observed migration of radium from the trenches during 30 years of operation and observation.

Vaults for solid and biological waste

Solid waste was disposed in four vaults, three of these are near surface rectangular vaults of monolithic reinforced concrete construction, each with a volume of 200 m^3 (Fig. 29). Each vault was divided into sections by wooden walls. The outer walls and the thickness of the bottom are between 30 cm and 50 cm. The concrete top has been covered with bitumen or asphalt, with an additional brick cover to reduce contact with water. The linear dimensions of the vault are 5.5 x 16.25 m in plan, and the bottom is at a depth of 3.5 m. Every section is covered with a reinforced concrete slab of 30 cm thickness. After waste was emplaced to a depth of 1.5 m, the waste was backfilled with concrete. The procedure was then repeated for the next 1.5 m depth. After the vault was filled it was covered by a temporary cover of a 30 cm layer of sand, a layer of tiles and a layer of bitumen.

Thus, the vaults have the following engineered barriers:

- Primary package, if it exists. These packages are polyethylene or kraft bags for small waste; or a cemented matrix for solidified liquid waste;
- Concrete backfill;
- Monolithic reinforced-concrete walls and base;
- A layer of bitumen or asphalt;
- Additional brick walls to protect the cover against mechanical damage;
- Upper reinforced concrete plates of 30 cm thickness covering the vault (with asphalt or bitumen layer); and
- The surface cap.

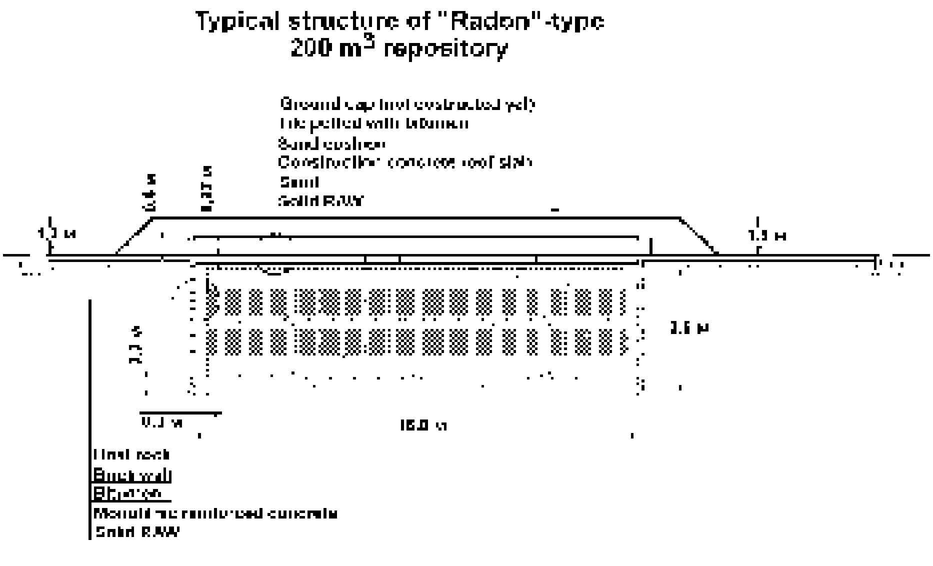


FIG. 29. Cross-section through a 200 m^3 Vault for Solid Waste at the RADON Site.

Full scale experiments and long term observation carried out by MosNPO "Radon" specialists for similar disposal facilities have produced the following estimates of the durability of these barriers.

- Concrete matrix – 15 years;
- The walls and the base of monolithic reinforced concrete design – 150 years (when MB-01 cement is used this may extend to 300 years); and
- Waterproofing – 5 years.

Based on expert judgements, the engineered barriers will keep radionuclides contained for a minimum of 70 years, and perhaps as long as 150 years. It's necessary to note that these values represent judgements for specific conditions of MosNPO "Radon" site, associated with the low conductivity in the surrounding rock (10^{-3}-10^{-4} m d^{-1}), the site geochemistry, and the presence of locally perched groundwater. Engineered barrier performance will likely be different for other sites with differing conditions.

According to the Sanitary Rules for Radioactive Waste Treatment (SPORO-85) all vaults and trenches filled in with radioactive waste, must be covered by mounding the vault with a layer of ground not less than 0.5 m in thickness. The planned slope of this cover is intended to provide drainage of precipitation.

For this test case it is assumed that the cap has a multi-layer structure. The first (base) layer is sand. Its thickness is about 35 cm, which covers the temporary cover and fills in the space between vaults. This layer is covered with a polyethylene film (0.5-0.8 mm) and an additional 10 cm layer of sand. Two packed layers of clay are emplaced over this layer. The total thickness of clay layers is not less than 50 cm. Two sand layers of 10 cm with polyethylene film between them are above the clay. The sand layer is covered with a packed clay layer of 20 cm thickness. Over all of this is a top layer of clayey soil (10 cm).

The fourth solid waste vault C is located 0 m to the southwest of the 200 m^3 vaults. It is of similar design to the other three but with a capacity of 940 m^3. The base and the walls of the sub-surface construction are made of monolithic reinforced concrete. The thickness of the walls is about 30 cm and the base is of 50 cm thickness. The bottom is at a depth of 3.5 m. The vault is divided into 10 sections by concrete walls for separate placement of different LILW types according to their half life and activity. Each section is covered from above with removable concrete slabs of 30 cm thickness. The waterproofing of sub-surface construction is of the same design as for 200 m^3 vaults. Solid waste are is packed into metal drums with a cementicious matrix. The vault had a temporary hangar (roof) to protect it against precipitation during its operation.

2.2.2. Waste characteristics

The inventory is made up of a wide range of radionuclides. Several classes of radionuclides are identified as having differing characteristics, and these are placed in different disposal units.

Spent sealed sources

The activity of the main radionuclides placed into the spent sealed source borehole is shown in Table 21.

TABLE 21. ACTIVITY IN THE SPENT SEALED SOURCES BOREHOLE

Radionuclides	**Inventory (Bq)**
Cs-137	6.01 E+13
Co-60	1.05 E+15
Ra-226	5.55 E+10
Pu-239	5.55 E+10
Sr-90	2.89 E+8
C-14	1.33 E+10

The total activity in the borehole is 1.11 E+15 Bq.

The radioactive part of the sealed sources is usually incorporated in metallic matrices, rods, wire and sometimes in powder. The active part is surrounded with a stainless steel housing.

Solid LILW

In some cases spent sealed sources are in their transport containers in the solid waste vaults. Sources with long-lived radionuclides are also stored in shielded containers in solid waste vaults until a decision is made on their final disposal.

Vault A

The total capacity of Vault A is 200 m^3. It is divided into six compartments. The inside walls were made of wood. The vault was only partially filled with waste during operation. When stored, the waste was layered with concrete. At the end of the disposal period the residual volume was filled with concrete and sand. The vault was closed in 1988, and only 67% of the vault volume was filled by waste. The vault was closed with 30 cm thick concrete blocks, which were coated by bitumen and 5 cm thick layer of asphalt. A sand layer of about 1.2 m was then placed on top of the vault.

Estimates of the properties of the reinforced concrete have been given by the site operator: density = 2.3 kg m^{-3}, porosity = 0.15, and diffusion coefficient = $2{\cdot}10^{-10}$ m^2 s^{-1}. There are currently no references for the basis for these estimates.

The inventory of Vault A is as shown in Table 22.

TABLE 22. INVENTORY OF VAULT A

Radionuclide	**Inventory (Bq)**
H-3	6.92 E+15
C-14	8.65 E+10
Cl-36	3.74 E+10
Co-60	5.91 E+12
Se-75	2.49 E+ 10
Sr-90	8.73 E+11
Cs-137	7.55 E+13
Eu-152	3.61 E+10
Tm-170	4.67 E+12
Ir-192	5.72 E+11
Ra-226	5.52 E+10
Pu-239	2.15 E+11

Besides this there are two stainless steel containers each of about 0.01 m^3, one Cs container and two Co-containers in the Vault A, which contain the inventory shown in Table 23.

TABLE 23. CONTAINERS IN VAULT A

Container	Radionuclide	Inventory (Bq)
1	Co-60	1.47 E+10
		1.2 E+11
	Sr-90	2.97 E+10
	Cs-137	
2		2.32 E+10
	Co-60	5.22 E+8
		8.82 E+8
	Se-75	5.16 E+11
		6.15 E+8
	Sr-90	9.32 E+10
		8.36 E+9
	Cs-137	
3	Ir-192	3.14E+12
	Tm-170	
4	Ra-226	1.90E+11
5	Co-60	2.13E+13
	Co-60	
	Cs-137	

Vault B

The total capacity of the Vault B is 200 m^3. The activity of the main radionuclides emplaced is shown in Table 24.

TABLE 24 ACTIVITY IN VAULT B

Radionuclide	Activity (Bq)
Cs-137	1.18 E +14
Co-60	7.56 E+11
Sr-90	2.49 E+11
Th-232	4.89 E+10
Pu-239	1.28 E+10
Tm-170	2.22 E +9
Ir-192	1.04 E +9

Vault C

The vault has been in operation since 1989. The total capacity of the vault is 940 m^3. The volume of waste emplaced to date is about 470 m^3. Solid waste is placed in 200 l metal drums and cemented. Voids between drums are filled with concrete. The activity of the main radionuclides placed into the vault is shown in Table 25.

TABLE 25. ACTIVITY IN THE C VAULT

Radionuclide	**Activity (Bq)**
Cs-137	3.07 E +14
Pu-239	4.14 E+12
Co-60	2.06 E+12
Sr-90	7.85 E+11
Ra-226 (contaminated soil)	5.83 E+10
Po-210	1.68 E10
Tm-170	6.70 E +9
Ir-192	2.95 E +9

Vault D

This contains biological wastes and has a volume of 200m^3. The inventory is shown in Table 26.

TABLE 26. ACTIVITY OF VAULT D

Radionuclide	Activity (Bq)
Cs-137	4.06 E+11
C-14	2.89 E+11
Sr-90	6.49 E+10
Y-90	6.49 E+10
Co-60	1.88 E+9

Trenches

There are also five trenches with a total capacity of 150 m^3. They were filled in 1965 with Ra-226 contaminated ground of 37 000 Bq kg^{-1} average specific activity.

Waste treatment

No waste treatment is carried out at the site, but in the 1980s the facility accepted up to 0.5m^3 per year of cemented liquid waste with an average specific activity of 10^{-4}–10^{-5} Bq kg^{-1}, which were cemented into blocks at the generators sites. The radionuclide composition of this waste is assumed to be up to 99% of Cs-137, but there are no records.

Waste packages

In most cases solid waste is packed into kraft or polyethylene bags, although large objects such as bubbling devices are usually not packaged. Spent sealed sources are usually in transport containers when placed into vaults. Solid wastes in Vault C are packed into metal drums with a cement matrix.

Spent sealed sources in the borehole have no other package besides their own double capsule of stainless steel (or aluminium for soft γ-radiation). Commercially available sources of Co-60 have diameters ranging from 6.0 to 26.0 mm, height from 7 to 99 mm and total activity from 5.11E+7 to 3.23E+14 Bq. Comparable values for Cs-137 sources are: diameter from 6.0 to 6.1cm, height of 10 cm and activity from 6.4 E+6 to 4.57 E+9 Bq.

The C-14 sealed sources are a thin film of a polymethyl metacrylate containing the C-14 isotope, marked on an aluminium substrate enclosed by a laminate of glue. Diameters of the substrates on various sources are 35, 52 and 66 mm, with active surface areas of 1, 4 and 10 cm^2. The thickness of the substrate is 1 mm. Activity varies from 120 up to 1.2 E + 5 Bq.

Sources containing Sr-90 and Y-90 are ampoules of aluminium and its alloys. These sources are 6 to 70 mm in diameter and 7.5 to 19 mm in height. Activities range 1.11E+8 to 2.22E+11 Bq.

Calibration sources containing Pu-239 are disks of steel, on one surface of which the isotope Pu-239 is fixed. The diameter of a source is 25 mm, height is 0.20 mm. The active part is 10.0 to 20.0 mm in diameter. Activities are 200 or 400 decays per second.

2.2.3. Geology

The RADON facility site is located at the southwest limb of Elshanskaja anticline. The oldest deposits in the core of the Elshansaja anticline are the Bajocian deposits of the middle Jurassic system, which are succeeded by Bathonian and upper Jurassic (Callovian) and also Barremian, Aptian and Albian formations of the lower Cretaceous in a south westerly direction (Fig. 30).

FIG. 30. Geology of the RADON Site.

Regional stratigraphic succession

Jurassic system

Middle sequence

Bajocian stage (J_2 bj)

The Bajocian is exposed at the northeast part of the territory in the lower parts of the Kurdjum river. The rocks lie unconformable on middle- and upper-carboniferous formations.

A conglomerate layer of 1m consisting of rounded pebbles of silicified limestones and phosphorites, cemented with clayey-calc and sandy material is found at the base of the stage.

Above the conglomerate lies 10–15m of yellow-grey irregular-grained quartz sand, quite often with fragments of limestone and dolomite and thin lenticular intercalations of dark grey sandy clays. This is succeeded by clay of dark grey colour with a greenish nuance, micaceous, aleuritic, with intercalations of dark grey aleurites, calcareous sandstones and limestones.

The total thickness of Bajocian deposits is up to 125 m.

Bathonian stage (J_2bt)

This is exposed in the middle reaches of the Kurdjum river. It is formed of sandy-aleuritic rocks with intercalations of calcareous sandstones, limestones and clays. The lower section of the stage is presented by a thin layer of quartz sandstone with an admixture of glauconite, in which fine-grained sand occurs. This is succeeded by brown-grey, feldspathic-quartz, coarse-grained aleurites. The upper layers of the stage consist of aleurites followed by Callovian clays.

The thickness of Bathonian deposits ranges from 20 m up to 33 m.

The upper sequence

Callovian stage (J_3k)

This is exposed in the east of the area. The deposits are divided into three substages.

The Lower Callovian substage is formed by aleuritic clay of dark grey colour with brownish nuance. Clayey ganister and pyrites quite often are present.

The deposits of Middle Callovian substage are submitted by dense light grey calcareous clays and aleurites with intercalations of fine-grained sand and light grey chalky clay. Bun-shaped ganister concretions and small-sized plaster often occurred in the top of the succession.

The Upper Callovian substage is formed by dark grey and greenish-grey clays with bluish nuance. Clays are low-micaceous, aleuritic, with occurrences of calcite, plaster and pyrites, calcareous concritions.

The total thickness of the Callovian stage ranges from 40 m up to 75 m.

Cretaceous system

The lower sequence

Barremian stage (K_1br)

This is traced as a tract (band) extended from the north to the south of the region. The horizon of nodule phosphorites scattered in clayey dark grey sand is traced in the basis of the stage. It is quite often cemented as a conglomerate by calcareous-sandy cement felspathic-and-quartz coarse-graded sand, into fine-grained and aleuritic rocks, with phosphorites. The total thickness of this sandy layer is 4–8 m.

Dark grey up to black aleurolites (siltstones), with an impurity of glauconote, opal substance and hydrooxides of iron, overlie the sand layer. Aleurolites are micaceous, layered due to light grey aleurite overburden on bedding planes.

The total thickness of Barremian deposits ranges from 32 m up to 62 m.

Aptian stage (K_1a)

This stage is mostly widespread in the central part of the region. It occurs conformably on underlying Barremian deposits. According to lithological features the stage is subdivided into two rock masses: the lower rock mass – sandy-aleuritic; and the upper rock mass – clayey-aleuritic.

The lower rock mass is formed by dark grey and yellow quartz sand, fine-grained, non-uniformly clayey, with intercalations of greenish-grey aleurites. The rock mass thickness is of 40–60 m. The layer of calcareous sandstone ("an Aptian plate") is traced in immediate proximity (1–4 m) from the base of the stage.

The upper part of the stage is formed by dark grey dense clays and aleurites with intercalations of aleurites and sandstones. Its thickness is of 30–40 m.

The total thickness of the Aptian stage is 85 m–117 m.

Albian stage (K_1al)

The stage occurs in the western and, partially, the southern parts of the region. The contact with underlying deposits is determined by the change of aleuritic-clayey Aptian rocks with sand. Sand is of grey and white colour, quartz, with a glauconite, fine-grained, clayey with intercalations of sandstones of the same structure on calcareous cement. The sand layer thickness is of 42–49 m. Dark grey up to black clay layer occurs above on the sequence. The clay is a hydromica and montmorillonite, and is interbeddied with aleurites of dark grey colour with greenish nuance. The aleuritick-clayey pack is 50–75 m thick. The total thickness of Albian stage is 90–120 m.

Upper sequence

Cenomanian stage (K_2c)

The stage is developed at the extreme western part of the region. The lowest part of the stage is formed by the pack of greenish-grey quartzous-glauconitic sand, which are succeeded by light-grey, micaceous aleurites which in turn passes into light grey quartz fine-grained sand closer to the top of the stage.

The stage is 80–125 m thick.

Quaternary deposits

Quaternary deposits are widespread in the region. They represent eluvium, deluvium, proluvium, and alluvium from middle Pleistocenic up to Holocenic age.

Middle-upper Pleistocene eluvial-deluvial deposits are advanced on watersheds and their slopes. The greatest thickness of these deposits is found in the east part of the region. In the remaining region their thickness does not exceed 1 m. In this case the lithological structure of the rocks depends on their underlying substratum. The deposits are loam, loamy sand and sand with debris.

The eluvial-and-deluvial deposits performing ancient relief depressions, are usually formed by brown dense loam with calcareous modules. The loam layer thickness, as a rule, does not exceed 10 m.

The upper Pleistocene alluvial deposits (Verhnehvalynski horizon) form the first terrace above the flood-plain of the Volga basin rivers (Kurdum river, Uteshov ravine). The terrace is loam of 15–20 m in thickness with intercalations of loamy sand and sand.

Holocene

Within the framework of considered territory the Holocene is represented by an alluvium of flood-plain terraces and by proluvium-and-deluvium formations.

Alluvial deposits

Alluvial deposits of the upper and lower flood-plains are developed in valleys of the River Kurdyum and its inflows. The deposits also are characterized by rather uniform structures. The lower part of flood-plain deposits is presented by varigrained sand with gravel and rubble of local rocks, which pass above into thin- and also fine-grained sand with intercalations and lenses of clays and buried soils. Alluvium thickness is of 10-18 m.

Proluvium-and-deluvium deposits

Proluvium-and-deluvium deposits are developed on slopes and in young ravine mouths. They are represented by unsorted loam and loamy sand. The deposits are wide spread but sometimes they are characterized by a thickness exceeding 20 m.

Site geology

Sandy-clayey Cretaceous rocks (presented by Albian (K_1al) clays of 26–27 m thickness and fine sand of 8 m thickness, Aptian (K_1ap) clays with sandy and sandstone interbeds (uncovered thickness is up to 45 m)) form the upper geological sequence of the site - 80 m depth (Figs 29–31). Specified deposits are covered with up to 13.3 m of clayey Deluvial deposits (dQ_{III}) just on the site.

All the disposal units at the site are located in a depression, the bottom of which is formed with Proluvium and Deluvium Quaternary deposits. The Quaternary deposits are located mainly in the thalweg (center) of the depression and are represented by brownish-yellow and dun (greyish-brown) loam and light yellow loamy sand with a total thickness up to 18.7 m, while the hillsides have no Quaternary deposits.

At the top of the hollow and up the hillsides, sand fractures are more prevalent in the Deluvial deposits: they are sandy rocks, low wet, ferruginated, with intercalations of varigrained clayey sand. Down the hillsides (closer to the bottom) and down the hollow (closer to the mouth), the deposits become more clayey. Deluvial loamy sand is substituted (replaced) with wet loam, hard plastic, ferrugunated with single lenses of loamy sand.

The succession of deposits at the site indicating engineering-and-geological elements (EGE) according to exploration researches made in 1999 is given below.

— EGE 1. Disturbed made-up ground (tQ_{IV}) – asphalt, aggregate of sedimentary rocks. It occurs within the area of existing disposal units, access roads and plots. Its thickness is 0.2 m.

— EGE 2. Soil layer (pdQ_{IV}) – heavy silty loam, semi-hard, tight plastic in places, black, dark – brown, with inclusions of organic matters, with grass and trees roots. It ocurs everywhere. Its thickness is 0.4–1.2 m.

Deluvial deposits (dQ_{III})

— EGE 3. Loamy sand (light loam), sandy, hard, occasionally semi-hard, solid (compact), yellow, yellow – brown. It occurs in the upper part of cross-section directly under soil grounds. Its thickness is 1.8–2.2 m.

— EGE 4. Light loam, occasionally heavy, sandy, tight plastic, occasionally soft plastic, brown, yellow – brown. It occurs in the intermediate part of deluvial deposits. Thickness of the layer is 2.6–6.2 m.

— EGE 5. Light loam, occasionally heavy, sandy, hard, occasionally semi-hard and tight plastic, brown, yellow – brown. It occurs in the East part of the site, outside the asphalted area. Its thickness is 2.6–4.9 m.

— EGE 6. Silty sand, tight, undersaturated (a little wet), yellow – brown. It was met in one of investigation boreholes as a 0.5 m thick lens in the middle part of the rock mass directly above the EGE 7.

— EGE 7. Loamy sand (light loam), occasionally heavy, sandy, semi-hard, dense (solid), with light intercalations and lenses of fine and silty sand (up to 15 % of the layer thickness), with single inclusions of lightly rounded rubble of siliceous rocks, dun, hazel. It spreads in the lower part of deluvial rock mass. The thickness is 3.8–7.2 m and more.

— EGE 8. Silty sand, dense (solid), low saturated (a little wet), with inclusions up to 20 % of gravel, rubble, sedimentary rock rubble, yellow – gray. It was met in the bottom of deluvial deposits. Its thickness is 0.5 m.

Upper Cretaceous deposits ($\hat{E}_1al$)

— EGE 9. Light clay, silty, semi-hard, poor to average swelling, dark gray, micaceous. It was uncovered at 13.5 m depth (actual elevation/absolute mark is 89.8 m). Uncovered thickness of the layer is 1.5 m.

This succession can be simplified into:

— Disturbed layer (tQ_{IV}), presented with loam and displaced soil, up to 0.4 m in thickness;

— Soil loam layer (pdQ_{IV}) from 0.4 to 1.2 m in thickness;
— Deluvial yellowish brown loamy sand (dQ_{III}), a little wet, with interlayers of various graded quartz clayey sand. The layer varies in thickness between 4.1–12 m;
— Deluvial brown to greenish grey loam (dQ_{III}), wet, heavy, hard plastic, weakly ferruginated. Thickness changes from 2.4 to 8.2 m;
— Terrigenous firm grey clay (K_1al), with won thickness of 1.5m (22–27 m is awaited);

Dark grey clay (K_1ap) with interlayers of sand and sandstone, changing in thickness between 10 and 45 m was not uncovered during the investigative drilling.

The longitudinal and lateral geological cross-sections of the site are shown in Figs 31–33.

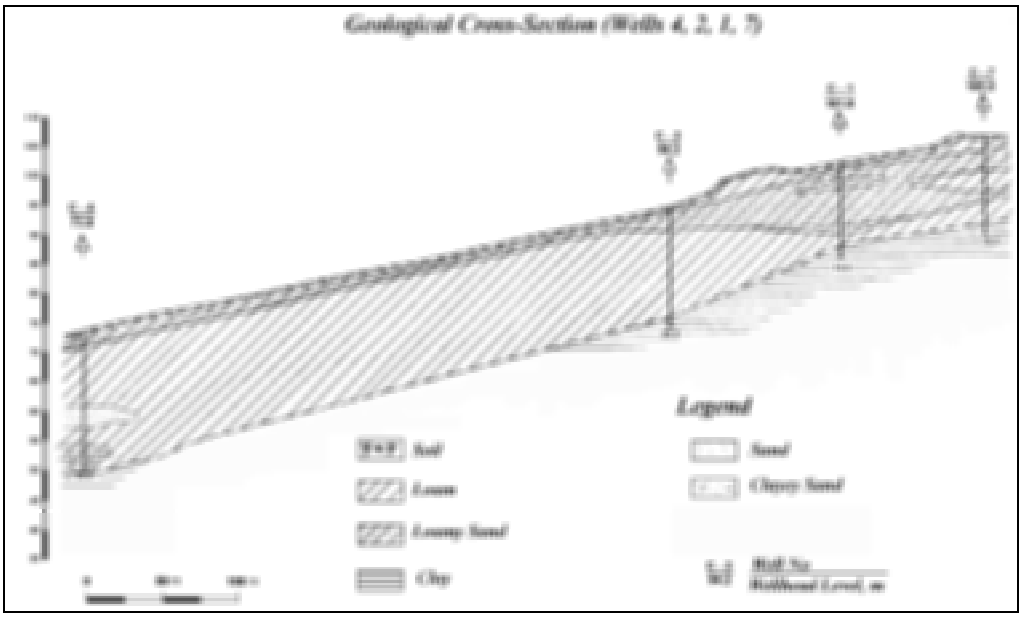


FIG. 31. Longitude Cross-section through the RADON Site.

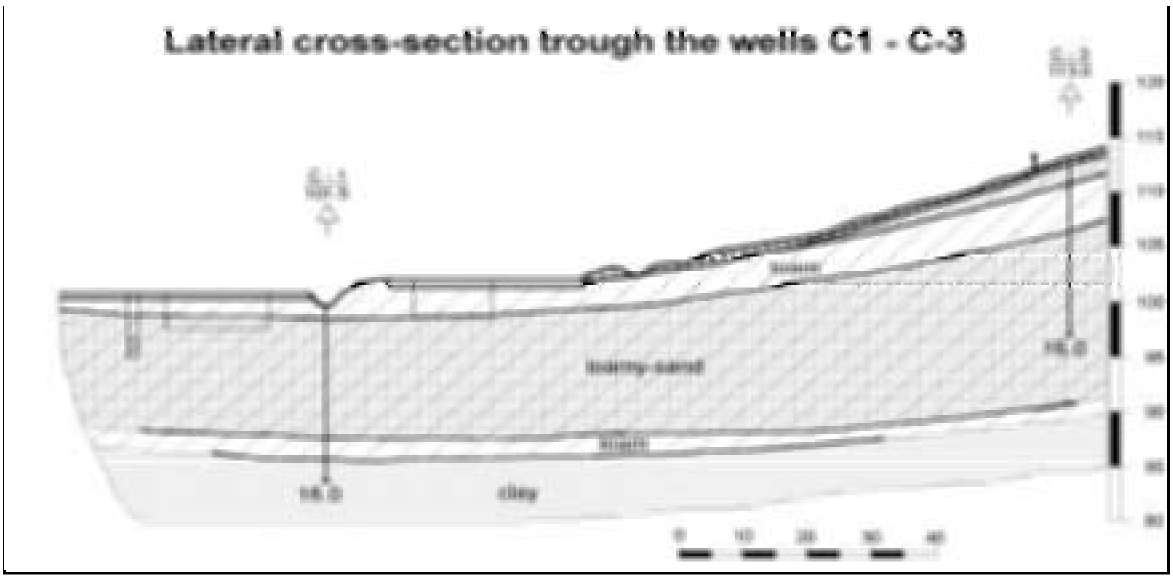


FIG. 32. Lateral Cross-section through the RADON Site.

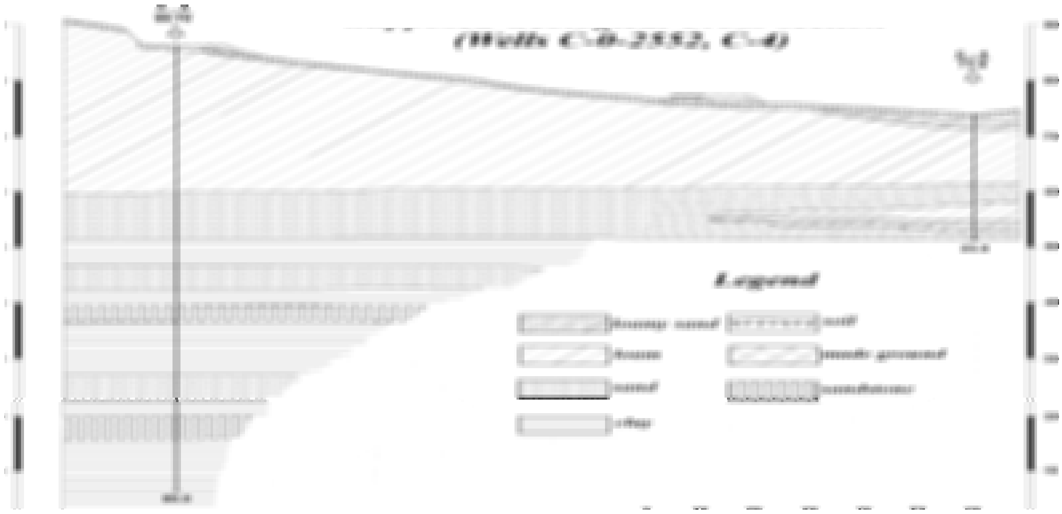


FIG. 33. Cross-section through wells C-0 (2252) and C-4 at the RADON Site.

Regional tectonics

Tectonically, the region belongs to the Saratov-region block, which neighbours upon the Atkarsko-Petrovsky depression to the northwest. On the Saratov-region context a number of third order structures are determined: Sleptsovsko-Orkinsky, Radishevsko-Teplovsky, Elshano-Sergievsky blocks and Korsakovskaya depression.

The largest third-order structure is the Elshano-Sergievsky block. Its length is about 70 kms and its width is up to 50 kms. The southern limb of the block is a scarp slope, with a 30^0 angle of layer inclination, the northern limb is flat-lying, with up to 5^0 angle of layer inclination. The block consists of the Smirnovskaya, Malinoovrazhnaya, Hlebnovskaya, Elshanskaya, Peschanoumetskaya and Ozersko-Suvorovskaya anticlines. The site is located within the Elshanskaya anticline. This structure is of isomeric form; its size in the across-track direction is 15–20 km. The layer inclination reaches 25^0 on the southeast scarp slope and 5^0 on the northwest flat one.

Hydrogeology

The hydro-geological conditions of the site are characterized by the presence of groundwater. The first aquifer occurs in the intercalations of sands and sandstones into Aptian clay strata at a depth of 60–100 m. In some areas it has a hydraulic head up to 2 m. Hydraulic conductivity is 0.8 m d^{-1}. Clays of the same age are the confining layers of the aquifer. The thickness of the top Aptian clay layer is about 25 m (plus 35 m of Albian clay stratum with sand interbeds without groundwater). The bottom Barremian clay layer is 32–60 m in thickness.

According to data from the technical water supply well, the aquifer is at a depth of 60 m and has a water head of 2 m. Taking into account that the wellhead level is 86.62m, the site level is about 102.6 m, and vault depth is about 3.5 m, the distance from the vault bottom to groundwater can be evaluated as 70–75 m. According to the regional description the thickness of the aquifer is likely to increase from 13–14 m at the site up to 20 m or more to the west and southwest. The aquifer water is bicarbonate-sulphate calcium with total mineralization of about 1.5–2 g l^{-1} and is not considered suitable for use as a drinking water supply.

Investigative drilling made during various seasons in different years has shown the absence of both productive groundwaters and perched waters in the Quaternary sediments within the confines of the site. They have shown the presence of clayey soils of soft and fluid-plastic consistence with a solid-to-liquid ratio of 0.66–0.80 and loamy sand in two boreholes. For one borehole, it has been suggested that this could be explained by two specific circumstances: 1) the absence of transpiration by plants and vaporisation under an asphaltic cover around the vault, and 2) the presence of a drainage ditch for removal of storm and melt waters, from the bottom of which some water infiltrates down into the underlying argillaceous sand. The other place on the site, where such high moist was found, is located in the lowest point of the hollow's mouth were most of the surface run-off water and infiltrating precipitation runs down. It should also be taken into account that the particular well was drilled soon after the end of field filtration and sorption experiments which were carried out near the vaults.

The absence of perched waters in the Quaternary sediments within the confines of the site could be a result of:

- The presence of the firm loam layer in the top part of unsaturated zone; and
- The significant slope of the site surface which leads precipitation mainly to drain by surface run-off, transpiration and evaporation.

However, the possibility of perched water cannot be entirely excluded from consideration for safety assessment purposes.

Properties of the engineered and geological elements

Nine engineered and geological elements (EGE) were identified at the top of the geological succession of the site. All elements were sampled and laboratory tested the following properties.

Physio-mechanical characteristics

The sand is estimated as compact (solid). The loam is low swelling in some cases. The clay is low and medium swelling.

All EGE's are non-aggressive in relation to concrete.

Loamy sand is practically non heave, loamy soil is low heave and tight plastic loamy sand from the middle part of Deluvial deposits is mean heave.

Filtration characteristics

Laboratory tests give hydraulic conductivity for sand as 1 m d^{-1}, for loam from 1.E-5 to 1.6E-4 m d^{-1}, for upper Albian clay from 6.0E-6 up to 1.9E-5 m d^{-1}.

Grain size measurements have shown that the overall Deluvial sediments are represented by non-homogeneous sandy and clayey rock with 9.34–14.83% of clayey fraction, 18.39–33.92% of silty fraction, and 72.27–51.25% of sandy fraction. For the purpose of the safety assessment it consideration could be given to one layer of loamy sand 4.1–12.0 m thick. Results of laboratory tests give the hydraulic conductivity for loamy sand as 0.4–0.8 m d^{-1}, porosity is 0.4–0.5, and density of 1910 kg m^{-3}.

As a result of field tests, carried out on the site between Vaults C and D, Deluvial loamy sands at the depths of 1.2–3.1 m have following characteristics: active porosity is 0.53, vertical hydraulic conductivity is 0.69 m d^{-1}, dispersion coefficient determined during field tracer tests is 0.00206 m^2 d^{-1}.

The granulometric composition of the Deluvial rocks sampled from different wells shows heterogeneity of the loamy sand both in the vertical and horizontal extent. This is a typical characteristic of Deluvial deposits. Whilst only vertical infiltration was studied during field tests, horizontal hydraulic conductivity in such conditions was evaluated to be very close to the vertical one – 0.69 m d^{-1}.

Sorption properties

The sorption properties of the host lithology have been studied in laboratory and field tests, studying the interaction of the loamy sand with real contaminated solutions from Vault B. Precipitates within contaminated water with specific activity 8 407 Bq l^{-1} of Cs-137. Ra-226 with activity 13.1 Bq l^{-1} and Co-60 with activity 41 Bq l^{-1} were detected in this solution. Because of the low concentration of Ra-226 and Cs-137, sorption properties for Cs-137 only were studied. Laboratory tests were carried out in the specific activity range from 5 550 up to 37 655 Bq l^{-1} (watered or saturated with Cs-137).

In the results of 15 static laboratory tests Cs-137 distribution coefficient varied from 3 949 to 24 868 ml g^{-1}, and the coefficient value decreased with specific activity growth or with increase of the solution volume. Within 70-100 hours loamy sand sorbs about 90% of initial activity from solution, but the equilibrium occurs only after 250 hours of contact. The interaction of the contaminated solutions and the soil proved to be characterized with slow kinetics and non-linear sorption isotherm. It was determined that the sorption isothermal curve has a convex shape, so, the interaction of real solutions contaminated with Cs-137 and the soil cannot be described with a constant distribution coefficient. In this case it may be expected that a soil sorption front with certain a width will be formed and it will shift in parallel along the sorption column. The shape of the front will depend on values of diffusion and longitudinal hydrodynamic dispersion coefficients, kinetics mode and other factors.

For studying sorption dynamics, two laboratory tests were conducted. Since saturation concentration in the soil during the dynamics tests was not reached, the dynamics capacity of the tested loamy sand in relation to Cs-137 may be considered as more than the obtained value of 12 814 Bq kg^{-1}. Estimation of the ultimate sorption capacity may be made from the maximal value of soil specific activity, that has been found in static tests which was 22 035 Bq kg^{-1}.

Field sorption tests made between Vaults C and D supported the assumption made earlier about forming the sorption front. Distribution of Cs-137 in the depth showed that the saturation concentration had also not been reached.

The distribution of Cs-137 in the rock during the laboratory and field dynamics tests allowed the use of an analytic solution of the problem for conditions of "unlimited" sorption capacity of the soil in the case of low Cs-137 specific activity in the fluid. For this case the calculated Cs-137 sorption rate factor is 19.303 day^{-1} or 0.804 h^{-1}.

Infiltrating a 3 m column (equal to the height of the vault) of contaminated water through loamy sand in a field test resulted all the activity being sorbed within 17 cm of the ground. It corresponds with analytic calculations of unlimited (in time) infiltration of such solution (8 407 Bq l^{-1} Cs-137) that resulted in 25 cm of contamination in the studied rock.

Hydrology and surface water bodies regional

The site is located in the region that hydrologically belongs to the Volga River basin. The main water flow in the region of the site is the River Kurdyum (Fig. 26), which is 2–3 kms to the southwest to north-west of the site and discharges into the Volga River 40 kms from the site.

The River Kurdyum's headstream is located near the town of Verhny Kurdyum, west of Saratov. The river passes Saratov to the north and flows into the Volga. The largest inflows (confluents) are the Stary Kurdyum, the Il'inovka and the Elshanka.

The recharge of the River Kurdyum is by precipitation and groundwaters. Due to the Jurassic deposit outcrop, the water of the Kurdyum is characterized by sulfate-and-hydrocarbonate mineralization of 1.1–1.4 g l^{-1}. The surface water of the River Kurdyum is now used mainly for industrial water supply. The river flows in a valley with mainly symmetrical slopes. One flood plain terrace and two terraces above the flood plain are clearly traced in its cross-sectional structure. The flood plain terrace is raised above the rim by 1–2 m.

The first terrace above the flood plain is separated from the flood plain by a cliff of 2–2.5 m height, and has an absolute elevation up to 45 m. Its width varies from several tens of metres up to 400–500 m.

The second terrace above the flood plain is either erosive, or accumulative. Its absolute elevation is 55–60 m. This terrace is 5–6 m above the river channel.

According to the maps and literature the River Kurdyum has a continuous watercourse only in the middle and lower reaches. Its width does not exceed 4–5 m, with a depth of 1 m. The average slope of the river channel is 3–3.5 m per 1 km. In the region of the site, the river Kurdyum intermittently dries. It is only 20 km downstream that the river flow becomes continuous, not far from the settlement of Gotovitskiy. A few cascaded ponds have been made on the river by people and beavers building dams.

Several inflows supply the river. The largest inflow in the upper reaches is the Il'inovka, a temporary watercourse flowing into the River Kurdyum in the region of the town of Kamenskiy Trud. The two largest confluents flow into the River Kurdyum in the lower reaches, upstream and downstream of the settlement Kleshchevka – Stary Kurdyum (left-hand confluent) and Elshanka (right confluent).

Downstream, at the village Novaya Lipovka, a hydrological monitoring station is located. The results of observations in 1966 are presented below in Tables 27 and 28. These data show the hydrological fluctuations of the River Kurdyum. The oscillation of an average water level in the river in 1966 is presented in the Table 27.

TABLE 27. OSCILLATION OF AN AVERAGE WATER LEVEL IN 1966

Level in 1966 (m)	**Months**											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Average	151	170	261	180	141	133	122	109	124	143	157	150
Max	157	261	401	238	158	218	189	123	135	155	172	169
Min	147	155	201	150	114	111	108	106	118	121	147	139

An average annual level in 1966 was 153 m, maximum – 401 m (March 15), lowest in summer – 106 m (August 9), lowest in winter – 132 m (November 15).

The river discharge at the gauging station in 1966 is shown in Table 28.

TABLE 28. RIVER DISCHARGE (L S^{-1} KM^{-2}) AT THE GAUGING STATION FROM 881 km^2 AREA IN 1966

Discharge in 1966 ($l\ s^{-1}km^2$)	**Months**											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Average	0.43	0.50	8.37	2.04	0.60	0.51	0.28	0.08	0.23	0.35	0.60	0.32
Max	0.54	2.50	29.5	5.88	1.04	4.10	2.30	0.22	0.32	0.49	0.94	0.86
Min	0.34	0.34	1.30	0.80	0.11	0.09	0.07	0.06	0.16	0.03	0.40	0.20

An average annual discharge in 1966 was 1.19 l s^{-1} km^{-2}, the maximum was 29.5 (March 16), the minimum in summer – 0.032 (August 6), the minimum in winter – 0.29 (November 15). The average discharge is 1.36 l s^{-1} km^2.

Local

The site is situated 80-100 m higher than the river.

Communities nearest to the site are located on the banks of the River Kurdyum: the village Kurdyum is 2.5 km upriver and the hamlet Doktorovka – downriver 2 km from the site.

The River Kurdyum is the main surface water body near the site (there are also several ponds on this river and some creeks flowing into it). Springs and continuous watercourses are absent within the site and its Sanitary-Protective Zone.

The watershed for the Restricted Zone is completely located within the limits of the site and is 91 296 m^2. For the hollow as a whole, the watershed is 341 423 m^2. This area provides 3.7 times the dilution of rainfall runoff passing through the Restricted Zone, which has the potential to contact radioactive waste. This surface water runs out of the site, where it meets the north and northwest drain formed by the outer (clean) slopes of the site with an area of 176 965 m^2. It dilutes the stream at least 1.3 times. Surface water from the hills outside the site provides several times more dilution of the surface run-off. Then it runs through the drain under the Saratov-Tatishchevo road to the ravine near the Doktorovka hamlet and then to the Kurdyum-river. The rest of the site area (267 010 m^2) forms the Southern outer drain along the Kolikhin Ravine to the Kurdyum Creek and then to the upstream (source) of the River Kurdyum (Fig. 34).

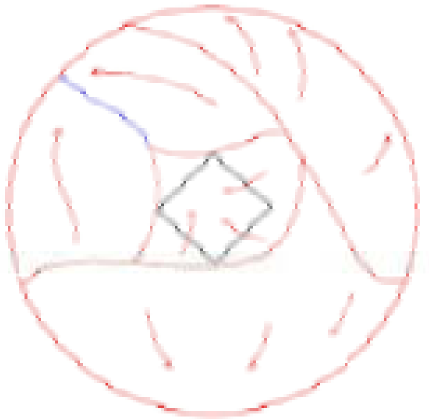


FIG. 34. Water-shed Area of the RADON Site.

Relief, geomorphology, physio-geological processes, seismic conditions

The site is situated in the southern part of the Privolzhsky Heights. The Privolzhsky Heights is a wide and elevated plateau with high erosion relief. The plateau has an asymmetrical structure: a sharp eastern hillside and a long gentle western slope. In some areas the density of the ravine and wash net is about 0.5–0.9 km per km^2, but in the low grounds it decreases to 0.2–0.1 km per km^2.

The facility is situated on the right bank of the Kuryum River. All investigations underline that erosion has a significant impact, mainly on the other (left) bank of River Kurdyum. This point is noted in all documents. According to the Map of Recent Physio-Geological Processes the erosion coefficient is 3.5 for the left bank, whereas on the right bank it does not exceed 0.8–1.2.

No adverse physic-geological processes (soil settlement, taluss, rock falls, quicksands, landslides, caves etc.) were detected during the operation of the site. The hollow bottom where all disposal units are located is believed to be a zone of accretion rather than erosion. One also should take into account that about 40% of the site area is covered with trees. Forest areas are known to make specific conditions for slow snow melting and therefore to reduce sheet erosion from hillside slopes. At the same time the presence or absence of trees is an important factor for gully development. In any case no denudation processes were indicated on the site during the whole operational period.

Geomorphologically the territory is located on a watershed plateau cut by a hollow. The hollow has a flat profile along the thalweg (its profile grade is about 0.06–0.08) and its maximum width is about 100 meters. It is surrounded with low (8–10 m) wooded hills. The hillside slope is up to 20 degrees. The actual elevations within the facility territory change from 74.5 m up to 125.8 m. The surface of the Restricted Zone, where disposal facilities are located, is planned and covered with asphalt. The drainage (intercepting) ditch for storm and melt water drained from overlying areas is located around the asphalted area.

According to the map "General Seismic Zoning of the Territory of Russian Federation (OSR-97)" the region around site belongs to the 7-mark zone on the MSK-64 scale. It means that the probability of seismic intensity to exceed this design value within 50 years is 0.01 (1 %). The lithology of the site meets the II (second) category of grounds on seismic properties according to classification at SniP 11-7-81 and PNAEG-5-006-87.

2.2.4. Climate, vegetation and human activity

Climate

The climate of the region is considered as temperate and continental. The winter is colder and the summer is warmer than in the west of the European part of Russia. The majority of atmospheric precipitation falls in summer. The precipitation quantity, both annual and monthly, may vary significantly between years: 250 mm (1957) to 654 mm (1973). Average annual snow cover achieves 23–26 cm in thickness and remains about 120–130 days per year. The transit from winter to summer occurs faster than from summer to winter. The average snow melting period is about two weeks.

(a) Temperature:

(i) Average annual temperature — +6.1° C;
(ii) Average month temperature in winter — –11.1° C;
(iii) Average month temperature in summer — +26.1° C;
(iv) Frost soil penetration in winter — from 0.4 up to 0.9 m;
(v) Maximum depth of frost soil in winter — 129 mm;

(b) Precipitation:

(i) Average annual precipitation — 350 mm;
(ii) Average annual water supply in snow — 88 mm;
(iii) Maximum daily precipitation — 105 mm (in 1985);

(c) An example of the annual precipitation variation is shown in Table 29. Average relative humidity of outside air is:

(i) In winter — 83%;
(ii) In summer — 41%.

In 1985, the relative humidity of air in winter achieved maximum values of 80-100%. In transition seasons relative humidity roughly decreases in spring and increases in autumn, due to fast changes of temperature. The smallest values were detected in May — early June (15–19%).

(d) Evaporation is determined by the deficit of air humidity and varies greatly, with dependence on season and time: it is larger in summer than in winter, and larger in the daytime than in the night. As a rule, in summer average evaporation exceeds precipitation (in 1985 evaporation exceeded precipitation by 3.8–4.5 times in July and in August). For 1985 annual evaporation totalled 503.8 mm and in particular totalled 92.3 mm a month on the average in the warm season and 3.9 mm per month in the cold season.

(e) Evapotranspiration on the site has not yet been studied.

TABLE 29. CLIMATIC DATA FOR THE RADON SITE

	I	*II*	*III*	*IV*	*V*	*VI*
Average month and annual temperature (^0C)	-12.2	-11.9	-6.0	5.3	14.0	18.4
Average month and annual precipitation (mm)	30	27	24	25	42	48
Number of days with precipitations ≥1.0 mm	7.3	5.8	5.6	5.3	6.4	6.9
Number of foggy days	4	4	6	3	0,5	0,5
Average month and annual wind rate (m/sec)	4.7	4.8	4.7	4.3	4.1	3.7

	VII	*VIII*	*IX*	*X*	*XI*	*XII*	*Year*
Average month and annual temperature (^0C)	20.6	18.9	12.5	4.7	-2.9	-8.9	4.4
Average month and annual precipitation (mm)	48	43	40	38	34	31	430
Number of days with precipitations ≥1.0 mm	7.3	6.0	6.2	6.4	6.9	7.4	78
Number of foggy days	0,7	0,7	1	3	7	6	36
Average month and annual wind rate (m/sec)	3.5	3.3	3.6	4.1	4.3	4.6	4.1

WIND SPEED (M S^{-1}) FREQUENCY IN GRADATIONS (%). ANNUAL

0-1	***2-3***	***4-5***	***6-7***	***8-9***	***10-11***	***12-13***	***14-15***	***16-17***	***18-20***	***21-24***
20.2	27.0	24.7	15.5	8.4	2.7	1.0	0.1	0.3	0.02	0.005

WIND DIRECTIONS AND CALMS (%). ANNUAL

N	***NE***	***E***	***SE***	***S***	***SW***	***W***	***NW***	***Calm***
8	11	22	8	7	12	21	11	10

Wind rate with excess possibility of 5% is 9 m s^{-1}.

Average month maximal air temperature for the hottest month (July) is 27.2 ^{0}C.

Average temperature of the coldest part of the year is –16.7 ^{0}C.

Vegetation

The region is located near the south boundary of the forest-steppe zone, where south alkaline blackearths and normal blackearths are found. In areas of alluvial land there are loamy sand soils. Deciduous forests are found in valley flats and separating ridges. The rest of the area is occupied with ploughed fields and farming lands. Relicts of forb step vegetation are kept only in the tops and slopes of hollows and ravines.

Steppe vegetation within and around the site is presented by Achillea millefolium L. (milfoil), Trifolium medium L. (clover), Verbascum nigrum L. (mullein black), Betonica officinalis L., Euphorbia seguieriana Neck. (spurge), Falcaria vulgaris Bernh., Plantago stepposa Kurp. (plantain), Gypsophila altissima L., Origanum vulgare L. (origan), Melampyrum arvense L., Artemisia service Web. (sagebrush). Grassland vegetation is presented by Vicia tenuifolia Roth., Salvia stepposa Schost. (sage), Malva excisa Rchb. (mallow), Silene vulgaris Garcke., Veronica longifolia L., Verbascum nigrum L., Melampyrum arvense L. Drinage mounds on the site are covered mainly with Artemisia sericea Web. Barley, wheat, oat, buckwheat, sunflower and various forage herbs are usually seeded on the fields around the site.

Oak, birch, linden (lime), poplar, asp, ash (Fraxinus excelsior L.), sycamore maple (Acer platanoides), acacia and such bushes as pussywillow and donnik grow up within the territory of the site and around it. Two apple trees (Malus silvestris Mill.) are within restricted zone of the site. The slopes of the hills both sides of the hollow on the site are covered with trees (mainly maples and oaks). Lombardy poplars were planted along both sides of the site entering road in Clear Zone and acacia was planted around asphalted areas within Restricted Zone.

Wild animals such as boar, elk, goat are rare, but there are marmots, foxes and hares, as well as beavers. Recently beavers have appeared on the river and now the population is about 200 animals. In summer quail fly in and spawn, wild ducks also can be found on the river ponds. Crucian, gudgeon and roach can be found in the River Kurdyum and some ponds.

Human activity

The 5 km-radius control area around the site includes several settlements: Doktorovka hamlet, Kurdyum village, Shevyrevka hamlet and some dachas. All settlements, as well as the site, have water-supply sources for various purposes. Human activity affects the hydrological situation and determines the exposure pathways for the public, and should be taken into account in safety assessment.

There is an industrial water supply well on the site. The water from the well is used for water supply to the fire tanks and for technical purposes: mechanism and equipment deactivation, personal sanitation, use in the heating system. The drinking water is transported from outside in hermetic cans.

Kurdyum village is the largest settlement in the vicinity of the site. Its population is about 600 people. There is the main farmstead of the “Raduga” agricultural enterprise (the former collective farm Kirov), cattle farms with 150 cows and a pig farm with 100 pigs, mechanical threshing-floor, agrimotor station, milk processing complex and a granary located in the village. There are also about 300 geese and ducks, 750 sheep, 200 pigs and 193 cows at family households. Kurdyum is the biggest water consumer near the site: about 203 000 m^3y^{-1}, including 152 000 m^3 for industrial use and 49 900 m^3 for public and watering. The water from Aptian aquifer (6 wells in total 4 in use), perched water (drawwells) and surface water (Kurdyum-creek, Kurdyum-river, ponds) is used for these purposes.

There are four water supply wells (80–130 m depth) and four drawwells of 8-14 m depth in use in Kurdyum. There are also some drawwells, located near the river bank with a depth up to 4 m, but they are not usually maintained.

Kurdyum village is located 2.5 km to the west-northwest from the site (upstream). Two major water supply wells and a water tower are located on the hill near the entrance to the village on the left bank of the river. The wells are about 100m deep. This part of the village is completely supplied with water by these wells. The water from the water tower reaches the houses by the pipeline. One further well is located near the farms at ae distance of 3 km from wells mentioned above, also on the left bank. Its depth exceeds 100 m. The water is used in cattle farms and houses of the western part of Kurdyum-village. Three cascaded ponds are arranged not far from these farms. They are supplied by the springs and redundant water outflow to the River Kurdyum by the farms and irrigated kitchen gardens.

A further well (its depth is about 80 m) and two drawwells (8 and 12 m depth) are used for the water supply of another part of the village on the right bank.

Two more wells on the right bank are the closest to the disposal site (around 2.5 km), but they are not in use.

The small separate part of the village on the right bank is 1.7 km to the southwest from the main part. There are no wells here, only two drawwells (the depth is 5–8 m) and a lake with a dam. The lake is water supplied with several springs. The lake discharge follows the Kolikhin ravine, then the Kurdyum creek and fall into the River Kurdyum. Crucian and gudgeon can be caught fishing here. A bee-garden (15 hives) is located on the banks of this lake. Up to 6 000 m^3 of river water is usually used for watering of 2 ha of land per season.

During the last three years the beavers (about 200 animals) have appeared on the river. They have created 6 dams, which are located upstream of Kurdyum village down to the hamlet Doktorovka. Their ponds are also used by villagers for raising geese, ducks, turkey-ducks and fishing.

Another water supply well of 45 m depth is located in the hamlet Doktorovka (population is about 15 humans), which is located 2 km to the north-northwest from the RADON site downstream. The water pumped out of Aptian aquifer is usually directed into an iron tank of 45–50 m^3 volume and then settled during a week before usage. It is used for domestic purposes (drinking, food preparation, cooking, washing), watering of vegetables and fruit trees, domestic animals drinking (2 cows, 40 pigs). Water consumption is about 250 m^3 per year.

In addition to aquifer water, Doktorovka villagers also use perched ground and river water. Three drawwells are located in the ravine behind the hamlet. The water from the dawwells is used for cooking and food preparation and watering of kitchen gardens. During rainfall and snow melting periods these drawwells as well as kitchen gardens in the ravine lowlands are usually flooded by the surface water bringing warp there. So, these drawwells are not used during winter-spring period because of melt water and silt, which usually accumulated there.

In the summer period, water from the River Kurdyum is used in Doktorovka mainly for watering of kitchen gardens, but sometimes also as drinking water for domestic animals. The river level decreases in summer, but does not dry up. Inhabitants of the village create a special dam near the river for accumulation of water and its consequent use for irrigation.

The river water in the summer period is also used by cottagers 1.5 km down the river from Doktorovka. An artificial channel is made for water accumulating in three cascade-arranged ponds. Medium-sized fish are found in these ponds (mainly crucian, gudgeon and roach) and are caught by local people. Three pump stations are located near dams for watering of about

3–4 hectares of kitchen gardens. The unwanted water is returned to the river via an offtake channel. For drinking and cooking purpose, cottagers use springs located in the river floodplain and floodplain meadow.

The hamlet Shevyrevka is located 4 km to the east-northeast from the disposal site. Now only twenty three people (mainly elderly people) live there. There is no well in the hamlet. Only one 10 m deep drawwell and a small water source (spring) are used for drinking, cooking and animal drinking (11 cows and 30 pigs). Average annual water consumption is about 400 m^3. The dam was made in the ravine to make a large pond. The water from the pond is used for kitchen garden watering. There are no fish in the pond. Some dachas with the total area of 150-200 hectares are also located close to Shevyrevka.In summer cottagers use the same water sources as people from the hamlet.

Most villagers are self-employed at their households. Only a few people from Kurdyum work at the nearest towns (14 in Saratov and 25 in Tatishchevo). About 150 people in Kurdyum work for the “Raduga” agricultural enterprise and another local factory.

The “Raduga” farmlands are about 2 400 ha. “Raduga” grows barley, wheat, oats, buckwheat, sunflower on these fields and grows forage herbs (koster, eskarcet) on about 200 ha in the vicinity of the site.

The private/individual Andreev farm specializes in sunflower growing and producing sunflower oil for sale not only within Saratov region but further a field.

Most people grow onions for sale (mainly to persons travelling through the region). They grow other vegetables (potato, carrot, tomato, cucumber etc.) mainly for their own consumption and the only agricultural surplus is usually sold within the neighbourhood and sometimes in Saratov. Some families specialize in pig breeding (up to 20 animals). Meat, milk, eggs are usually used from their own property or bought/bartered within the neighbourhood.

There are also 83 beehives in Doktorovka and 15 hives in Kurdyum. In summer people also pick mushrooms, strawberries, raspberries around the site.

The site relief and its hydrological conditions make this area unattractive for individual housing. The elevation drop on the site is about 30 m; there is no water source on the site; the first aquifer is at a depth of 70–100 m. There are a lot of areas within 2–3 km around the site that are flatter and located closer to the river, 80–100 m lower than the site level and therefore much closer to the aquifer water source. Agricultural activity is unlikely to take place on the site without previous levelling (land grading). Taking into account that there are a lot of nearby flat areas, such expensive work is unlikely to be undertaken. At the same time the availability of the industrial water supply well means that it is not possible to exclude the use of the site for animal husbandry in future.

Radioecological control and previous safety assessment results

Monitoring of Ra-226 migration in soil from the trenches has been carried out since the time of waste emplacement. The Ra-226 content in these tests is lower than can be measured. The Ra-226 migration into soil has not been detected.

The analysis of ground 1 m under the disposal units, made in 1998 using inclined well drilling and ground sampling, have not shown any radionuclide contamination. Moisture content is the same value as for natural conditions 5 m from the vault.

The gamma dose rates on the surfaces of the closed vaults (without cap) do not exceed 0.2–5.0 mR h^{-1}.

Once a quarter, the Radiological Department of the Regional Sanitary-Epidemiological Station carries out sampling of environmental media: soil, ground, water, precipitation and aerosols as well as vegetable samples from the Sanitary Protective Zone. Cs-134 and Cs-137 specific activity has in all measurements been found to be below 1 Bq g^{-1}. Measured values were at or below the detection limits of the measurement methods. From these measurements it can be said that there is no evidence of elevated caesium levels at the site.

No influence of the facility on water-supply sources in the nearby communities has been detected.

A preliminary safety assessment was made in 1995 using geological, hydrogeological, and sorption property data from the literature. Cs-137, Sr-90 and Co-60 were used as indicators. It was assumed that these radionuclides from the wastes completely dissolved into accumulated water, migrates into the host rock and infiltrates down to the aquifer. The depth of contamination was determined comparing calculated values of specific activity with the limits for low level wastes adjusted by Russian regulations NRB 76. It was supposed that all disposal units are located within loam with low permeability and high sorption properties. It was calculated that underlying loamy layer deeper than 5–10 cm will be contaminated with radionuclides mentioned above less than it is limited by norms in use and can be considered as “clean”. The aquifer 70 m deeper was found “protected” from contamination, people using this water for drinking and domestic purposes were considered as “protected” too and the facility was declared as “safe”.

After additional field and laboratory investigations were carried out, the geological structure of the site, chemical and radionuclide composition of real contaminated water, filtration and sorption properties of the host sediments were obtained, the next iteration of preliminary safety assessment was made in 1997. This time concentration of contaminated water was assumed to be 10^4, 10^5, 10^6 Bq l^{-1} due to results of inspection of Russian RADON facilities. Sixteen facilities were operated for more than 30 years and nowhere, including this site, specific activity of accumulated water exceeds 10^4 Bq l^{-1}. Calculations made for timeless infiltration of contaminated water resulted in 25 cm contaminated underlying loamy layer with specific activity higher than it is determined for low level waste by NRB-96. Full-scale field tests showed that in case of infiltration of a 3 m column of real contaminated water the depth of contaminated soil did not exceed 17 cm.

After that, additional geological and hydrogeological data were obtained, and the inventory re-assessed and a significant amount of long-lived radionuclides was found in the disposal units.

2.3. DEVELOPMENT AND JUSTIFICATION OF SCENARIOS: FIRST ITERATION

The RADON Test Case Group considered a number of alternative approaches to scenario development. Given the resource constraints of the test case, it was decided to develop some simplified approach based mainly on expert judgment and evaluation of scenarios using the ISAM FEPs list.

Generally, a scenario can be considered as a hypothetical sequence of processes and events leading to human exposure, and is one of a set devised for the purposes of illustrating the range of future behaviours, for the purposes of evaluating a safety assessment. Scenarios are intended to portray alternative future states of the system.

In preparing a safety assessment, the objective of the scenario development is to establish the framework for calculating the radiological consequences, taking into account the uncertainties related to the system components, for the different combinations of events, processes and features which have the potential to impair the capabilities of the disposal system to confine the waste.

Scenarios depend on the environment and disposal system characteristics and on events and processes that could initiate release of radionuclides from waste or influence their fate and transport in the environment. When analysing data available on the detailed system description, analyst keep in mind some preliminary scenarios or their components. The more data that are available on scenarios that are generated, the more credible they are. The list of possible scenarios seems to be limited only by the imagination of the analyst. As a result, the first step of the safety assessment (assessment context) helps to focus efforts in this regard. Attention must focus on waste inventory, disposal unit designs and engineered barriers, transport properties of geological surrounding, and human activity. Human activities must be accounted for that could affect the disposal system directly, and also those that determine possible exposure pathways.

The detailed description of the site, disposal units and waste forms cover all elements of engineered barriers. The process of compiling the detailed description permits identification of the main elements of the engineered barrier system, and the beginning of identification of possible failure modes. While analysing these data, mechanisms of possible radionuclide release from the wastes into the surroundings under normal conditions as well as for possible human activities associated with intrusion can be identified. Such assumptions could generate distinct scenarios if they are considered to be of sufficient concern (especially if the aim of safety assessment is improvement, testing or comparing of different disposal unit designs). While engineering barriers are acknowledged to be very significant to safety, natural barriers also play a significant role for long term safety of LILW disposal.

Analysis of the geological surroundings permits identification of possible transport routes for radionuclides from the disposal facility to humans. Additional natural characteristics, such as surface morphology and site location, may additionally determine the distance between the source term and the recipient, as well as the main pathways for release and transport. This analysis also identifies any natural disruptive events, such as erosion, earthquake etc., potentially relevant for the site. In analysing these data, additional scenarios or sub-scenarios important for the assessment can be identified.

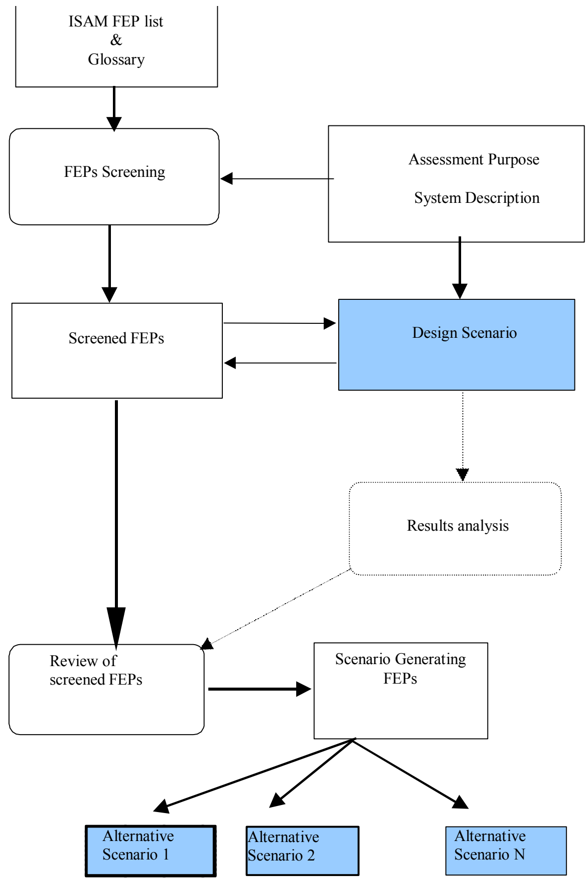


FIG. 35. The RADON Test Case Scenario Generating Approach.

The biosphere is the next main element in the safety assessment, following engineered barriers and the geosphere, which should be described in detail and analysed by the assessor. These data describe assumptions about human locations and activities relative to the waste as a source term. On the one hand, humans are possible recipients of exposure, but on the other hand they can affect the disposal system. In analysing potential human activities, both intrusive and non-intrusive, both on-site and off-site scenarios can be generated. Additional scenarios can also be determined in some cases by national regulations or specific requirements, such as consideration of airplane crashes, meteorite fall etc. Generating preliminary scenarios cannot be avoided while analysing the detailed system description even when this activity still remains informal and is done implicitly. The basis of the approach adopted by the RADON Test Case participants was developed at the first meeting of the Group and is illustrated in Fig. 35.

— Screen the ISAM FEPs list on the basis of the assessment context and system description. Record the justification for excluding any FEPs from further consideration. Identify additional FEPs related data to be obtained, clarified or substantiated;
— Develop and agree a simplified Design Scenario as the main case of the safety assessment. In common with the Vault Test Case, the Design Scenario is considered to represent how the system might be expected to evolve assuming the design functions as planned;

— Obtain and check the necessary data, screen the FEPs list, and review the Design Scenario. Compare the FEPs involved in the Design Scenario against the screened FEP list;
— Make preliminary calculations on the Design Scenario. Identify safety-relevant FEPs. Screen unrecorded FEPs and select scenario-generating FEPs; and
— Identify a limited number of representative alternative scenarios rather than comprehensively identify every possible alternative scenario by revisiting the screened ISAM FEPs list, especially focusing on the external FEPs.

2.3.1. Screening of FEPs

An initial screening of a FEP list based on the ISAM FEPs list was conducted using expert judgement (see Table 30). Information from the assessment context and system description was used as input to the screening process. Four categories of excluded FEPs were identified based on the following criteria:

(a) FEPs that are clearly not relevant to the assessment. There should be no argument about the exclusion of these FEPs. An example of this category of screened FEP for the RADON Test Case is the exclusion of FEPs associated with discharge to a marine environment;
(b) FEPs that are not relevant because of the chosen assessment context. These FEPs might potentially be important in the future, if other assessment contexts are applied. An example is collective dose, which is not relevant because the current assessment context only requires consideration of individual dose;
(c) FEPs that are not considered to be important. The lack of importance may be the result of the type of disposal system considered, or because other FEPs have been judged to be more important for overall system performance. Inclusion in this set of FEPs is more judgmental than the first two exclusion categories; and
(d) FEPs that are not considered because there is no information about them, and for which it is unreasonable to expect information to be available for the assessment. Inclusion in this set of FEPs is the most judgmental of the four.

The results of this process are documented in Table 30. Care has been taken to document the reason for screening FEPs. The FEPs listed as “Considered” are the only ones that are carried forward beyond this point.

An additional step was taken in screening the FEPs in which similar FEPs were combined together.

TABLE 30. SCREENED FEP LIST FOR THE RADON TEST CASE

0. Assessment context

For the purpose of the subsequent safety assessment, FEPs at a lower level than assessment context have been included in this single category

1	**External factors**
1.1	Repository issues
1.1.01	Site investigation
1.1.01.02	Site context/*Considered. See Test Case Description.*
1.1.01.03	General climate description/*Considered. See Test Case Description.*
1.1.01.04	General biosphere description/*Considered. See Test Case Description.*
1.1.01.05	Environments: Natural and Semi-natural/*Considered. See Test Case Description.*
1.1.01.06	Agriculture/*Considered. See Test Case Description.*
1.1.02	Excavation/construction
1.1.02.01	Defects in disposal system (barriers, cover, etc.)/*Considered. See Test Case Description.*
1.1.02.02	Excavation of trenches, holes, vaults/*Considered. See Test Case Description.*
1.1.02.03	Construction of walls, floors, mounds, layers of mounds/*Considered. See Test Case Description.*
1.1.03	Emplacement of wastes and backfilling
1.03.01	Methods and schedule of emplacement/*Only considered to the extent of decaying the inventory. Other considerations are not relevant for past disposals.*
1.1.04	Closure
1.1.04.01	Capping/*Considered. See Test Case Description.*
1.1.07	Repository design
1.1.07.01	Repository type/*Considered. See Test Case Description.*
1.1.08	Quality control
1.1.08.01	Defects in disposal system (barriers, cover, …)/*Considered in the assessment of the current status of the repository.*
1.1.10	Administrative control, repository site/*Considered. See Test Case Description*
1.2	Geological processes and effects
1.2.01	Tectonic movements and orogeny
1.2.01.01	Tectonic effects

There is lifting of the territory with 1 mm/year rate (from literature). This may lead to changing of the erosion base and to a revival of the erosion

1.2.07	Erosion and sedimentation
1.2.07.01	Erosion/Considered. Rain wash, sedimentation and gullying
1.2.07.03	Sedimentation
1.3	Climatic processes and effects
1.3.02	Climate change, regional and local/*Considered*, *to the extent of considering their influences on average behaviour.*
1.3.02.01	Periglacial effects
1.3.04.02	Strong seasonal influences

Altered seasonal influences associated with climate change are not considered. Seasonal influences with today's climate are considered

1.3.07	Hydrological/hydrogeological response to climate changes/*Considered to the extent of seasonal influences.*
1.3.07.03	Change in regional infiltration/*Considered*.
1.4	Future human actions (active)
1.4.04	Drilling activities (human intrusion) / *Based on the assessment context, the different types of drilling intrusion are seen to be irrelevant, since they pertain mainly to the probability of drilling intrusion. Consequently, they have been lumped into a single FEP. This FEP is a potential scenario-generating FEP.*
1.4.04.01	Exploratory and/or exploitation drilling for natural resources and raw materials/*Considered*.

According to performed exploration study there is no any natural resources in the confines of the Site

1.4.04.02	Water well drilling/*Considered*.
1.4.04.03	Drilling for research or site characterization studies/*Considered*.
1.4.04.04	Drilling for waste injection;/*Considered*.

This seems to be unlikely

1.4.04.05	Drilling for hydrothermal resources/*Considered*.

Impossible

1.4.06	Surface environment, human activites
1.4.05.01	Surface excavations

For the purposes of this assessment, all types of potential surface excavations will be lumped into this single category. There are likely to be differences in the types of exposure pathways that would result from the occurrence of these FEPs. This is an issue that may need to be dealt with in a future iteration of the safety assessment.

1.4.06.01.02 Excavation for construction/*Considered*.

1.4.06.01.03 Residential, industrial, transport and road construction/*Considered*.

1.4.06.01.05 Drainage/*Considered*.

There may be only drainage for facility's needs

1.4.06.01.07 Land reclamation/extension/*Considered*.

1.4.06.01.09 Soil fertilization/*Considered*.

1.4.06.01.11 Earthworks/*Considered*.

1.4.06.01.13 Ploughing/*Considered.*

1.4.06.03 *For the purposes of this assessment, all types of potential site development activities will be included into this single category. There are likely to be differences in the types of exposure pathways that would result from the occurrence of these FEPs. This is an issue that may need to be dealt with in a future iteration of the safety assessment.*

1.4.06.03.01 Construction of roads, buildings, dams, etc./*Considered*.

1.4.06.03.02 Levelling of hills (airport lay out,…)/*Considered.*

1.4.06.03.03 Site occupation/*Considered*

1.4.06.03.04 Human modification of the site drainage/*Considered* 1.4.06.03.05 Levelling/*Considered*

1.4.06.03.06 Land reclamation/*Considered* 1.4.07 Water management (wells, reservoirs, dams)

1.4.07.01 Extraction of contaminated water from aquifer via a well/*Considered*

1.4.07.02 Waterworks/*Considered*

1.4.07.03 Intentional artificial groundwater recharge/discharge by humans/*Considered*

1.4.07.07 Irrigation/*Considered* 1.4.07.09 Human effects on water potential/*Considered*

1.4.07.10 Water extraction for irrigation/*Considered* – Unlikely

2 Disposal system domain: environmental factors

2.1 Wastes and engineered features

2.1.01 Inventory, radionuclide and other material

2.1.01.01 Radionuclide content/*Considered*.

2.1.02 Waste form materials and characteristics

2.1.02.02 Subsidence/*Considered*.

2.1.03 Container materials and characteristics

2.1.03.01 Interaction of container with pore water

2.1.03.01.01 Matrix corrosion/*Considered*

2.1.03.01.02 Gas generation/*Considered*

2.1.03.02 Interaction of waste with container

2.1.03.02.02 Gas generation/*Considered*

2.1.03.03 Fracturing of concrete components caused by hydraulic change/*Considered*

2.1.04 Buffer/backfill materials and characteristics

2.1.04.01 Reduction in flow through structures due to grouting/*Considered*

2.1.04.03 Interaction of backfill with pore water

2.1.04.03.04 Effect of chelating agents/*Considered*

2.1.04.03.05 Colloid formation/*Considered*

2.1.05 Engineered barrier system

2.1.05.01 Caps/*Considered*

2.1.05.03 Interaction of vault materials with pore water

2.1.05.03.01 pH change/*Considered.*

2.1.05.03.02 Redox potential change/*Considered*

2.1.05.04 Interaction of vault materials with host groundwater

There is no a contact with host groundwater, only porous waters

2.1.05.04.01 Chloride attack/*Considered*.

2.1.05.04.02 Sulphate attack/*Considered*.

2.1.05.04.03 Carbonation/*Considered*.

2.1.05.05 Fracturing of concrete components caused by hydraulic change/*Considered*.

2.1.05.06 Mechanically induced processes/*Considered*.

2.1.05.07 Differential behaviour of joints/*Considered*.

2.1.05.08 Cover degradation/*Considered*.

2.1.06 Other engineered features materials and characteristics

2.1.06.02 Trenches, holes, vaults/*Considered*

2.1.06.03 Walls, floors, mounds, layers of mounds/*Considered*

2.1.07 Mechanical processes and conditions (in wastes and EBS)

2.1.07.01 Container collapse/*Considered*

2.1.07.03 Material volume changes/*Considered*

2.1.07.04 Tunnel roof or lining collapse/*Considered*

2.1.07.05 Container movement/*Considered Voids between the containers are supposed to be filled with concrete*

2.1.07.06 Subsidence as a result of compression of waste and cover layers/*Considered*

2.1.07.07 Fracture formation in vault, backfill, joints, cover materials, host geology (local fractures)/*Considered*

2.1.08	Hydraulic/hydrogeological processes and conditions (in wastes and EBS)
2.1.08.01	Infiltration and movement of fluids in the repository environment/*Considered*
2.1.08.02	Restoration/desaturation of the repository or its components/*Considered*
2.1.08.03	Water flow and contaminant transport paths within the repository/*Considered.* Only diffusion
2.1.08.07	Failure of cap/cover/*Considered*
2.1.08.08	Failure of the joints/*Considered*
2.1.08.09	Bathtubbing/*Considered*
2.1.08.10	Fracturing of concrete components/*Considered*
2.1.08.11	Effect of cap+cover+backfill/*Considered*
2.1.09	Chemical/geochemical processes and conditions (in wastes and EBS)
2.1.09.01	Chemical interaction of waste with pore water/*Considered*
2.1.09.01.01	Metallic corrosion processes (general and pitting)/*Considered*
2.1.09.02	Chemical interaction of containers (including overpacks) with pore water
2.1.09.02.01	Metallic corrosion/*Considered*
2.1.09.05	Chemical interaction of backfill with pore water
2.1.09.05.01	pH changes/*Considered*
2.1.09.05.02	Redox changes/*Considered*
2.1.09.06	Chemical interaction of vault materials with pore water
2.1.09.06.01	pH changes/*Considered*
2.1.09.06.02	Redox potential changes/*Considered*
2.1.09.07	Chemical interaction of vault materials with host groundwater

There is no a contact with host groundwater, only porous waters

2.1.09.07.01	Carbonation/*Considered*
2.1.09.07.02	Chloride attack/*Considered*
2.1.09.07.03	Sulphate attack/*Considered*
2.1.11	Thermal processes and conditions (in wastes and EBS)
2.1.11.01	Radiogenic, chemical and biological heat production from the wastes/*Considered.* Important for SSS
2.1.12	Gas sources and effects (in wastes and EBS)
2.1.12.01	Explosion

May be possible for SSS storage without matrix

2.1.12.03	Gas generation
2.1.12.03.01	Corrosion/*Considered*

2.1.12.03.02	Decomposition of organic matter (microbial)/C*onsidered*
2.1.13	Radiation effects (in wastes and EBS)
2.1.13.02	Radiolysis /Possible for SSS
2.1.13.03	Decay product gas generation/*Considered*
2.2	Geological environment
2.2.01	Excavation disturbed zone, host rock/*Considered*
2.2.01.02	Altered hydraulic properties/*Considered*
2.2.02	Host rock/*Considered*
2.2.02.01	Thermal and hydraulic conductivity/*Considered*
2.2.02.03	Porosity/*Considered*
2.2.03	Geological units, other
2.2.03.01	Non-uniform stratigraphy /*Considered*
2.2.03.02	Heterogeneity/*Considered at a coarse level. More detailed data are not available.*
2.2.05	Contaminant transport path characteristics (in geosphere)
2.2.05.01	Fracture flow/*Considered in the primary fractured limestone aquifer.*
2.2.07	Hydraulic/hydrogeological processes and conditions (in geosphere)
2.2.07.02	Darcy flow/*Considered*
2.2.07.04	Fracture flow/*Considered in the limestone formation.*
2.2.07.05	Saturated/unsaturated conditions/*Considered*
2.2.07.06	Aquifer (groundwater) discharge/recharge (e.g. well)/*Considered.*
2.2.07.07	Infiltration/*Considered.*
2.2.07.08	Channeling and preferential flow pathways/*Considered.*
2.2.07.09	Flow direction/*Considered*
2.2.07.10	Flow between two aquifers/*Considered.* Interesting for discussion. It may be near the river
2.2.07.11	Groundwater discharge to surface water, Soil, Estuary, Seas, Wells/*Considered.*
2.2.08	Chemical/geochemical processes and conditions (in geosphere)/*Considered.*
2.2.08.02	pH change/*Considered.*
2.2.08.03	pH effects of cement on the environment, soil, etc./*Considered.*
2.2.08.04	Redox potential changes/*Considered.*
2.3	Surface environment
2.3.01	Topography and morphology/*Considered*
2.3.02	Soil and sediment/*Considered*
2.3.02.01	Soil and sediment development/*Considered*

2.3.02.02	Soil conversion/*Considered*
2.3.03	Aquifers and water-bearing features, near surface/C*onsidered*
2.3.04	Lakes, rivers, streams and springs
2.3.04.01	Stream flow-/*Considered*
2.3.07	Atmosphere/*Considered.*
2.3.07.01	Physical transport of gases/*Considered.*
2.3.07.02	Aerosols and dust in the atmosphere/*Considered.*
2.3.07.04	Vegetation
2.3.08.01	Chemical changes caused by plants/Of potential importance, but a secondary effect. Will be neglected for this iteration.
2.3.09	Animal populations
2.3.09.01	Animal diets/*Considered.*
2.3.09.02	External contamination of animals/*Considered.*
2.3.10	Meteorology
2.3.10.01	Rainfall/*Considered.*
2.3.10.02	Snowfall/*Considered.*
2.3.10.03	Flooding related to high precipitation/*Considered.*
2.3.10.05	Seasonality/*Considered.*
2.3.10.06	Climate fluctuation/*Considered.*
2.3.10.06.01	Dew-freezing cycles/*Considered.*
2.3.10.06.02	Wet-dry cycles/*Considered.*
2.3.10.08	High rainfall / Flooding/*Considered.* It seems as impossible
2.3.11	Hydrological regime and water balance (near-surface)
2.3.11.01	Groundwater discharge to surface water, soils, estuaries/marines/*Considered.*
2.3.11.04	Evaporation /*Considered.*
2.3.11.05	Evapotranspiration/*Considered.*
2.3.11.06	Infiltration/*Considered.*
2.3.11.07	Water discharge/recharge processes that effecting radionuclide content/*Considered.*
2.3.12	Erosion and deposition
2.3.12.01	Deposition
2.3.12.06	Erosion of cover/*Considered*
2.3.12.07	Agriculture erosion/*Considered.* At the Site
2.3.12.08	Land sliding /*Considered*
2.3.12.09	Erosion/*Considered*
2.3.13	Ecological/biological/microbial systems

2.3.13.01	Ecological and biological features/*Considered.*
2.3.14	Animal/Plant intrusion
2.3.14.02	Burrowing animals/*Considered.*
2.3.14.03	Bio-intrusion by plants and animals/*Considered.*
2.3.14.04	Animal intrusion/*Considered.*
2.3.14.05	Root intrusion/*Considered.*
2.4	Human behaviour
2.4.01	Human characteristics (physiology, metabolism)/*Considered.*
2.4.03	Diet and fluid intake/*Considered.*
2.4.04	Habits (non-diet-related behaviour)/*Considered. The Site is not acceptable for population in the period of institutional control*
2.4.04.01	Resource usage/*Considered.*
2.4.04.02	Storage of products/*Considered.*
2.4.04.03	Air filtration/*Considered.*
2.4.04.04	Ventilation/*Considered.*
2.4.04.05	Location of shielding factors/*Considered.*
2.4.05	Community characteristics/*Considered.*
2.4.05.01	Demographic changes/*Considered.*
2.4.05.02	General human society description/*Considered.*
2.4.07	Dwellings
2.4.07.01	Construction of buildings, houses/*Considered.*
2.4.07.02	Site occupation/*Considered.* No occupation
2.4.07.03	Ventilation/*Considered.*
2.4.07.04	Location and shielding factors/*Considered.*
2.4.09	Rural and agricultural land and water use (incl. Fisheries2.4.09.01 Use of land for agriculture/*Considered.*
2.4.09.01.01	Ploughing/*Considered.*
2.4.09.01.02	Fertilization/*Considered.*
2.4.09.02	Land use change/*Considered.*
2.4.10	Urban and industrial land and water use/ Co*nsidered.*
2.4.10.01	Water works/*Considered.*
2.4.10.02	Urban and industrial environments / *Considered.*
2.4.10.03	Human water extraction /*Considered.*
2.4.10.04	Water extraction through wells /*Considered.*
2.4.10.05	Water extraction for irrigation /*Considered.*
2.4.10.06	Radionuclide/contaminant factors

3.1	Contaminant characteristics
3.1.01	Radioactive decay and in-growth /*Considered.*
3.1.01.01	Production of aqueous progeny / *Considered.*
3.1.01.02	Radon emanation /*Considered.*
3.1.03	Inorganic solids/solutes / *Considered*
3.1.03.01	Source terms content /*Considered.*
3.1.04	Volatiles and potential for volatility /*Considered.*
3.1.05	Organics and potential for organic forms /*Considered.*
3.1.05.01	Source term content /*Considered.*
3.2	Contaminant release/migration factors
3.2.01	Dissolution, precipitation and crystallization, contaminant /*Considered.*
3.2.01.01	Chemical reactions caused by dissolution and precipitation of radionuclides/*Considered.*
3.2.02	Speciation and solubility, contaminant /*Considered.*
3.2.02.01	Solubility / *Considered.*
3.2.02.02	Solubility change caused by chemical interaction between waste and pore water / *Considered.*
3.2.03	Sorption/desorption processes, contaminant / *Considered.*
3.2.03.01	Sorption /*Considered*
3.2.03.02	Effect of sorption / *Considered.*
3.2.03.02.01	Caused by chemical interaction of waste with pore water /*Considered.*
3.2.03.03	Chemical reactions caused by adsorption or desorption / *Considered.*
3.2.04	Colloids, contaminant interactions and transport with / The colloid transport may not be considered in a certain porous medium due to its quick sedimentation
3.2.04.01	Colloid transport /*Considered*
3.2.04.02	Colloid formation / *Considered*
3.2.04.02.01	Caused by chemical interaction of waste with pore water /*Considered*
3.2.04.02.02	Caused by chemical interaction of backfill with pore water /*Considered*
3.2.04.02.03	Caused by chemical interaction of non-radioactive waste with radioactive waste /*Considered*
3.2.05	Chemical/complexing agents, effects on contaminant speciation/transport / *Considered*
3.2.05.01	Effects of chelating agents/*Considered*
3.2.05.01.01	Caused by chemical interaction of waste with pore water /*Considered*
3.2.05.01.02	Caused by chemical interaction of backfill with pore water /*Considered*
3.2.05.01.03	Caused by chemical interaction of non-radioactive waste with radioactive waste /*Considered.*

3.2.07	Water-mediated transport of contaminants
3.2.07.01	Advection/*Considered.*
3.2.07.02	Molecular diffusion /*Considered.*
3.2.07.03	Dispersion /*Considered.*
3.2.07.04	Matrix diffusion /*Considered.*
3.2.07.05	Percolation, i.e. movement of the fluid under gravity / *Considered.*
3.2.07.07	Surface water aqueous transport / *Considered.* Depends on flooding, run-off + colloids
3.2.07.08	Transport by surface run-off / *Considered.* Only in a case of release upon a surface
3.2.07.09	Transport in water bodies /*Considered.* If the contaminants reach the bodies
3.2.07.10	Capillary rise /*Considered.*
3.2.07.11	Groundwater transport /*Considered.* If the contaminants reach the aquifer
3.2.07.12	Infiltration /*Considered.*
3.2.07.13	Dual flow systems /*Considered.*
3.2.07.14	Transport of suspended sediment /*Considered.* Only in a case of release upon a surface
3.2.07.15	Transport of colloids /*Considered.* Only in a case of release upon a surface with run-off
3.2.07.16	Transport processes between surface water and porous media /*Considered.*
3.2.07.21	Fracture-matrix interaction /*Considered*.
3.2.08	Solid-mediated transport of contaminants
3.2.08.01	Transport by suspended sediments (sedimentation)/*Considered*.
3.2.08.02	Erosion /*Considered*.
3.2.08.03	Solid material release /*Considered*.
3.2.08.04	Solid phase transport by water /*Considered*.
3.2.08.05	Resuspension/deposition / *Considered*.
3.2.08.06	Land slides /*Considered*.
3.2.08.07	Rock falls /*Considered*. This phenomenon seems to be unlikely in this area
3.2.08.08	Rain splash /*Considered*
3.2.08.09	Washout / *Considered.*
3.2.08.10	Wet Deposition / *Considered*.
3.2.09	Gas mediated transport of contaminants / *Considered*.
3.2.09.01	Gas mediated water flow / *Considered*.
3.2.09.02	Gaseous release / *Considered*.
3.2.09.03	Atmospheric gas transport / *Considered*.

3.2.09.04	Atmospheric aerosol transport / *Considered*.
3.2.09.05	Gas phase processes / *Considered*.
3.2.09.05.01	Diffusion / *Considered*.
3.2.09.05.02	Barometric pumping / *Considered*.
3.2.11	Animal, plant and microbe mediated transport of contaminants / *Considered*.
3.2.11.01	Discharge of radionuclides to soil layer (biotic intrusion) / *Considered*.
3.2.11.02	Transport mediated by flora and fauna / *Considered*.
3.2.11.02.01	Uptake and desorption / *Considered*.
3.2.11.02.02	Bioturbation / *Considered*.
3.2.11.02.03	Intake and emission by animals / *Considered*.
3.2.11.03	Animal/Plant intrusion / *Considered*.
3.2.12	Human-action-mediated transport of contaminants / *Considered*.
3.2.12.02	Ploughing /*Considered*.
3.2.13	Foodchains, uptake of contaminants in
3.2.13.01	Crops and natural and semi-natural flora and fauna / *Considered*.
3.2.13.02	Internal transfer of radionuclides within animals /*Considered*.
3.2.13.04	External contamination of animals / *Considered*.
3.3	Exposure factors
3.3.01	Drinking water, foodstuffs and drugs, contaminant concentrations in / *Considered*.
3.3.01.01	Crops and natural and semi-natural flora and fauna /*Considered*.
3.3.01.02	Internal transfer of radionuclides within animals / *Considered*.
3.3.02	Environmental media, contaminant concentrations in /*Considered*.
3.3.03	Non-food products, contaminant concentrations in / *Considered*.
3.3.04	Exposure modes / *Considered*.
3.3.04.01	Ingestion (internal exposure) /*Considered*.
3.3.04.02	Inhalation (internal exposure) / *Considered*.
3.3.04.03	External exposure / *Considered*.
3.3.04.05	Direct radiation from airborne plumes of radioactive materials /*Considered*.
3.3.04.08	External exposure through water or sediment / *Considered*.
3.3.04.09	Dermal exposure / *Considered*.
3.3.05	Dosimetry /*Considered*.
3.3.08	Radon and radon daughter exposure /*Considered*.
3.3.08.01	Radon emanation / *Considered*.
3.3.08.02	Radon subsurface transport / *Considered*.
3.3.08.03	Radon-progeny equilibrium /*Considered*.

2.3.2. Representation of FEPs and FEP interactions

The next step in the process was to link the screened FEPs into a coherent structure capable of being analysed. Effectively, this step involves developing a Process System Model and identifying the External FEPs acting on it. Formal approaches have been proposed for this step, which are intended to address increasing requirements on justification and traceability. Approaches that have been described in the literature for this step include: lists and tables [20]; influence diagrams; and the interaction matrix approach [21, 22].

For the RADON Test Case, the process system model was developed using professional judgement since time constraints did not allow more formal methods to be used. This procedure highlighted some important uncertainties relating to the system description and even the assessment context. It was decided to continue the assessment procedure recognising that it was a first iteration and additional data could be collated for use in future iterations.

Design scenario

Introduction

It is assumed that geosphere and biosphere conditions remain as they are at present. The design scenario supposes that the engineered barriers function according to their design. Even though this scenario is called the Design Scenario, no judgment should be made about the likelihood of occurrence of these conditions. Scenarios should be viewed simply as being illustrative of the possible future states of the system; they are not viewed as predictive. The design scenario is a high level description of the evolution of the engineering barriers and near field. This should also include a brief description of the most probable pathways and interactions between the geosphere and the biosphere.

Calculation results obtained according to this scenario should be considered as an indicator of facility safety. Fundamental assumptions adopted for the Design Scenario are listed below:

— Climate remains as present day conditions (FEPs 1.3, 1.4.01 from the ISAM FEPs list are screened out for the Design Scenario and all other scenarios).

— Total period of institutional control of 400 years (FEPs 1.1.05 and 1.1.10):

- 300 years of active institutional controls (e.g. to maintain the cap, monitor environmental performance, restrict access, etc.) for Design Scenario, as well as for the others,
- Further 100 years of passive institutional control (e.g. site location on official maps, land use restrictions, local informal knowledge about the site, etc.).

— Biosphere practices will be as present day.
— Design Scenario will not consider any human intrusion events (FEP 1.4 screened out).

Variations on these assumptions could be considered as alternate scenarios.

Operational period

The RADON Test Case only assessed post-closure safety. This section is included to clarify the status of the facility at the end of the operational period, which is considered as a starting point for safety assessment calculations. The site is built and operated as planned (FEPs 1.1.02, 1.1.03, 1.1.06, 1.1.07, 1.1.08, 1.1.09 and 1.1.11 assumed to be as planned). Although, there may be minor handling accidents these do not damage the vault structure or underlying materials, or any damage is made good (FEP 1.1.12).

As was mentioned in the assessment context and facility description, there are three types of disposal unit on the site: trenches, vaults and a borehole. During operations, the vaults are assumed to be covered by temporary roofs to minimize entry of precipitation water (rainfall, snowmelt etc.), completely filled vaults are covered by temporary caps. Three 200 m^3 vaults are supposed to be filled in and covered within eight years one after another, i.e. after 8, 16 and 24 years of operation. After closure of the third vault, the temporary caps over each vault are built up to form the joint final cap for these three vaults according to the design (FEP 1.1.04 closure as planned). The largest vault is supposed to be built 20 years after the commissioning of the facility and completely filled shortly before the end of operational period.

It is assumed that each trench is excavated, filled and covered with a final cap over a timescale of a few years.

The borehole is supposed to be in operation during the entire operational period.

It is supposed for that there is no water in any disposal unit at closure.

The whole site area is controlled to prevent animal and unauthorized human access (FEP 1.1.10). All site investigation and monitoring activities are managed to ensure no effect on post-closure performance (FEP 1.1.01 and 1.1.11).

At closure, the facility appears as several mounds with low gradient sides. The engineered drainage system around the mounds (special drainage canals filled in with gravel) are assumed to function for some time after closure.

Active institutional control period

Active site control is assumed to be maintained for a period of 300 years after the end of disposal operations. In this period, the site area is fenced and patrolled to prevent animal and unauthorized human access. Occasional short term unauthorized access may occur, but this is assumed to be not significant for the purposes of long term safety assessment.

The design of the cap will be effective in reducing infiltration water reaching the disposal units to an insignificant level. It also prevents animal intrusion into the disposal units. It is assumed that any burrowing animals are controlled by the site personnel. The condition of the cap will be monitoring and will be repaired as necessary. Radiological monitoring is also assumed to be ongoing for re-assurance purposes and control. Any containment failure detected will be repaired.

Some investigations may also be carried out at the site to obtain additional data for the final safety assessment prior to the finalisation of institutional control. All site investigation and monitoring activities are managed so as to ensure that they have no adverse effect on the performance of the disposal facility in the post institutional control period (e.g. monitoring boreholes are sealed and correctly closed) (FEP 1.1.01 and 1.1.11).

There will be pore water in the materials contained in the disposal units (e.g. waste, grout, concrete, etc). The saturation level will depend upon the water retention coefficients. Some moisture will enter and leave the disposal units as an unsaturated water flux and water vapour due to barrier and waste degradation.

Some degradation of the concrete walls and bottom of the vault, as well as the borehole will take place, as will corrosion of the stainless steel capsules of spent sealed sources in the borehole and its cylindrical vessel will have begun. Some corrosion of the steel drums in Vault C will also have begun as well as some small amount of degradation of the wastes within the drums. Much more degradation of the wastes is expected in Vaults A, B and D.

Passive institutional control period

After active control ends, local damage to the caps (e.g. due to animal intrusion, human activities, erosion etc.) will not be repaired. Infiltration through the cap will increase as it degrades. However, degradation of the concrete and waste during this time period is similar to the active period.

As noted earlier, during this passive control period there will still be institutional controls on land use (site usage and occupancy). This will prevent people living on the site and building houses. Road construction, mining and other industrial activities are supposed to be screened out for design scenario. Agricultural activity within the site is supposed to be excluded too for this period of time.

Post institutional control period

At some point the degradation of the cap, which began in the passive control period is assumed to result in the exposure of the trenches. For the purposes of the Design Scenario, this exposure event is assumed to be at the end of institutional control period (i.e. 400– years after the closure).

It is assumed that the cap over the vaults, which are located at the ravine bottom, will not completely disappear. Total cap fail and erosion may be considered within alternate scenarios.

There will be cracks and joints in the concrete constructions of the vaults and borehole so that water can contact the waste form. Thus corrosion of the drums and spent sealed sources and degradation of the wastes in affected sections of the vaults and in the borehole will proceed more rapidly and radionuclides will be leached from the waste.

At some time the waste, drums and concrete gradually become totally degraded. It is assumed that they will mix with the surrounding near surface geosphere and probably cap materials forming a heterogeneous mix.

Taking into account that the site is located on a hillside and the sedimentological layers below the site disposal unit, it is assumed that some part of the infiltration water flows down through the unsaturated zone and ends up in the underlying aquifer. It is assumed that near surface groundwater discharges occurs to the River Kurdyum and drawwells in Doctorovka. The aquifer is assumed to be used for supplying domestic areas via a water supply well in Kurdyum and Doctorovka. The direction and the value of water flow in the aquifer can be preliminary assumed to be consistent with water consumption in the two villages.

For the purposes of this safety assessment the Design Scenario assumes that there is no intrusion into the facility. Even after memory of the existence of the facility is lost, individual homes and dachas are unlikely to be built on the site. The site seems unattractive for individual housing because of its relief: the altitude drop on the site is about 30 m. There is no source of water on the site and the first aquifer is at a depth of 70-100m. At the same time there are a lot of free areas 2–3 km around the site with flatter relief, which are located near the river and much closer to the aquifer water supply. The safety is assessed for inhabitants of the nearest village (Doctorovka), 2.5 km from the site.

About 18.5 hectares of the site is currently arable land and about 28 hectares by pasture. Therefore some agricultural activity on the site is assumed to take place. At the same time the collection of mushrooms, raspberries, and the making of hay seems to be much more likely after the control is terminated.

Drinking water for individuals near the disposal facility will be assumed to be from an existing water supply well, which is derived from the primary aquifer. It will be assumed that individual homeowners may supplement their food intake from individual gardens. These individual gardens may become contaminated from contact with perched near-surface water as well as by irrigation with contaminated water from the aquifer, drawwells or river. Contaminated river water is supposed to be used for irrigation and to supply of drinking water for cows, contaminated soil and grass can also be ingested by cows.

2.3.3. Preliminary list of alternative scenarios

As mentioned earlier, alternative scenarios are identified after the Design Scenario is defined.

It is clear that the Design Scenario is only one possible variant of the future behaviour of the disposal system. Some alternative variants could be defined according to the list of scenario generating FEPs, obtained when screening the ISAM FEPs list. Most of them are usually considered for near surface facilities independent of the scenario generation method adopted for safety assessment.

General scenarios for a near-surface disposal facility may be divided into three groups: undisturbed performance (leaching, groundwater, gas generation); naturally disturbed performance (erosion, bathtubbing, earthquake, earth creep, frost heave, plant and animal intrusion); and inadvertent intrusion (construction, agriculture). All these cases should in general be considered for both on-site and off-site human residence. Combining these scenarios with the FEPs that have to be considered, the following groups of scenarios were identified:

(a) Variations of the design scenario without human intrusion for on-site and off-site situations with: leaching to and transport in groundwater and subsequent discharge into river, drawwells and use by humans;
(b) Variations of normal evolution scenario without human intrusion for on-site and off-site situations with: leaching to and transport through the unsaturated zone into the aquifer and subsequent discharge into wells and use by humans for domestic and agricultural purposes; biotic intrusion could be included;
(c) Human intrusion scenarios resulting in exposure of intruders and off-site dwellers who farm on the contaminated land. Surface construction and site development (e.g. drilling with intrusion and post-intrusion dose, road construction with intrusion and post-intrusion dose, house building with intrusion and post-intrusion dose, use of vault as house foundation);
(d) Flooding associated with high precipitation;
(e) Erosion-accretion; and
(f) Societal changes.

These groups of scenarios are considered to cover all previously discussed features of the disposal facility and site and a review of the literature shows that such scenarios are in accordance with other referenced assessments dealing with the same kind of subject. It should be noted that the bathtubbing scenario, which has often been analysed in previous assessments, was excluded after screening calculations. It turned out that infiltration is less than outflow and the bathtubbing effect is unlikely to occur.

As discussed above, in the scenario approach used in this report, scenarios are not intended to be comprehensive, nor need they be mutually exclusive. Instead, the scenarios are chosen to illustrate the consequences of key selected FEPs acting on the system. Consequently, the scenarios should be chosen to illustrate the conditions that are most likely to be of concern at the site.

It is important to emphasize that this list has been developed using judgment about the most important FEPs that might affect the system. For all scenarios developed for this report, it is assumed that closure of the facility is undertaken using normal practices.

Different scenarios have different probabilities of occurrence. According to usual practice, some could be considered at first, and others could be deferred for possible later consideration. It is recommended that screened out scenarios should be considered in later assessments only if there is a significant argument that they are likely to be important for decisions about the disposal facility. Each of the identified alternative scenarios is screened in the following sub-sections.

2.3.4. Screening of alternative scenarios

Undisturbed performance

This group of scenarios consists of different variations of the Design Scenario, which could be subdivided into separate cases according to release media (leachate, solid waste or contaminated soil, gas), pathway (perched water in unsaturated zone, groundwater in the aquifer, surface water), etc.

Naturally disturbed performance

Flooding Scenario: A small amount of bathtubbing of water in the vault is considered as part of the Design Scenario. The site is located about 100 m above the river level and has a continuous slope preventing precipitation accumulating on the site and on the way to the river. The river water is unlikely to raise so high. Therefore vault flooding is assumed to be only associated with high precipitation. In general, vault flooding is likely for sites with low permeability host rock. In such cases, precipitation water can infiltrate and accumulate in the disrupted ground near the vault walls and then infiltrate into the vault and accumulate there. When evaluating the top geological cross-section of this site, a loam layer can be found that is low permeability. This, together with the high surface slope, serves to protect underlying layers against deep percolation of precipitation. However, the depth of this layer varies from 0.4 to 1.2 m, while the bottom of repository is 3.5 m. In other words, more than a half of the vault is surrounded and underlain by loamy sand with a relatively high hydraulic conductivity 0.69 m/day This more permeable layer varies in thickness between 4.1 and 12 m. Such soils have no significant differences in flow properties between natural and disrupted conditions. It appears unlikely that water can accumulate within this permeable border. In the upper loamy layer, disrupted ground near the walls of repository could potentially serve as a collector for precipitation water to percolate down to the more permeable loamy sand layer and flow out. At the same time, the average annual and maximum daily precipitation appear insufficient for direct flooding. Consequently, only an extreme meteorological event could produce a bathtub effect, to the extent of flooding the vaults. This scenario appears possible, but unlikely, and has not been considered of sufficient concern to include in this iteration of the safety assessment. Flooding seems likely to be associated with the subsidence scenario or some other initiating event resulting in the cap collapsing.

Erosion: The site is located in a region with rather high erosion activity. Despite this observation, all available data suggest that this process has most impact mainly on the other bank of the River Kurdyum. Moreover Quaternary deposits are located on the bottom of the hollow while the hillsides have no Quaternary deposits. This means that the site is mainly affected by deposition rather than erosion. The gully bottom, where the disposal units are located, is believed to be covered with soil eroded from the hillsides. Additionally, vegetation inhibits erosion, and both sides of the hollow are covered with trees. Taking into account these factors, the erosion scenario has been discarded from consideration in this iteration.

However, erosion processes should be studied at the site to clarify the situation further.

Vault Subsidence Scenario: Past disposal practices may have led to considerable void space in the filled vaults. Once the structural strength of the vault walls and roof is lost, the potential exists for collapse of the structure. This would tend to allow increased water to infiltrate the vault. This scenario has been judged to be of secondary significance to others, and has therefore been omitted from this iteration of the safety assessment. Since the waste is grouted in place according to the usual practice at "Radon" facilities it seems to be more important for biological waste repositories.

Biotic Intrusion Scenario: The implications of this intrusion for vault integrity are addressed in the design scenario (the base case). However, the potential exists for active root uptake and dispersal in tree materials in the post closure period. This scenario is judged to be of secondary importance compared to the scenarios included in the assessment, and has been omitted from this iteration of the safety assessment.

Human intrusion scenarios

Drilling: The consequences from this scenario are likely to be bounded by the construction and site development scenario. However, it is among the most likely scenarios for the site, and is included for that reason. In this scenario, a driller is assumed to intrude into the facility, and to be exposed by direct radiation and by inhalation of contaminated dust. Intrusion and post-intrusion doses should be assessed.

Surface Construction and Site Development: This scenario has been included to account for the potential for inadvertent human intrusion during the post-institutional control period. There are many activities that may lead to disruption of the disposal facility during that period. For the purposes of this initial safety assessment, a scenario will be used that has been found to provide the most severe intrusion consequences in most situations.

This scenario will consider the construction of a building foundation that excavates a substantial proportion of the waste, and distributes it around the surface. Agricultural activities such as the growing of crops are assumed to take place in the contaminated soil. Doses are assumed to result from external exposure to contaminated soil, from inhalation of contaminated dust, and from ingestion of contaminated foods. Doses will be calculated for a worker engaged in construction activities and to an individual living in a house constructed at the site.

This intrusion scenario could be divided into several simplified ones according to all the points mentioned above (house building and agricultural activity) or supposing other activities that may lead to disruption of the disposal facility during that period, such as: road construction, with intrusion and post-intrusion dose; house building without disposal facility disruption, with intrusion and post-intrusion dose; house building using the vault as a house foundation.

Farming: In the Farm Scenario it is assumed that after 300 years a farm is built at the site for the purpose of raising cattle or sheep. Drinking water for people will be assumed to be from a municipal water supply, which is which is uncontaminated by the facility. Animals raised on the site, and their fodder, however, are assumed to receive their water from an onsite well to the primary aquifer, and to be contaminated as a result. Individuals receive doses in this scenario by consuming meat and milk from contaminated animals.

2.4. FORMULATION AND IMPLEMENTATION OF MODELS: FIRST ITERATION

2.4.1. Devlopment of conceptual models

The Design Scenario considered in this test case is activity distribution from the disposal facility into the environment by the groundwater pathway. As a result, geological and hydrological processes and conditions in the surroundings have higher priority than others in this scenario. It is clear that there are many different features that are specific for each facility. However, only the most important features have been taken into account in this first assessment, owing to difficulties in measuring parameters and uncertainty in modelling.

For RADON type facilities, hydrogeological conditions seem to represent the greatest differences from one site to another. Consequently, these are among the most important features taken into account in this safety assessment.

Because of the uncertainties in the hydrogeological conditions of the site considered , the attention in the first iteration was paid mainly to modelling the hydrogeology and groundwater flow. The disposal facility was considered as an integrated source term combining all the disposal units of the site.

The geological structure of the site, as described in Section 2.2, is generally clear, although there are some specific uncertainties. Nevertheless, it is possible to interpret the available geological and hydrological information in different ways, and to build several variants of the cross section between the facility and the nearest villages. These variants may be considered to represent alternative conceptual models of the site. For a conceptual model to remain viable for consideration, it should be consistent with the available data. One variant of the geological structure is presented in the Fig. 36.

This geological structure of the site allows one to assume three different cases for the water pathway. Accordingly, three cases of activity migration with groundwater have been investigated:

- Water from the perched aquifer above the Aptian clay may discharge at the contact of the Quaternary sand and loam (or in another place) due to the difference in hydraulic conductivity;
- Water from the perched aquifer may flow through a window in the clay layer into an aquifer of the sand layer; and
- Activity transport above the clay layer and discharge to the River Kurdyum.

A simplified representation of the conceptual model for the Design Scenario is shown in Fig. 37.

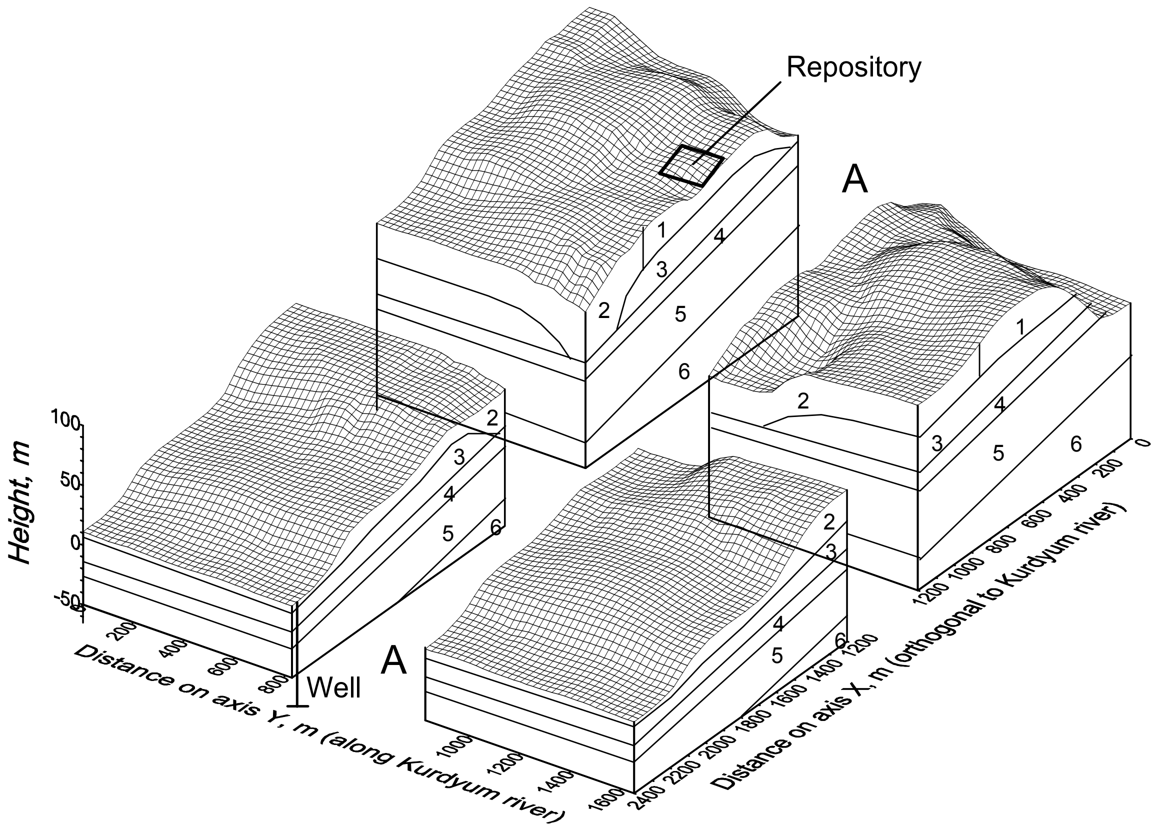


FIG 36. Scheme of Repository Site Geology Used for Safety Assessment.

1 – Quaternary sandy rocks, 2 – Quaternary loam, 3 – Aptian clay, 4 – Aptian sand,

5 – Aptian sandy clay and alevrolits, 6 – Barremian clay.

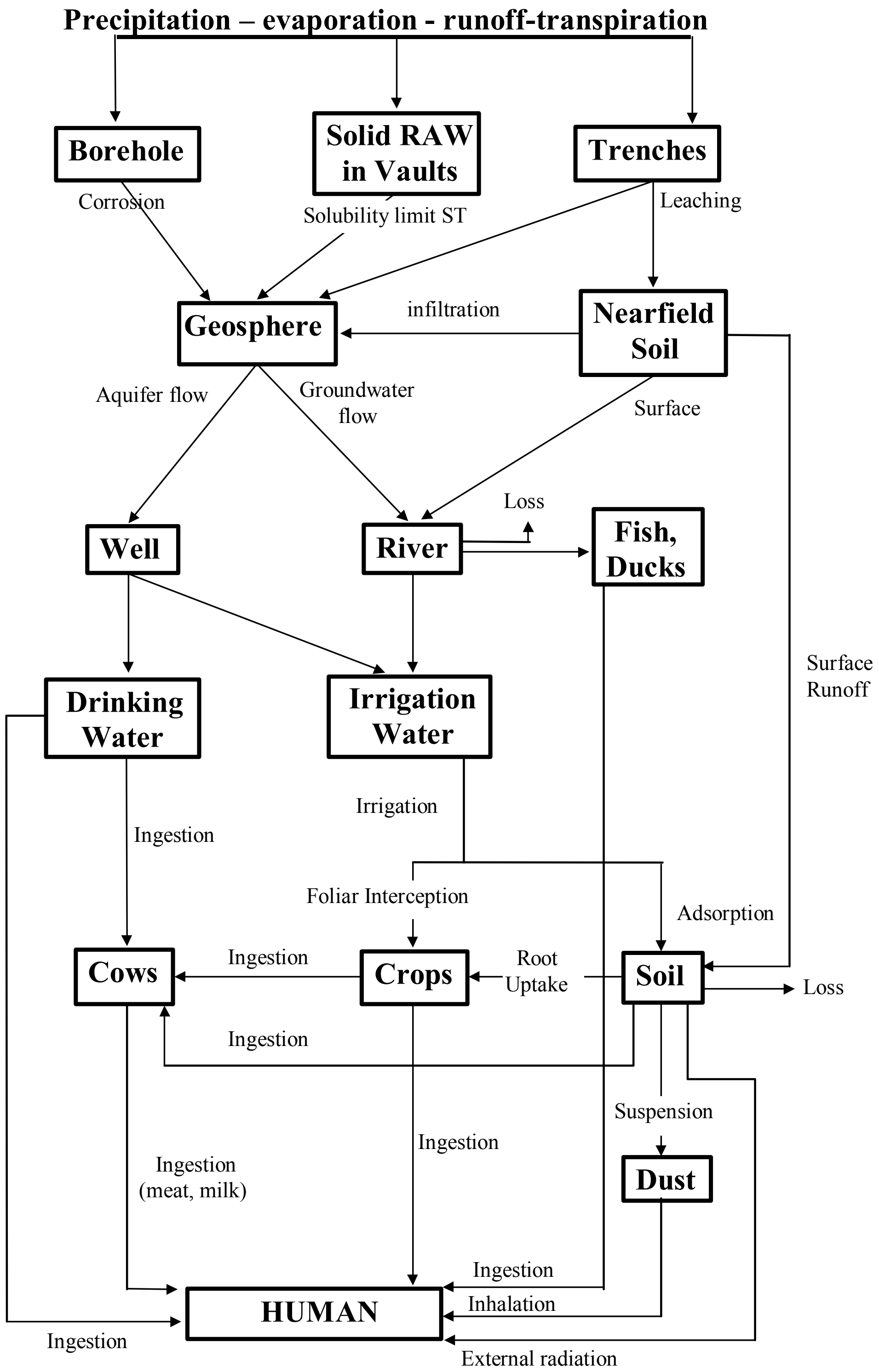


FIG. 37. Simplified Representation of the Conceptual Model for the Design Scenario.

In the assessment of ground water transport it was found necessary to model water flow in both layers together. A key aspect of the flow behaviour was found to be vertical groundwater movement in the upper layer.

2.4.2. Development of mathematical models and implementation in software

Water flow model

As can be seen from the Fig. 37, the hydrogeology of the site is rather complex. The model of water flow must be able to describe the main features of water flow both in saturated and in unsaturated conditions. The model of water flow is based on a numerical solution of the common equation for pressure head in three dimensions [23].

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial\Psi}{\partial x_j}+\delta_{i3}\rho_w K_{ij}\right)+Q \qquad (2)$$

where

- θ is the relative moisture content (–);
- t is the time (s);
- x_I is the coordinate in the I-th direction (m); (I=3 is vertical coordinate z with upward direction) the Descartes system of Euler coordinates is used in this document when concerning iteration 1. Throughout the description of iteration 1 the sum of the indexes (all three directions) is assumed. K_{ij} is the tensor of hydraulic conductivity, (ms^{-1});
- Ψ is the pressure head, or pressure, or suction potential for unsaturated condition (m);
- Q is the water source or sink term (divergence of infiltration flux or evaporation flux, etc) (s^{-1});
- ρ_w is the relative density of groundwater ($\rho_w=\rho/\rho_o$, ρ_o=1000 kgm^{-3});
- δ_{ij} Kroneker symbol. (–).

The water flux (Darcy velocity – V_I, ms^{-1}) may be obtained by Darcy's law:

$$V_i=-K_{ij}\left(\frac{\partial\Psi}{\partial x_j}+\delta_{i3}\rho_w\right)=-K_{ij}\frac{\partial h}{\partial x_j} \qquad (3)$$

where

$\partial h/\partial x$ is the head gradient (x-).

To obtain the water flow velocity, the Darcy velocity should be divided by the effective porosity (n_e) in saturated conditions, which can be measured only in field tests (trace experiments).

The Van Genuchten empirical model [24] for the unsaturated zone is often used for evaluation of the relationship between pressure and moisture content. In this model, this relationship was approximated by the following empirical formulae, which were fitted to data:

$$\theta=\theta_r+\frac{(\theta_s-\theta_r)}{\left[1+(\alpha|\Psi|^{\beta}\right]^m} \qquad (4)$$

where

- θ is the soil moisture content (–);
- θ_r is the residual soil moisture content (–);
- θ_s is the soil moisture content in saturated conditions (–);
- Ψ is the suction pressure (m);

α, β and m, are the empirical coefficients with $m=1-1/\beta$.

A combination of the van Genuchten model with Mualem's model for the pore space leads to an expression for the coefficient of hydraulic conductivity:

$$K=K_sS^{0,5}[1-(1-S^{1/m})^m]^2 \quad (5)$$

where

K_s is the coefficient of hydraulic conductivity in saturated conditions (ms^{-1}).

$$S=(\theta-\theta_r)/(\theta_s-\theta_r).$$

It is difficult to solve Equation 2 numerically using the non-linear formulas of the van Genuchten/Mualem model. Moreover, the empirical parameters used in the van Genuchten model are not known for the site considered. Consequently, with some simplifications an alternative model was used in the analysis:

$$\theta = n/|\Psi|;\ K = K_s/\Psi^2 \text{ for } \Psi \leq -1 \text{ m}. \quad (6)$$

Activity migration model

The model used for analyses of transport in groundwater is based on a numerical three-dimensional solution of the advective-dispersive equation, which may be obtained from [24]. The dimensionless distribution coefficient and total (sum) concentration of radionuclides in the liquid and solid phases are used in this work (rather than the more customary equation for activity in the liquid phase and the dimensional ($m^3\ kg^{-1}$) distribution coefficient). The following equation was used to model the mass transfer processes:

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left[\theta D\frac{\partial}{\partial x_j}\left(\frac{C}{K_d+\theta}\right)-V_i\frac{C}{K_d+\theta}\right]-\lambda(C-C^m)+Q \quad (7)$$

where

C is the sum activity in solid and liquid phases (Bqm^{-3}) (C^m – parent nuclide);
K_d is the dimensionless distribution coefficient (-);
λ decay constant (5^{-1});
Q precipitation nuclide in solid phase, $Bq.m-^3.s^{-1}$;
D dispersion diffusion coefficient, ($m^2\ 5^{-1)}$;
$D = D^* + D_{ij}$, where D^* is the –effective diffusion coefficient ($m^2\ 5^{-1}$);
D_{ij} is the coefficient of hydrodynamic dispersion ($m^2\ 5^{-1}$).

$$D_{ij} = \alpha_t\,|V|\delta_{ij}\,/\theta+(\alpha_l-\alpha_t)\ V_I\ V_j\,/|V|/\theta; \quad (8)$$

where

α_l is the longitudinal;
α_t is the transverse dispersivity (m).

No analytical solutions of the equation was used. Instead it was solved numerically.

Model of public exposure

To simplify the dose calculation in the first iteration, an existing code, GENII [25] was used for the safety assessment, using the generic default parameter values. This simplified generic approach was appropriate for the first iteration, because no real data about water and food consumption were available when this model was first used, the effective dose equivalent (i.e. ICRP 30 dose model) was calculated for consumption of drinking water, meat, poultry, eggs, milk, leaf and root vegetables and fruits. It was assumed that the water for domestic purposes is taken by the villagers from a well, located near the River Kurdyum (Fig. 30) in Doktorovka.

The dose coefficients for this calculation were taken from the interim report of the International Basic Safety Standards [26]. Because the dose coefficients in GENII are taken from [28], the doses calculated with GENII were then multiplied by the relationship of dose coefficients in [28] and [29]. Thus, the doses in this iteration were calculated in compliance with [27].

2.4.3. Assessment data

Most of the parameters used in the models described above were not known for this specific facility before the first iteration started. Some of the values were taken from the literature and some others were defined by expert judgment, taking into account the experience of the RADON test case participants. The following principle was used: the degree of conservatism is proportional to parameter uncertainty.

Source term

Taking into account the insignificant quantity of some radionuclides and short half-life for others, the total inventory in Table 31 was used in the first iteration.

TABLE 31. TOTAL INVENTORY FOR THE FIRST ITERATION OF THE RADON TEST CASE

Radionuclide	**Inventory (Bq)**
H-3	6.9E15
C-14	3.9E11
C1-36	3.7E10
Co-60	1.1E15
Sr-90	2.1E12
Cs-137	4.8E14
Ra-226	2.2E11
Pu-239	4.4E12

The partition coefficients used for source-term modelling (the partition coefficient is the ratio of activity in the solid phase to that in the liquid phase in the disposal unit) were defined on the basis of known activity levels in the liquid phase at some operating RADON facilities. The dimensionless values given in Table 32 were used.

TABLE 32. PARTITION COEFFICIENTS FOR THE FIRST ITERATION OF THE RADON TEST CASE

Radionuclide	Partition Coefficient (-)
Cs-137	7.5E4
Sr-90	1.1E4
Ra-226	300
Co-60	1.2E6
H-3	0
C14	10
C1-36	10
Pu-239	1E4

It was assumed that during the first 500 years all the vaults are filled with water. The water flux from the vaults in this case is the sum of fluxes through their bottom (F_1) and walls (F_2):

$$F_1 = K\,S_1\,(h/d+1) = 3520K \quad (9)$$

$$F_2 = K\,S_2\,h/d/2 = 2520K \quad (10)$$

where

K is the hydraulic conductivity of concrete (m d^{-1});
S_1 is the area of vaults bottoms (320 m^2);
S_2 is the area of vaults walls, (504. m^2);
H is the water level in vaults (3 m);
D is the thickness of walls and bottoms (0.3 m).

After 500 years water flux was assumed to be equal to the infiltration rate.

It was assumed that the hydraulic conductivity of concrete is 1E-5 m d^{-1} during the first 150 year, 1E-4 m d^{-1} between 150 and 500 years, after 500 years the conductivity of concrete is equal to the conductivity of the surrounding rock.

The concentration of radionuclides in the vaults was calculated as in (Derivation of Quantitative Acceptance Criteria for Disposal of Radioactive Waste to Near Surface Facilities: Development and Implementation of an Approach. Draft Safety Report Working Document, IAEA, Vienna, 1999):

$$C = C_o\,exp(-(ALF + \lambda)t),\ ALF=F/V/(N+K_p) \quad (11)$$

where

C_o is the initial concentration (kg m^{-3});
λ is the is the rate (y^{-1});
F is the water flux through the vaults ($F = F_1 + F_2$) ($m^3\ y^{-1}$);
V is the volume of the vaults (800 m^3);
N is the ratio of the water volume to the waste volume (water filled porosity inside of vaults), assumed to be *0.4;*
K_p is the partition coefficient (–).

$$C = \lambda U C_{oPu}/((ALF_U + \lambda_U) - (ALF_{Pu}+\lambda_{Pu}))(exp(-(ALF_{Pu} + \lambda_{Pu})t) - exp(-(ALF_U + \lambda_U)t)) \quad (12)$$

The value of the source term (Q) in equation (7) was calculated as:

$$Q = C*F \tag{13}$$

Hydrogeological and sorption data

A hydraulic conductivity of Quaternary loamy sand equal to 0.69 m d^{-1} (6.9E-6 m s^{-1}) was used for calculations taken from the results of field tests. For the Aptian sand layer a value was used equal to 2 m d^{-1} (2E-5 m s^{-1}). For Quaternary loam, the conductivity was taken to be 0.1 m d^{-1} (1E-6 m s^{-1}), and for Cretaceous clays 1E-5 m d^{-1} (1E-10 m s^{-1}). For the total Cretaceous Aptian layer of sandy clay and alevrolits with thickness 50 m the value of conductivity obtained was 0.1 m d^{-1} (1E-6 m s^{-1}), by the modelling of water head distribution.

Total porosity was taken to be 0.3, and effective porosity 0.2. Longitudinal dispersivity in the horizontal plane was taken to be 50 m, and the transverse to be 10 m. In the vertical direction longitudinal dispersivity was taken to be 2 m, and transverse 0.5 m. The infiltration flux (0.12 m y^{-1}) was assumed to be equal to 1/3 of the annual precipitation (0.36m y^{-1}).

Distribution coefficients taken from the literature [29] were assessed by the RADON test case participants for the conditions at the site. These were converted into dimensionless distribution coefficients for use in the first iteration as follows: H – 0, Cl - 1, C – 1 for all rocks; Co - 5, Sr - 3, Cs - 50, Ra - 100, Pu - 100, U – 5 for sandy rock and 3 times higher for clay and loam.

2.5. ASSESSMENT OF RESULTS: FIRST ITERATION

The steady state calculated distribution of hydraulic pressure is shown on Fig. 38. This solution was obtained by numerical integration of Equation (2) with an infiltration flux 0.12 my^{-1} for more than 20 years. But even for such a time period, steady state conditions in the clay were not obtained due to the low permeability of the clay. The saturated condition in Aptian clay was obtained only in the upper part of layer. In reality, saturated conditions in all the clay may not occur due to evaporation which is not considered in the model, and some uncertainty will result.

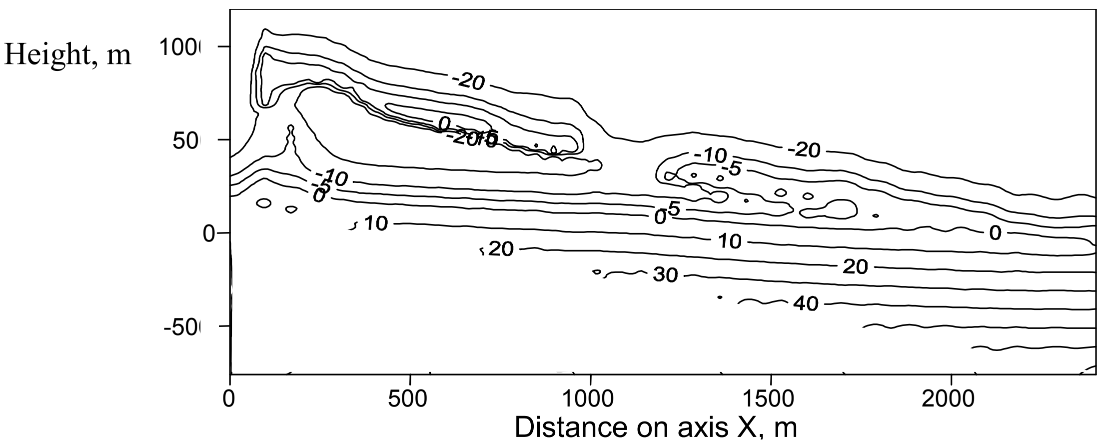


FIG. 38. Calculated hydraulic pressure head (m) in vertical plain A-A of FIG. 31.

The pressure heads of Fig. 39 were used for activity transport calculations.

Special calculations with an infiltration rate of 0.25m over a month were undertaken in order to eliminate possible repository flooding. But even with such a high infiltration rate it was not possible to generate repository flooding. Therefore it was concluded that a flooding conceptual model was unlikely.

The variation with time of activity in the well illustrated in Fig. 37 are shown in Fig. 39. Activities of the mobile radionuclides such as H-3, C-14, Cl-36 rapidly reach their maximum values. Sr-90, Cs-137, Ra-226 and Co-60 have very low activities and cannot be considered as significant. Activities of Cs-137 and Co-60 even are not shown on Fig. 39.

Only Pu-239 may be considered as a potential significant radionuclide.

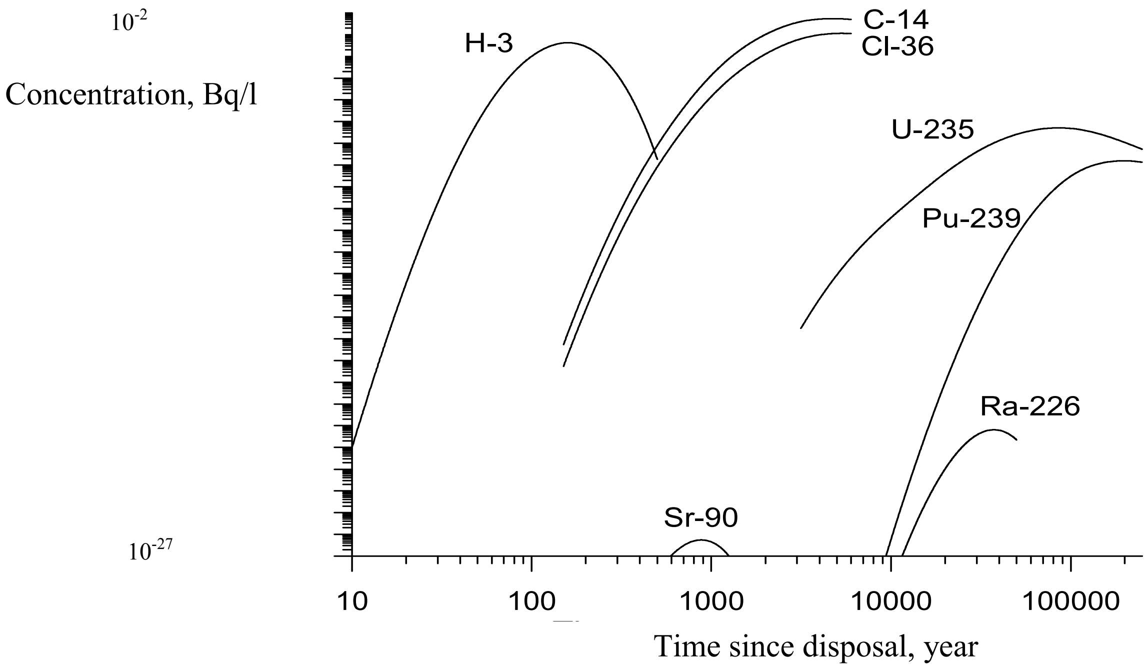


FIG. 39. Variation with time of calculated nuclides activity in water of well in FIG. 31.

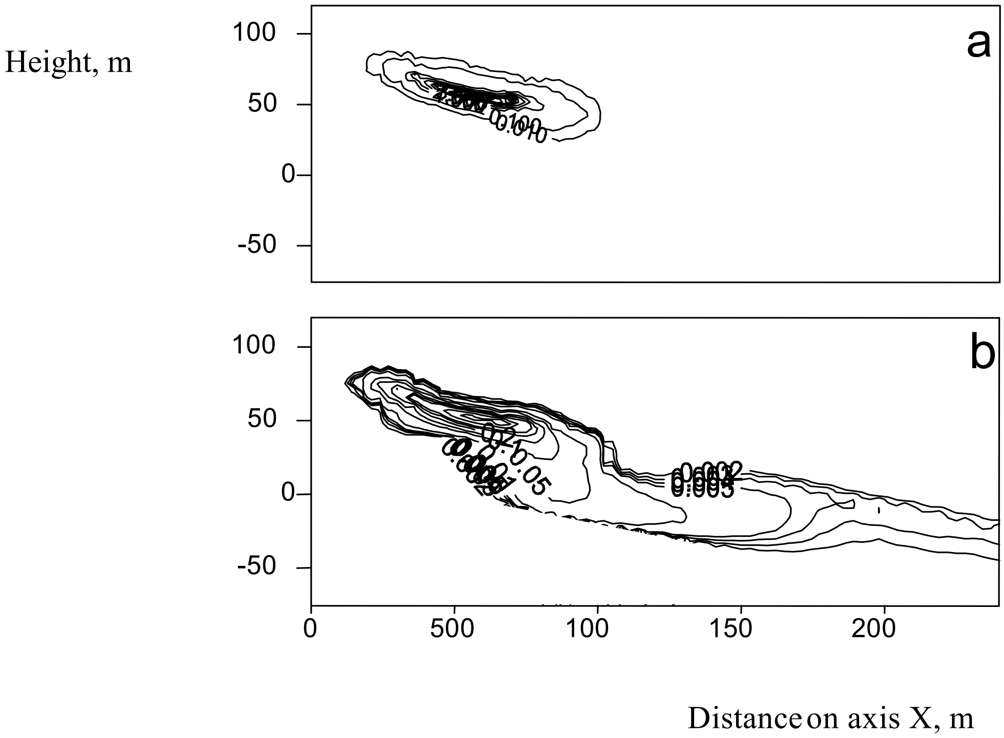


FIG. 40. Activity of C-14 (Bq/l) after 500 (a) and 3000 Years (b) since Disposal in Vertical Plain A-A of FIG. 31.

The calculated values of radionuclide concentrations in well water are many orders less in comparison with the limits of NRB-76 [29] in Bq/kg: H-3 - 3E4, C-14 - 2200, Cl-36 - 1300, Sr-90 45, Ra-226 - 4.5, Pu-239 - 5, U-235 - 3.3.

From Fig. 40 it is evident that the radionuclides move in the perched aquifer unlike they would in usual saturated aquifers. There is a low vertical velocity present in the perched aquifer. With this vertical velocity the radionuclides come to clay level which has a very low water flow velocity and high values of distribution coefficients. Some radionuclides are retained in the clay layer. This mechanism works as a very effective natural barrier against migration of activity in the environment.

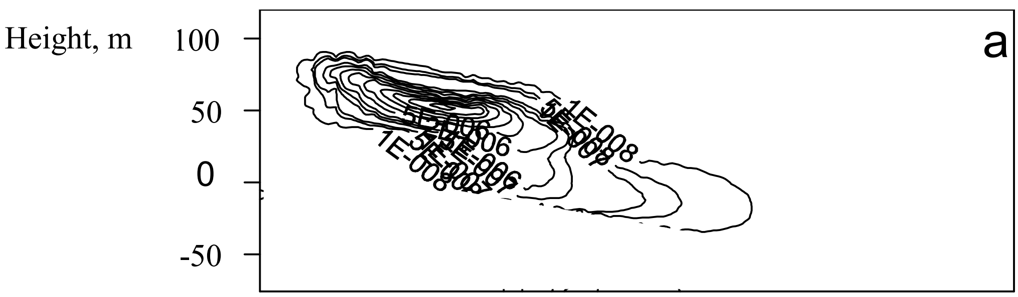


FIG. 41. Activity of Pu-239 (a) and U-235 (b) after 250000 Years since Disposal in Vertical Plain A-A of FIG. 31.

In Fig. 41 distributions of P-239 and U-235 are presented. It is evident that some activity moves in the perched aquifer, then moves down through a window in the clay layer and in to the aquifer in Aptian sands to the well. Some activity also moves down through the clay layer and in to the aquifer in Aptian sediments to the well. The travel time of both routes is very long and so, activity in the well water has very low values.

From Figs 40 and 41 it is evident that with the assumed geology, the radioactive material cannot be transported to the River Kurdyum directly above of Aptian clay layer. For this reason it is possible to conclude that the third proposed conceptual pathway giving rise to public exposure cannot be realised for this repository unless an alternative conceptual model of the geology is assumed.

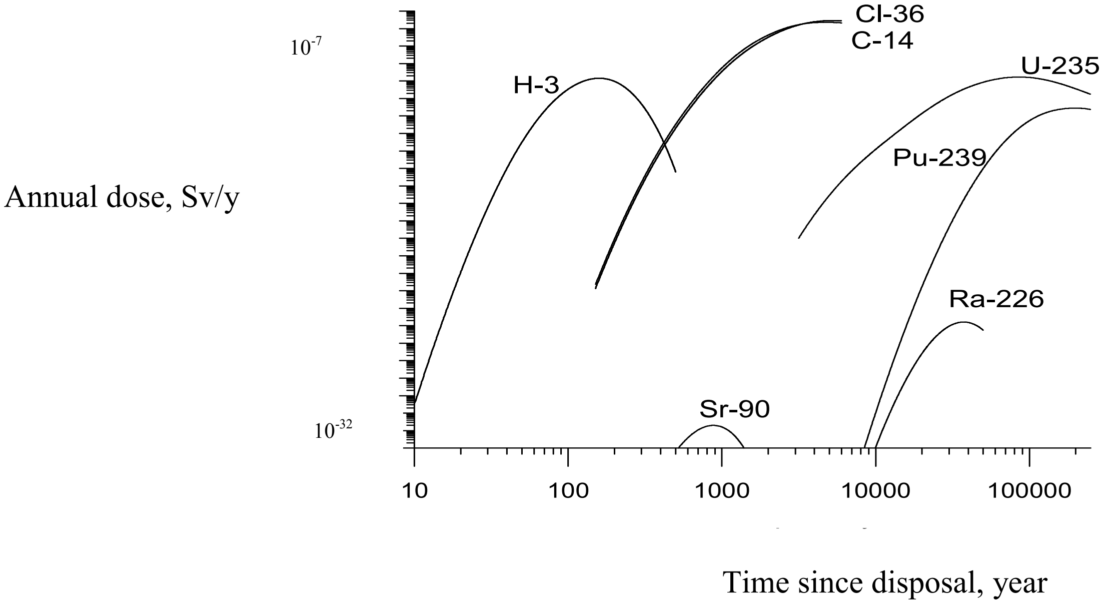


FIG. 42. Variation with time Annual Effective Dose Connected with Water Using from Well in FIG. 37.

The dose calculations are present in Fig. 42. Effective dose values are several orders of magnitude less than the dose constraint of $0.1 mSvy^{-1}$ (Section 2.1.2).

2.6. DEVELOPMENT AND JUSTIFICATION OF SCENARIOS: SECOND ITERATION

In light of the lessons learnt from the first iteration, the Design Scenario was modified. For the first iteration it was assumed in the Design Scenario that infiltrating water migrates down into the Aptian aquifer (see Section 2.2.3). For the second iteration, an alternative assumption was adopted. It was assumed that the clay later overlying the aquifer was continuous and so a perched aquifer was formed above the clay. It was assumed that infiltrating water migrates along this perched aquifer, rather than infiltrating down into the Aptian aquifer, and discharging into the river.

However, this simplification left some important FEPs unconsidered. To address them, and to resolve the uncertainties mentioned in Section 2.2.4, the following scenarios were added, in light of expert judgement, for further consideration in the second iteration:

(1) Cap Erosion Scenario — ff-site scenario taking into account solid release due to the cap erosion;

(2) Radon Gas Scenario — on site resident scenario assuming that a house is built over an undisturbed vault and radon gas migrates from the facility through the soil into the house;

Aquifer Contamination Scenario — altered Design Scenario assuming that infiltrating water reaches the Aptian aquifer and humans abstract contaminated groundwater via a well for domestic and agricultural purposes, and the water supply well is at the border of the site;

(3) Farming Scenario — human intrusion scenario resulting in exposure of site dwellers who farm on the contaminated land; and

(4) Excavation Scenario — human intrusion scenario resulting in exposure of intruders.

These scenarios were considered to cover all key features of the disposal facility and potential exposures. A review of the safety assessment literature shows that such results are in accordance with references on near-surface safety assessments.

2.7. FORMULATION AND IMPLEMENTATION OF MODELS: SECOND ITERATION

2.7.1. Development of conceptual models

The conceptual model allows the identification of how impacts arise from waste disposal for each scenario, its environmental setting and the associated release, transport and exposure mechanisms and media. The conceptual model development approach used for the second iteration is based on [28].

The conceptual model considers:

— The source of contaminants;
— The release media - the form in which the contaminants escape from the source;
— The release mechanisms - how the contaminants escape;
— The geosphere transport media - the form in which the contaminants migrate through the geosphere;
— The geosphere transport mechanisms - how the contaminants migrate through the geosphere;
— The biosphere media - the form in which the contaminants migrate through the biosphere;
— The biosphere transport mechanisms - how the contaminants move between biosphere media; and
— The exposure mechanisms - how the contaminants result in human and environmental effects.

The first step in the conceptual model development approach used for the second iteration is to identify the release and transport media, exposure points, and human and environmental effects for each scenario. This allows the identification of the key release and transport media, exposure points, and human and environmental effects, although no links are made at this stage between the media, exposure points, or human and environmental effects.

In the RADON Test Case, the following release media can be identified: leachate for the Design Scenario and the Aquifer Contamination Scenario; eroded waste for the Cap Erosion Scenario; gas for Radon Gas Scenario; excavated waste for Farming and Excavation Scenarios and dust for Excavation Scenario too.

Transport media for each scenario is:

- Infiltrated water and lateral perched water flow in an unsaturated zone, surface water — for the Design Scenario;
- Soil and atmosphere – for the Cap Erosion Scenario;
- Atmosphere — for the Radon Gas Scenario;
- Infiltration water in the unsaturated zone, groundwater, soil, atmosphere — for the Aquifer Contamination Scenario; and
- Soil and atmosphere — for the Farming and Excavation Scenarios.

The following potential exposure points for humans have been identified: groundwater, river water, soil, atmosphere, fish, crops, and domestic animals.

Once this first step has been completed, the mechanisms by which the associated release, transport and exposure may occur have been considered for each scenario (i.e. the links between the media, exposure points, or human and environmental effects. Two strategies can be used:

- The *deductive strategy* starts with the consideration of how release events might occur, then considers the possible transport and exposure mechanisms, and finally considers the associated impacts; and

- The *inductive strategy* starts with the consideration of the impacts and considers the exposure and transport mechanisms which might cause such impacts. Finally the associated release mechanisms are considered.

Both strategies can be used together to identify release, transport and exposure mechanisms. FEPs previously identified in the scenarios identification and justification step of the assessment approach can be used.

In the Design and Aquifer Contamination scenarios leaching of wastes provides a direct route for introduction of radionuclides into groundwater. For the leachate release model, contaminated groundwater may recharge to a well or to the river and then be used for drinking, preparation of food, and other domestic purposes.

Human activities are based on an agricultural community, with a diet of local animal and vegetable products being consumed. Three farming exposure groups need to be considered in this case. One is based on the use of river and perched groundwater, including drinking water, irrigation of crops, watering of animals, and consumption of fish. It is assumed that this group lives in the nearest village (Doktorovka). The second is based on the abstraction of groundwater from the aquifer near the disposal facility, with subsequent use for drinking, irrigation of crops and watering of animals. The second group is assumed to live at the repository site boundary. Additional exposure pathways for these scenarios are inhalation of contaminated dust, inadvertent ingestion of contaminated soil and external irradiation from this soil. The third group is assumed to live or to work on the site.

Solid releases may occur due to cover erosion. After complete cap erosion radionuclides may be exposed at the surface, suspended in the air, and inhaled. Contamination in soil may be taken up by plant roots and contaminated edible parts of the vegetable. Contaminated soil can be also ingested or cause external exposure. As was discussed above, this release media is considered in the safety case only in a screening analysis of erosion.

For ^{222}Rn gas release it is assumed that a house is built over the facility, with radon gas migration from the facility through the soil into the house. As a bounding assumption, the person is supposed to spend all the time indoors.

Present day drilling practices and excavation techniques are assumed for the human intrusion scenarios [30]. Workers could be engaged in excavation activities and would be primarily exposed to inhalation of contaminated dust, external radiation from the exposed waste, and inadvertent ingestion of contaminated material. It is assumed that exposures to a site dweller (Farming Scenario) following the intrusion may occur by one additional pathway - the consumption of vegetables grown in contaminated soil.

The resulting conceptual models for each scenario with release, transport media, exposure points and links between the media and exposure point are presented in Figs 43-48.

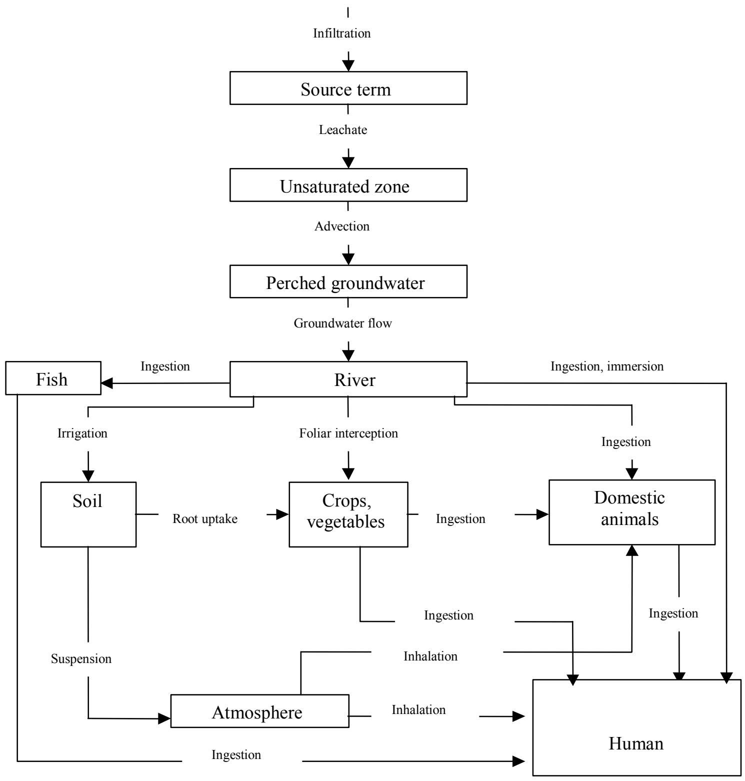


FIG. 43. Conceptual Model for the RADON Test Case Design Scenario.

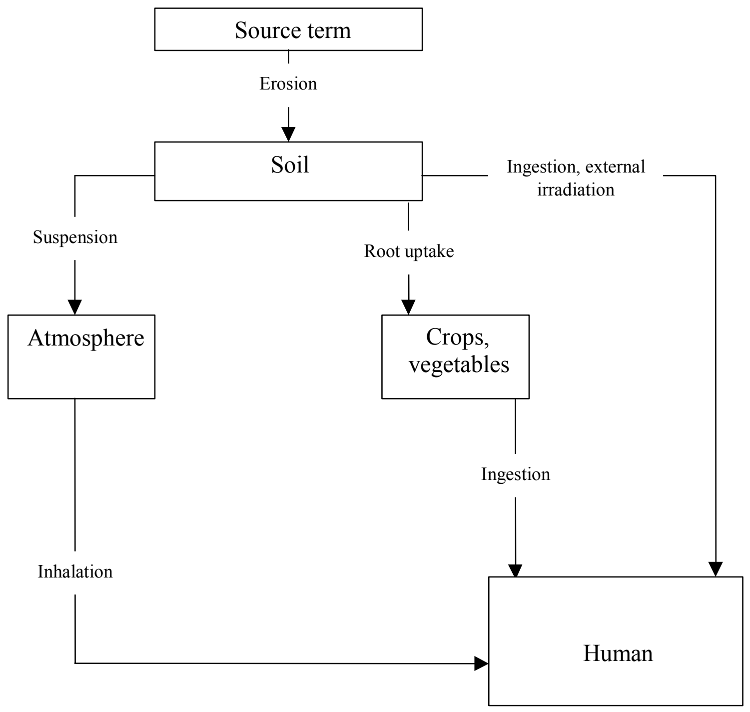


FIG. 44. Conceptual Model for the RADON Test Case Cap Erosion Scenario.

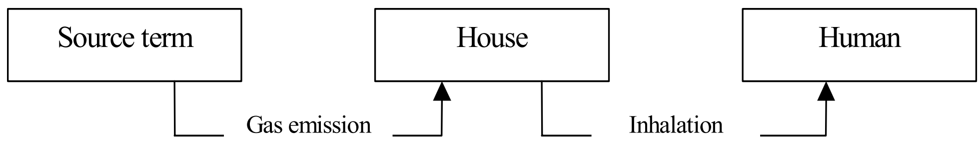


FIG. 45. Conceptual Model for the RADON Test Case Radon Gas Scenario.

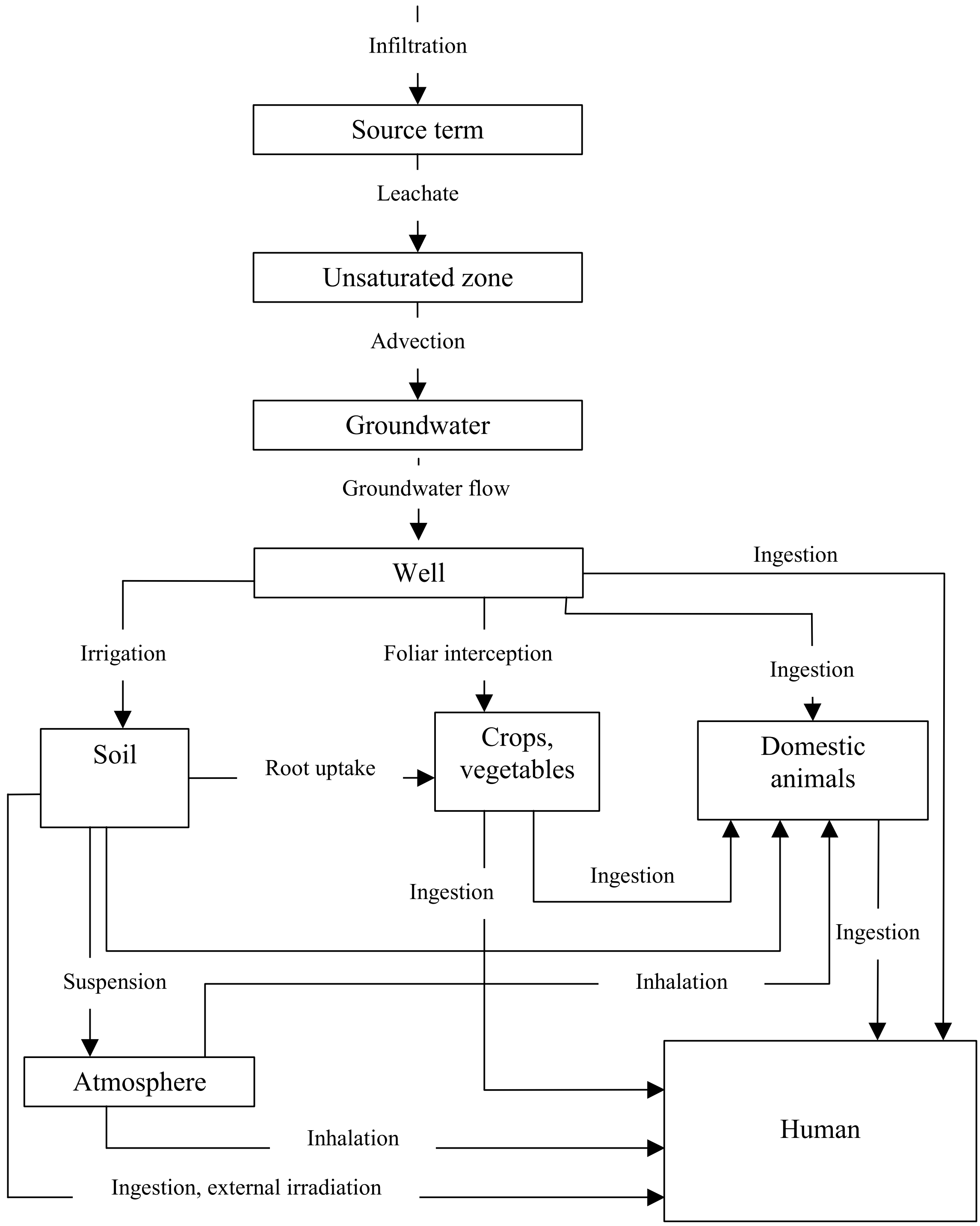


FIG. 46. Conceptual Model for the RADON Test Case Aquifer Contamination Scenario.

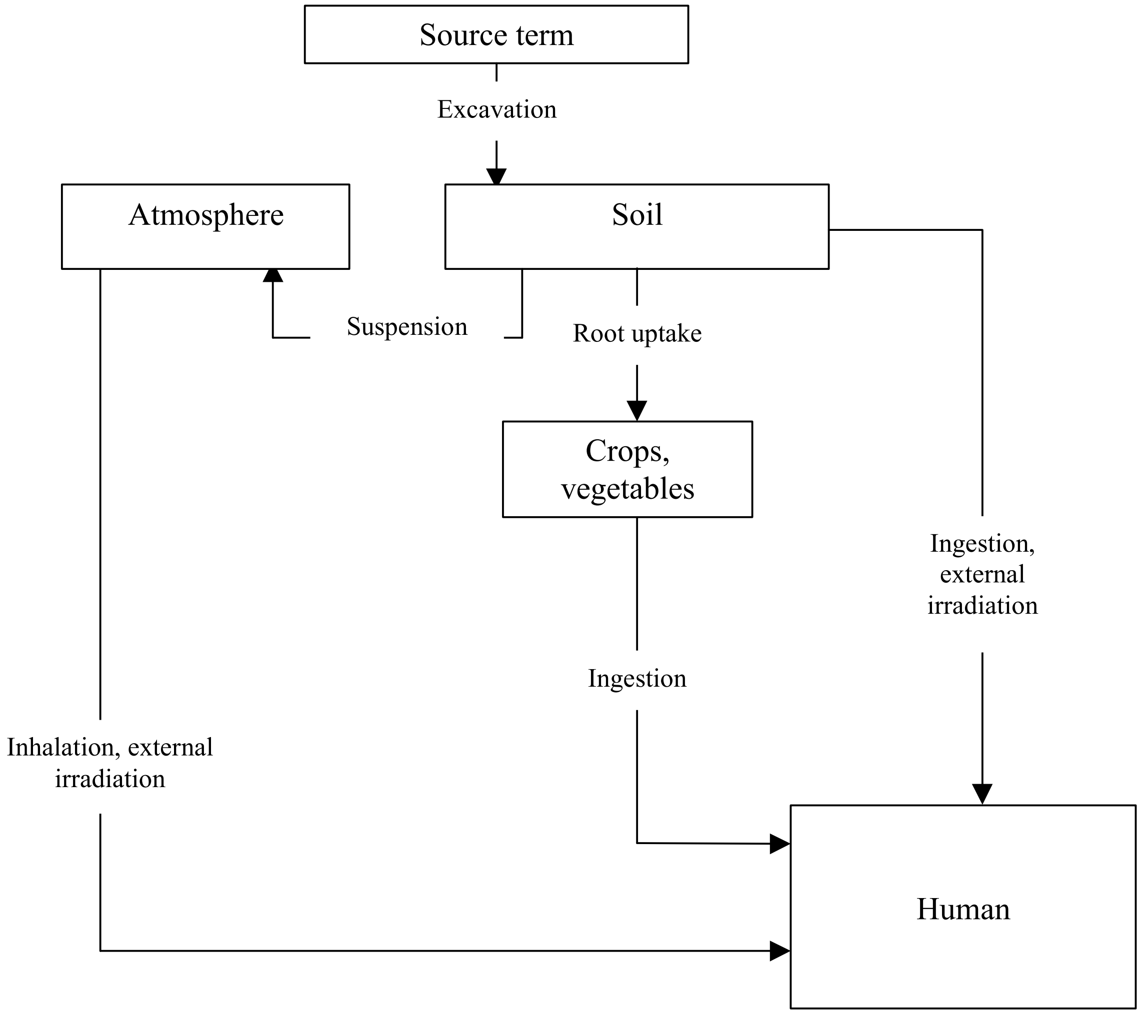


FIG. 47. Conceptual Model for the RADON Test Case Human Intrusion: Farming Scenario (Site Dweller).

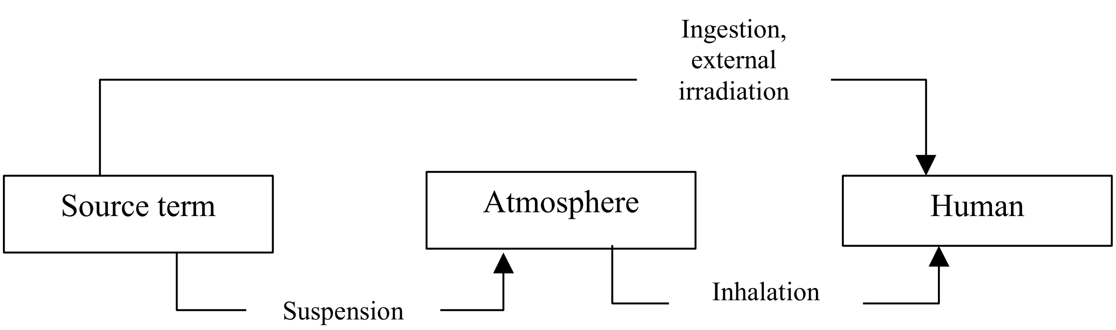


FIG. 48. Conceptual Model for the RADON Test Case Human intrusion: Excavation Scenario (Construction Worker).

Development of mathematical models

For the purposes of this second iteration, the AMBER software application [31] was used to solve the mathematical models. The mathematical model for each conceptual model, and the form they are implemented in AMBER are described below.

Mathematical model for the design scenario

Consistent with the conceptual model for a liquid release, several processes and exposure pathways need to be considered: leaching radionuclides from the waste, transport in an unsaturated zone, migration in the perched aquifer, migration in the river, ingestion of crops, ingestion of animal products, ingestion of water, ingestion of fish, inadvertent ingestion of soil, immersion in water, inhalation of sediment and external irradiation. A mathematical description for each process is presented below.

Leaching radionuclides from the waste

The leaching rate from the waste depends on the flow rate through the facility. Some recommendations on how to evaluate the flow through the waste can be found in [32, 33, 34].

A vertical advective transfer (leaching) rate λ_{Flow} can be used and is defined as:

$$\lambda_{Flow} = \frac{v_{Adv}}{D} = \frac{v_D}{n_e \varepsilon D R}, [\mathrm{y}^{-1}] \tag{14}$$

where

v_{Adv} is the advective velocity (m y^{-1});
v_D is the Darcy velocity through the medium (m y^{-1});
n_e is the effective porosity (–) in the medium;
ε is the degree of saturation of the medium;
D is depth of the medium through which the radionuclide is transported (m); and
R is the retardation coefficient given by:

$$R = 1 + \frac{\rho_b K_d}{\theta}, \tag{15}$$

where

ρ_b is the bulk density of the medium (kg m^{-3});
θ is the moisture content (–) in the medium; and
K_d is the sorption coefficient of the medium (m^3 kg^{-1}).

The basic assumption needed for the use of Equation 14 is that the waste is well mixed at the scale over which this rate expression is applied.

In the case of unsaturated waste v_D is equivalent to the infiltration rate for steady-state, unit-gradient flow. In this assessment the flow through the vault is time-dependent, but will be treated as a steady process. This assumption is appropriate when the time scale for the change of flow is long compared to the response of the system to come to a new state of equilibrium. It is assumed that for the first 10 years after closure of the vaults, the cap and isolating materials prevent any water infiltrating into the repository (this is an average service life of the isolating materials). After this period, flow through the facility starts, but the cap reduces infiltration. In this safety case a linear cap degradation is assumed starting from 0% at 10 years and increasing to 100% at 500 years.

Transport in the unsaturated zone

As the radionuclides are leached from the repository, they move vertically through the unsaturated zone until they reach the perched aquifer. The transfer rate equation in the unsaturated zone is the same as for the vault (Equation 14), and the same assumptions are required to use this approach.

Transport in the perched aquifer

The flow in the perched aquifer in general is described by an advection-dispersion equation, which in two dimensions is:

$$\frac{d_x}{n\,\varepsilon}\frac{\partial^2 C}{\partial x^2}+\frac{d_y}{n\,\varepsilon}\frac{\partial^2 C}{\partial y^2}-\frac{q\,C}{n\,\varepsilon}=R\frac{\partial C}{\partial t}+R\,\lambda_T\,C \qquad (16)$$

where

- x denotes the axis of groundwater flow;
- y the axis perpendicular to the flow;
- q is the water velocity (m y^{-1});
- n is the total porosity in the medium (–);
- t is the time (y) and C is the concentration of a contaminant in the water (mol m^{-3});
- d_x is the longitudinal dispersion coefficient (m^2 y^{-1}), approximately equal to $\alpha_x \cdot q$ where α_x (m) is the longitudinal dispersivity;
- d_y is similarly defined for transverse dispersion. λ_T is the rate of decay of the radionuclide (y^{-1}).

Elemental retardation in the geosphere (R) is taken into account using the approach of equilibrium sorption coefficients (Equation 15). These empirical parameters represent a number of physical and chemical processes with the ratio of the equilibrium concentration of an element adsorbed to a surface to the concentration in the groundwater. (Molecular diffusion in this equation is omitted, as it is assumed to be negligible under advective groundwater flow conditions.)

The most significant processes in the groundwater transport are advection and dispersion. It is proposed that the model implemented in AMBER should not consider molecular diffusion, as it is negligible compared with them. The advective flow transfer rate λ_{Adv} (y^{-1}) is:

$$\lambda_{Adv}=\frac{v_D}{L}=-k\frac{\partial H}{\partial x}\frac{1}{L\theta R} \qquad (17)$$

where

- $\partial H/\partial x$ is the hydraulic gradient (–);
- k is the hydraulic conductivity of the medium (m y^{-1});
- L is compartment length (m).

The approach used to solve this equation in AMBER is to divide the perched aquifer into a number of compartments. The number of compartments required may be determined by comparing the advective and dispersive components of flow thus:

$$Pe = \frac{L_T}{\alpha_x} \tag{18}$$

where

Pe is the Peclet number;
L_T is the total length of the far field path (m).
a_X is the longitudinal dispersivity (m).

The number of compartments required should exceed the Peclet number, otherwise the accuracy of the model will significantly decrease [10].

The dispersion rate is calculated as:

$$\lambda_D = \frac{\alpha_x}{\Delta_x} \lambda_{Adv} \tag{19}$$

where

λ_D is the rate of transfer of a contaminant by dispersion (y^{-1});
Δ_x is the distance over which the gradient is calculated (m).

Thus, for a one-dimensional representation of flow in the geosphere, there are three transfers between each compartment:

Advective flux from *i* to *j*

$$\lambda_{Adv,ij} = \frac{v_D}{L_i} \tag{20}$$

Forward dispersion (i to j)

$$\lambda_{D,ij} = \frac{\alpha_x}{\Delta_x} \lambda_{Adv,ij} \tag{21}$$

Backward dispersion (j to i)

$$\lambda_{D,ji} = \frac{\alpha_x}{\Delta_x} \lambda_{Adv,ji} \tag{22}$$

Subscripts i and j show to which compartment they are related.

Transport into the surface water

According to the modified Design Scenario, the perched aquifer discharges into a river, which is used by humans for agricultural and domestic purposes. In this iteration, it is assumed that humans use the water 1 km downstream from the discharge point.

The radionuclide transfer rate in the river, λ_{River} (y^{-1}) is given as:

$$\lambda_{River} = \frac{Q_{River}}{V_{River}} \tag{23}$$

where

Q_{River} is the river flow rate (m^3 y^{-1});
V_{River} is the volume of river compartment (m^3).

Transport in irrigation water

If contaminated surface water is used for irrigation, contaminants will build up in the soil. The rate of build up is determined by a mass balance in the upper soil layer. The transfer rate into this layer from contaminated irrigation, λ_{Irr} (y^{-1}) can be expressed as:

$$\lambda_{Irr} = \frac{q_{Irr}}{D_{Soil}} \tag{24}$$

where

q_{Irr} is the amount of irrigation water applied to the upper soil (m y^{-1});
D_{Soil} is the depth of the compartment representing the soil (m).

Ingestion of crops

The annual individual effective dose to a human from the consumption of a crop, (E_{Crop}, in Sv y^{-1}), is given by:

$$E_{Crop} = C_{Crop} Ing_{Crop} DC_{Ing} \tag{25}$$

where

C_{Crop} is the radionuclide concentration in the crop (Bq kg^{-1} fresh weight of crop);
Ing_{Crop} is the individual ingestion rate of the crop (kg fresh weight y^{-1}),
DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1});

The C_{crop} term is calculated using the following equation:

$$C_{Crop} = (CF_{Crop} + (1 - f_{Prep}) s_{Crop}) C_{Dry} + \mu_{Crop} q_{Irr} C_W \frac{(1 - f_{Prep}) + f_{Trans}}{Y_{Crop} \lambda_{Weather}} \tag{26}$$

where

CF_{crop} is the concentration factor for the crop (Bq kg^{-1} fresh weight of crop/Bq kg^{-1} dry weight of soil);
f_{Prep} the fraction of external contamination on the crop lost due to food processing (-);
s_{Crop} is the soil contamination on the crop (kg dry weight soil kg^{-1} fresh weight of crop);
μ_{Crop} is the interception fraction for irrigation water on the crop;
C_W is the radionuclide concentration in the river from which irrigation water is taken (Bq m^{-3});
f_{Trans} is the fraction of activity transferred from external to internal plant surfaces (-);
Y_{Crop} is the yield of the crop (kg fresh weight of crop m^{-2}); and
$\lambda_{Weather}$ is the removal rate of irrigation water from the crop by weathering processes (weathering rate) (y^{-1}).
C_{Dry} is the radionuclide concentration in the dry surface soil (Bq kg^{-1} dry weight soil) given by:

$$C_{Dry} = \frac{C_{Soil}}{(1-n)\rho_{Soil}} \tag{27}$$

where

C_{soil} is the radionuclide concentration in the soil (Bq m^{-3});
ρ_{Soil} is the grain density of the soil (kg m^{-3}).

In Equation 26, it is assumed that the crop can be contaminated due to internal uptake of contaminants via roots (term $CF_{Crop}C_{Dry}$), external contamination of crop due to deposition of re-suspended sediment from the soil (term $s_{Crop}C_{Dry}$) and irrigation (term $\mu_{Crop}q_{Irr}C_W$). It is assumed that contamination can be lost due to food preparation (f_{Prep} term) and weathering ($(Y_{Crop}\lambda_{Weather})^{-1}$ term). For each type of crop (root vegetables, green vegetables, and grain) the dose is calculated separately and then added together.

Ingestion of animal produce

The annual individual effective dose to a human from the consumption of animal produce (E_{Anm}, in Sv y^{-1}) is given by:

$$E_{Anm} = C_{Anm} Ing_{Anm} DC_{Ing} \tag{28}$$

where

C_{Anm} is the radionuclide concentration in the animal product (Bq kg^{-1} fresh weight of product);
Ing_{Anm} is the individual consumption rate of the animal product (kg fresh weight of product y^{-1}).
The C_{Anm} term is calculated using the following equation:

$$C_{Anm} = CF_{Anm}\left(C_{Fodd}\, Ing_{Fodd} + C_W\, Ing_{AW} + C_{Wet}\, Ing_{ASoil} + Inh_{Anm} O_{Anm} C_{Air}\right) \tag{29}$$

where

CF_{Anm} is the concentration factor for the animal product (d kg^{-1} fresh weight of product);
C_{Fodd} is the radionuclide concentration in the animal fodder (Bq kg^{-1} fresh weight of fodder);
Ing_{Fodd} is the consumption rate of fodder by the animal (kg fresh weight of fodder d^{-1});
Ing_{AW} is the consumption rate of water by the animal (m^3 d^{-1});
C_{Wet} is the radionuclide concentration in the wet soil (Bq kg^{-1});
Ing_{ASoil} is the consumption rate of soil by the animal (kg wet weight of soil d^{-1});
Inh_{Anm} is the breathing rate of the animal (m^3 h^{-1}), O_{Anm} is the occupancy time of the animal on the soil (h d^{-1});
C_{Air} is the radionuclide concentration in the air above the soil (Bq m^{-3}).

C_{Wet} is given by:

$$C_{Wet} = \frac{C_{Soil}}{(1-n_{Soil})\rho_{Soil} + n_{Soil}\varepsilon_{Soil}\rho_{Wat}} \tag{30}$$

In Equation 30 n indicates total porosity (–), ε the degree of saturation (–) and ρ the grain density (kg m^{-3}). The subscript *Soil* indicates the value for soil, *Wat* indicates the value related to water.

In a long term assessment it is usually assumed that the concentration in the atmosphere is in equilibrium with soil and C_{Air} is given by:

$$C_{Air} = C_{Dry} \frac{(R_{Soil} - 1)}{R_{Soil}} c_{Dust} \tag{31}$$

where

R_{Soil} is the retardation coefficient for surface soil compartment (–);
C_{Dust} is the dust level in the air above the surface soil compartment (kg m^{-3}).

In the case of the animals eating pasture (e.g. cows), the C_{Fodd} term is equivalent to the C_{Past} term:

$$C_{Past} = (CF_{Past} + s_{Past})C_{Dry} + \frac{\mu_{Past} q_{Irr} C_W}{Y_{Past}\lambda_{Weather} + N_{Anm} Ing_{Past}\ 365} \tag{32}$$

where:

CF_{Past} is the concentration factor for pasture (Bq kg^{-1} fresh weight of pasture per Bq kg^{-1} dry weight of soil);
s_{Past} is the soil contamination on pasture (kg dry weight soil kg^{-1} fresh weight of pasture);
μ_{Past} is the interception fraction for irrigation water on pasture (-);
Y_{Past} is the yield of pasture (kg fresh weight m^{-2});
N_{Anm} is the stocking density of the animals (m^{-2});
Ing_{Past} is the consumption rate of pasture by the animals (kg fresh weight of pasture d^{-1}). The factor of 365 is applied to convert from d^{-1} to y^{-1}.

Ingestion of water

The annual individual effective dose to a human from the consumption of unfiltered drinking water (E_{Wat}, in Sv y^{-1}) is given by:

$$E_{Wat} = C_W\ Ing_{Wat}\ DC_{Ing} \tag{33}$$

where:

C_w is the radionuclide concentration in the river from which the water is taken (Bq m^{-3});
Ing_{Wat} is the individual ingestion rate of freshwater (m^3 y^{-1});
DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}).

Ingestion of fish

The annual individual dose to a human from the consumption of fish (E_{Aq}, in Sv y^{-1}) is given by:

$$E_{Aq} = FF_w\ C_w\ CF_{Aq}\ 10^{-3}\ Ing_{Aq}\ DC_{Ing} \tag{34}$$

where

FF_w is the fraction of activity in the filtered water (-);
CF_{Aq} is the concentration factor for fish (Bq kg^{-1} fresh weight of edible fraction of fish per Bq l^{-1} of filtered water), the factor of 10^{-3} is applied to convert from m^3 to l;
Ing_{Aq} is the individual consumption rate of fish (kg fresh weight y^{-1});
DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}).

The FF_w term is calculated using the following equation:

$$FF_w = \frac{1}{1 + K_{d\,Sed}\ \alpha_w} \tag{35}$$

where

$K_{d\,Sed}$ is the sorption coefficient for the river ($m^3\ kg^{-1}$), and α_w is the suspended sediment load in the river ($kg\ m^{-3}$).

Inadvertent ingestion of soil

Soil can be inadvertently ingested by humans (e.g. with vegetables). The annual individual dose to a human from the ingestion of soil (E_{Sed}, in $Sv\ y^{-1}$) is given by:

$$E_{Sed} = C_{Wet}\ Ing_{Sed}\ DC_{Ing} \tag{36}$$

where

C_{Wet} is the radionuclide concentration in the soil (Bq kg^{-1} wet weight) (given by Equation 30);
Ing_{Sed} is the ingestion rate of the soil (kg wet weight soil y^{-1}).

Inhalation of suspended sediment

The annual individual dose to a human from the inhalation of suspended sediment/soil (E_{Dust}, in $Sv\ y^{-1}$) is given by:

$$E_{Dust} = C_{Air}\ O_{Out}\ Inh_{Sed}\ DC_{Inh} \tag{37}$$

where

C_{Air} is the radionuclide concentration in the air above the soil ($Bq\ m^{-3}$) (given by Equation 31);
O_{Out} is the individual occupancy on the contaminated soil ($h\ y^{-1}$);
Inh_{Sed} is the breathing rate of the human on the contaminated soil ($m^3\ h^{-1}$);
DC_{In} is the dose coefficient for inhalation ($Sv\ Bq^{-1}$).

External irradiation from immersion in water

The annual individual dose to human from external irradiation from immersion in water (E_{ExWat}, in $Sv\ y^{-1}$) is given by:

$$E_{ExWat} = C_W O_{Wat} DC_{ExtW} \tag{38}$$

where

O_{Wa} is the individual occupancy in the water ($h\ y^{-1}$);
DC_{ExtW} is the dose coefficient for external irradiation from immersion in water ($Sv\ h^{-1}$ / $Bq\ m^{-3}$).

External irradiation from sediment/soil

The annual individual dose to a human from external irradiation from soil (E_{ExSed}, in Sv y^{-1}) is given by:

$$E_{ExSed} = C_{Soil} \left(O_{In} SF_{In} + O_{Out} \right) DC_{ExtS} \quad (39)$$

where

C_{Soil} is the concentration in the soil (Bq m^{-3});

O_{In} and O_{Out} are the individual occupancy inside and outdoors on the contaminated soil (h y^{-1});

DC_{ExtS} is the dose coefficient for external irradiation from soil (Sv h^{-1}/Bq m^{-3}).

The factor SF_{In} is used to account for the shielding from building walls. However, in this assessment for conservative calculation it is assumed that exposed group does not reside in the building and the term $O_{In}SF_{In}$ is excluded.

Mathematical model for the cap erosion scenario

Consistent with the conceptual model for solid release, it is assumed that an exposed group of ten individuals is living on the contaminated ground and using it as farmland. From the consideration of this model, the following processes and exposure pathways need to be taken into account: erosion of soil, leaching, ingestion of crops, inadvertent ingestion of soil, inhalation of sediment and external irradiation.

The transfer of radionuclides by erosion λ_{Eros} (y^{-1}) is given by:

$$\lambda_{Eros} = \frac{q_{Eros}}{D_{Soil}} \quad (40)$$

where

q_{Eros} is the erosion rate (m y^{-1}) and D_{Soil} is the depth of soil (m).

For other exposure pathways it is possible to use the corresponding equations for the Design Scenario, but with the modification that the concentration in the soil is equal to the concentration in the unleached waste multiplied by a dilution factor to account for the dilution of waste with clean soil.

Mathematical model for radon gas scenario

The mathematical model for ^{222}Rn gas release used in this assessment is taken from the IAEA study on derivation of reference activity limits:

$$E_{Rn} = 2 \cdot Inh \cdot O_{In} \cdot 0.8 \cdot 5.54 \cdot 10^{-9} \cdot \frac{66}{\lambda_{House}} \cdot \frac{S}{V} \cdot C_{W_{Ra226}} \cdot dil \cdot \tau \cdot 0.2 \cdot e^{-\frac{h_2}{0.2}} \cdot e^{-\lambda_{226Ra} \cdot t_1} \quad (41)$$

where

2 Sv J^{-1}= K_1 (effective dose equivalent corresponding to an absorbed energy of 1 joule), 0.8 = f, (equilibrium factor), 5.54 10^{-9} J Bq^{-1} = K_2 (potential α-energy (J m^{-3}) for 1 Bq m^{-3} of Rn-222 in equilibrium with its daughters), 66 y^{-1} = ^{222}Rn decay constant;

λ_{House} is the air renewal rate (y^{-1});

S is basement area (m^2);

V is house volume (m^3);

$C_{w,\ Ra226}$ is the concentration of the unleached ^{226}Ra in the waste (Bq m^{-3} of waste);
dil is the dilution factor (dil = 1 (–));
τ is the emanation factor (–), 0.2 m = H_1 = H_2 (effective diffusion relaxation length for the soil);
h_2 is the cover thickness (m);
$\lambda_{Ra226} = 4.33\ 10^{-4}\ y^{-1}$ is ^{226}Ra decay constant; and
t_1 is the time before the scenario takes place (y).

Mathematical model for aquifer contamination scenario

From consideration of the conceptual model for possible aquifer contamination (Fig. 46), the following processes and exposure pathways need to be considered: leaching radionuclides from the waste, transport in the unsaturated zone, migration in the groundwater, ingestion of the crops, ingestion of the animal products, ingestion of the water, inhalation and external irradiation. In each case it is possible to use the corresponding equations for the Design Scenario. The only difference is that instead of river water, well water is used 500 m from the vaults.

Mathematical model for site dweller - farming scenario

From consideration of the conceptual model (Fig. 47), the processes and exposure pathways that need to be considered are: leaching, erosion, ingestion of crops, inadvertent ingestion of soil, inhalation and external irradiation. In each case, it is possible to use the corresponding equation for the Design Scenario, but with the modification that the concentration in soil is equal to the concentration in the unleached waste multiplied by a dilution factor to account for the dilution of waste with uncontaminated material.

Mathematical model for intruder - excavation scenario

From consideration of the conceptual model (Fig. 48), the exposure pathways for this scenario are: inadvertent ingestion of soil, inhalation and external irradiation. In each case, it is possible to use the corresponding equation for the Design Scenario, but with the modification that the concentration in soil is equal to the concentration in the unleached waste multiplied by a dilution factor to account for the dilution of the waste with uncontaminated material.

2.7.2. Assessment data

As the geological structure and hydrological conditions of the site seem to be the most important for the assessment, the main activity of the RADON Test Case participants dealt with collecting data to clarify them.

A new hydrogeological cross section from the site to the hamlet Doktorovka was built (see Fig. 49). In this representation, the river Kurdyum has no hydraulic connection with the Aptian aquifer. The river and aquifer are divided by a clay stratum of Aptian age (about 15 m thickness) that forms the upper aquitard of the aquifer, and is 25 m down from the riverbed. The water table is about 15 m from the riverbed. All the slopes of the hill around the site down to the river and both villages were surveyed and no spring brooks were found.

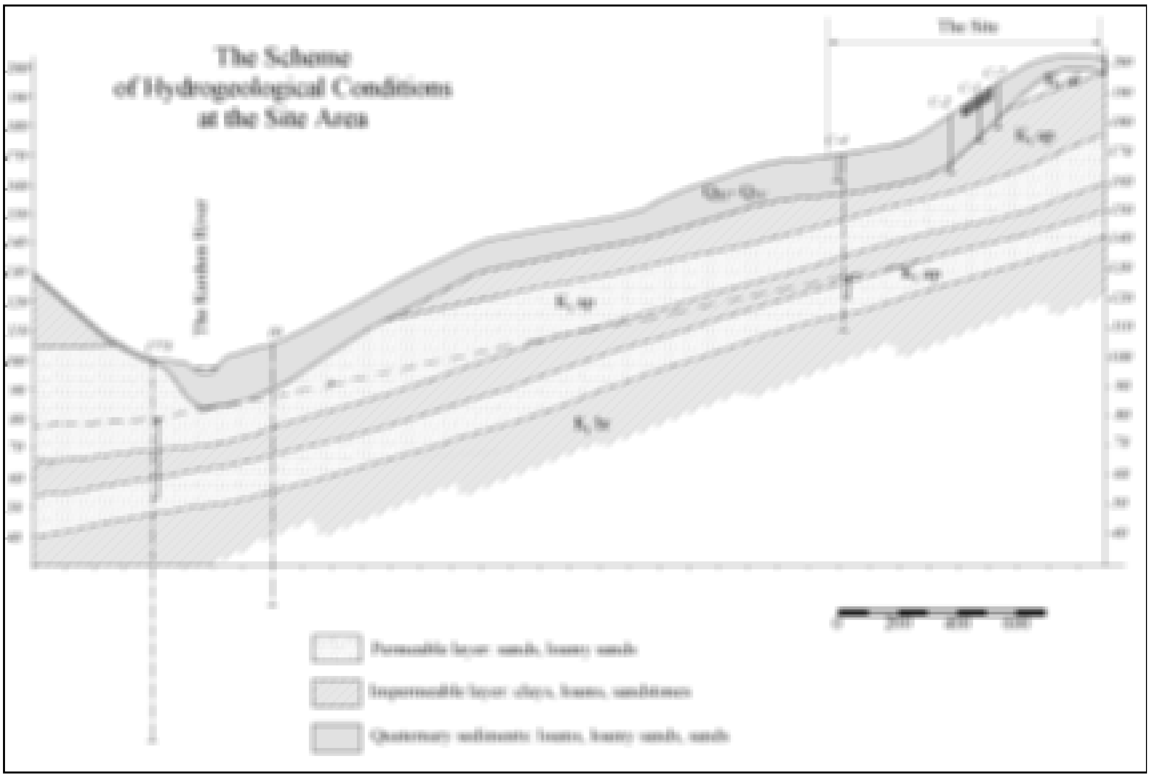


FIG. 49. Hydro-geological Conditions between the Site and Doktorovka Hamlet.

Consequently, the aquifer flow seems to be independent from the perched groundwater. The perched water is unlikely to discharge into the aquifer, but rather to recharge the river. According to the surface relief and geological structure, temporary perched water should flow to the north–northwest. By contrast the local direction of the aquifer flow is west–northwest. Thus, contaminated perched water could discharge to wells in the Doktorovka hamlet and to the nearby river. At the same time water from wells in Kurdyum village (perched water) could not be contaminated from the facility as easily as from river water (Kurdyum village is upstream the Doktorovka). On the other hand the aquifer in the vicinity of Doktorovka seems unlikely to be contaminated from the disposal facility.

Some additional information concerning the biosphere modelling was also collected during this stage.

Information collected during this stage caused the working group to make corresponding changes in assessment context, especially concerning the interface between the biosphere and geosphere. It was also decided to consider only three vaults with solid waste as separate source terms.

The additional data and parameters used for the second iteration are presented in Appendix E.

2.8. ASSESSMENT OF RESULTS: SECOND ITERATION

2.8.1. Results presentation

Before discussing the results, it should be noted that these are initial results. In a real safety assessment further iterations would be undertaken. The calculations were performed with a lack of much site-specific data, and the results were sometimes derived using cautious assumptions to make up for the limitations of the data. For the RADON Test Case, time was particularly limited, which prevented detailed study of the system and collection of many site-specific data that would be available in a real assessment. Furthermore, uncertainty in the evolution of the disposal system and uncertainty in the conceptual and mathematical models developed and used in Section 2.7 should be taken into consideration, when reviewing the results (see Section 2.8.2).

A summary of the second iteration results is presented in Table 33, and in Figs 50–55. Table 33 shows the peaks of annual individual effective dose for each scenario and for each radionuclide. Figs 50 and 51 present the changes of total annual dose over time. It should be noted that for this iteration probabilities were not assigned to the scenarios, so each result is to be viewed independently. As is seen in these figures, the doses for four on-site scenarios (erosion, radon gas, human intrusion: farming, human intrusion: evacuation) were calculated to be higher than the dose constraint (0.1 mSv y^{-1}) (see Section 2.1.3).

The Erosion and Human Intrusion and Farming Scenarios result in the highest doses. The dose rate in these scenarios are more than 0.01 Sv y^{-1}. The peak doses for the Erosion Scenario occur at 7 500 y after closure of the vaults, after cap erosion permits releases. Peak doses for the Human Intrusion: Farming Scenario occurs at 300 years, after the end of institutional control period. At the same time the peak doses are observed for the Human Intrusion: Excavation Scenario.

The highest contribution to the total dose for the Human Intrusion Scenario: **Erosion Scenario** for vaults A and B is from ^{228}Ra, which is the decay product of ^{232}Th. Another decay product of ^{232}Th is ^{228}Th, which also has a significant contribution to the total dose, as well as ^{239}Pu. As there is no ^{232}Th in the vault C inventory, ^{239}Pu is the most important radionuclide in this case. ^{226}Ra with its decay product ^{210}Pb are less important, but still give the high doses (about 1 mSv y^{-1}). The doses from disposal of short lived radionuclides are insignificant for all the on-site scenarios, because there is enough time for decay before human activity on the site is assumed to start. ^{36}Cl is a long-lived radionuclide, but also very mobile and even the low infiltration defined for this scenario results in high leaching and migration outside the system boundary. There is a similar situation in this case for ^{14}C.

The highest contribution to the total dose in case of the **Farming Scenario** for vaults A and B is from ^{137}Cs, ^{210}Pb and both isotopes of Ra. The most important radionuclide for vault C for this scenario is ^{239}Pu. Other radionuclides, which cause high doses, are the same as for vaults A and B, except for ^{228}Ra. The doses from other radionuclides range from 10^{-7} to 10^{-3} Sv y^{-1}. ^{60}Co and ^{152}Eu play insignificant roles in this scenario.

For the **Human Intrusion Scenario** (Excavation) the maximum doses are about a factor of three above the acceptable limit. The main reason for this is that the time spent in the contaminated area is much shorter than for erosion and human intrusion: farming scenarios. The total dose for this case depends mostly on ^{226}Ra (for vaults A and B), ^{226}Ra decay products, ^{228}Ra (for vaults A and B) and ^{239}Pu. Again, the impact from ^{60}Co, ^{152}Eu and in this case ^{3}H is insignificant.

TABLE 33. SUMMARY OF PEAK DOSES FOR DIFFERENT SCENARIOS AND DIFFERENT RADIONUCLIDES, (SV Y^{-1}) FOR THE RADON TEST CASE

	Design scenario	**Erosion Scenario**	**Radon Scenario**	**Aquifer Contamination**	**Human Intrusion: Farming Scenario**	**Human Intrusion: Excavation Scenario**
Radionuclide	Vault AB; Vault C	Vault AB; Vault C	Vault AB; Vault C	Vault AB; Vault C	Vault AB; Vault C	Vault AB; Vault C
H-3	2.00E-14	0.00E+00		5.32E-05	4.76E-07	6.93E13
C-14	2.00E-11	9.80E-05		2.6E-07	7.17E-05	5.12E-09
C1-36	1.02E-07	8.42E-25		6.91E-05	2.52E-03	1.33E-08
Co-60	3.86E-23; 2.71E-24	0.00E+00; 6.80E-40		2.7E-24; 2.70E-24	1.30E-17; 5.08E-17	1.69E-19; 3.68E-19
Sr 90	3.24E-22; 2.58E-23	2.81E-30; 4.36E-16		6.68E-17; 8.74E-17	3.11E-04; 3.92E-04	1.03E-08; 4.48E-09
Cs-137	2.13E-22; 1.25E-24	2.12E-30; 1.8E-12		1.21E-24; 1.21E-24	7.85E-03; 1.51E-02	8.67E-05; 8.5E-05
Eu-152	1.51E-23	0.00E+00		1.43E-24	4.77E-10	6.26E-12
Ra-226	2.65E-21; 1.26E-23	2.15E-03; 3.24E-03		5.16E-15 9.46E-15	1.78E-02; 2.68E-02	1.10E-04; 6.96E-05
Rn-222						
Pb-210	3.73E-21; 7.52E-24	8.30E-04; 1.52E-03		1.28E-14; 2.34E-14	6.86E-03; 1.26E-02	4.18E-06; 2.63E-06
Po-210	1.16E-20; 4.67E-24	2.74E-04; 5.01E-04		4.06E-14; 7.44E-14	2.26E-03; 4.14E-03	7.18E-06; 4.53E-06
Th-232	1.39E-09	1.4E-03		1.96E-06	4.54E-04	1.23E-06
Ra-228	2.84E-08	7.39E-02	1.52E-03; 4.78E-04	4.03E-05	2.26E-02	3.03E-05
Th-228	1.31E-09	1.42E-02		1.85E-06	4.34E-03	5.42E-05
Pu-239	1.96E-19; 2.39E-18	6.73E-03; 2.44E-01		2.31E-07; 8.38E-06	2.53E-03; 9.19E-02	6.16E-06; 7.69E-05
U-235	2.14E-13; 7.80E-12	3.82E-08; 1001E-06		2.82E-10; 1.02E-08	5.53E-08; 1.47E-06	5.45E-10; 6.81E-09
Pa-231	9.90E-12; 3.66E-10	4.31E-07; 1.56E-05		1.31E-08; 4.74E-07	3.93E-06; 1.23E-04	7.54E-10; 9.42E-09
Ac-227	9.95E-12; 3.62E-10	7.17E-08; 2.38E-06		1.31E-08; 4.74E-07	5.66E-07; 1.88E-05	2.62E-09; 3.72E-08
Total	1.02E-07; 7.29E-10	9.97E-02; 2.49E-01	1.52E-03; 9.57E-04	6.91E-05; 8.43E-06	6.77E-02; 1.51E-01	3.00E-04 2.39E-04

Low doses for the **Design Scenario** can be explained due to the long transit times between the repository and the river, and the dilution in the aquifer river flow. Because of this, all short lived radionuclides decay to insignificant levels before they reach the biosphere. The decay for long-lived radionuclides is not so important, but their geochemical properties (K_d) and dilution in river water result in low doses.

As can be seen in Fig. 50, the total dose from vaults A and B for this scenario is more then two orders higher than that from vault C. This difference is caused by the inventory and activity of the waste placed there. The inventory significantly influences the character of the dose curves. For the vaults A and B there are multi-peak curves, while for the vault C there is only one main peak. Figs 49 and 50 show that those peaks are associated with different radionuclides.

Analysis of the changes of the total dose with time for the **Aquifer Contamination** Scenario shows that there are peaks that reflect the distribution of the radionuclides in time and their contribution to the total dose (see for example Fig. 46). As there is a large amount of ^{3}H in vaults A and B, which is extremely mobile, the first peak of the dose is related with a high concentration of these radionuclides in the well water. However, immediately after this peak the next one is observed, which is even higher and is caused by ^{36}Cl. ^{36}Cl is also a mobile radionuclide and has a long half-life. This is the main reason why the dose peak is so high. The next rise in the dose curve appears when ^{14}C reaches the food chain. After that, additional peaks can be seen. They are related to the long-lived radionuclides ^{232}Th and ^{239}Pu and their decay products. At first the dose rises in this period because of ^{239}Pu and becomes larger due to ingrowth of the ^{228}Ra. Some time later the main contribution to the dose is from ^{228}Ra. Although the doses from ^{228}Th and ^{232}Th are significantly higher than from the other radionuclides, their impact on the total dose in this case is not the most important. The total dose curve for vault C is quite uniform, as none of the radionuclides that caused the first three peaks in vaults A and B are in the inventory. The main contributors to the total dose for the vault C are ^{239}Pu, ^{227}Ac and ^{231}Pa.

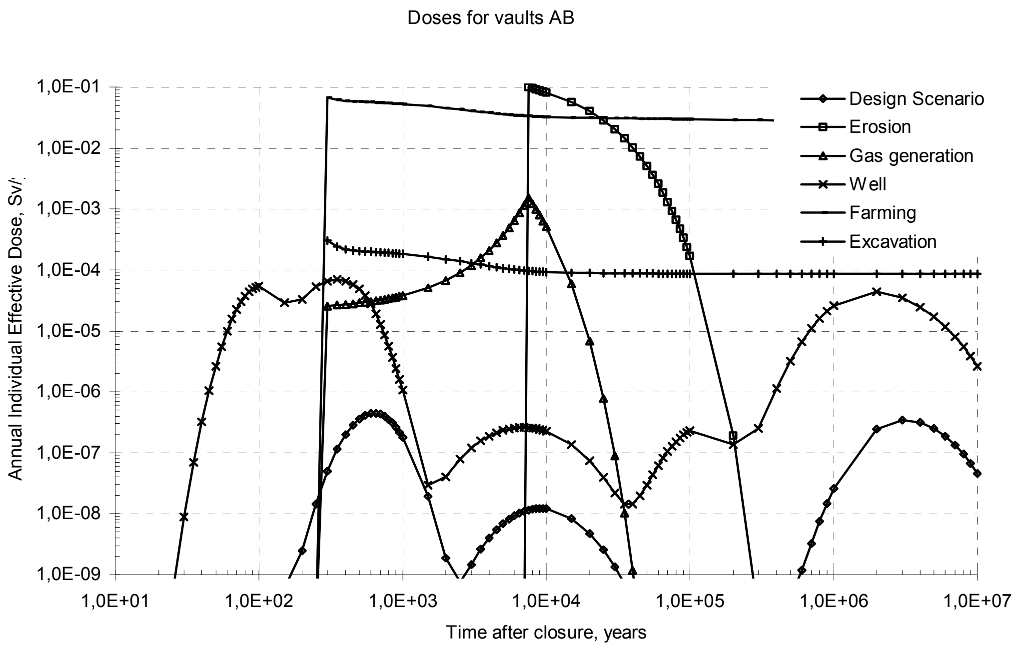


FIG. 50. Doses for Vaults AB for Different Scenarios for the RADON Test Case.

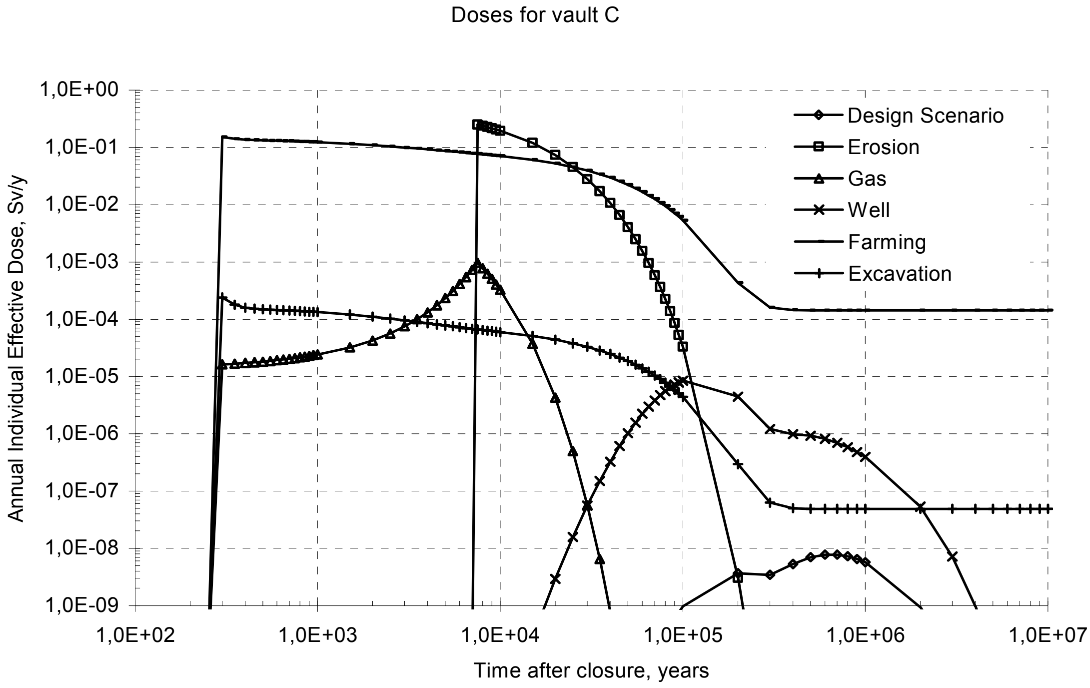


FIG. 51. Doses for Vault C for the Different Scenarios for the RADON Test Case.

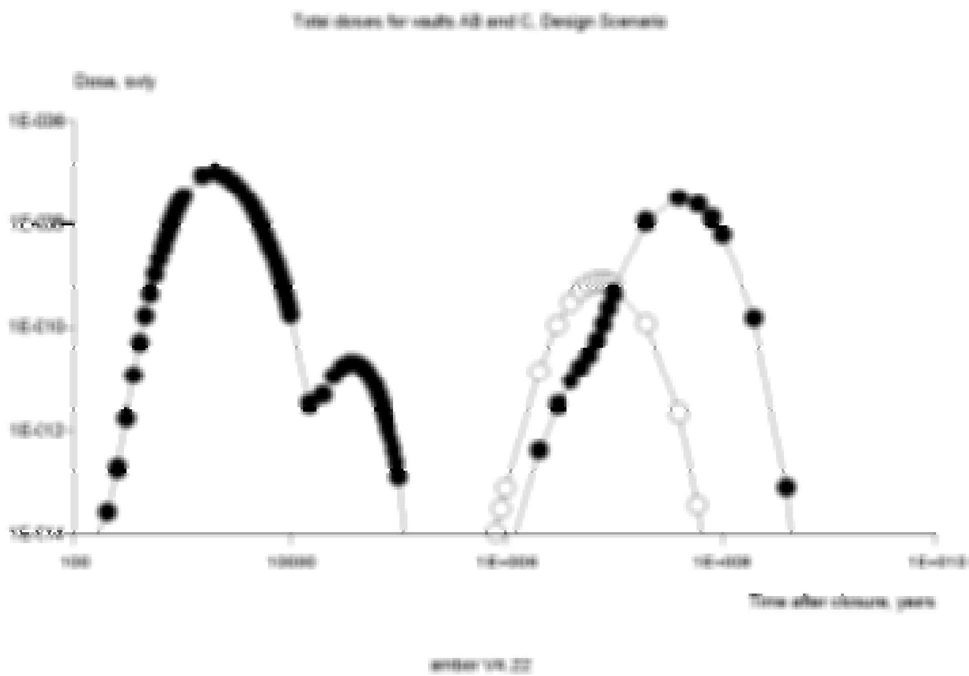


FIG. 52. Total Doses for Vaults AB and C for Design Scenario for the RADON Test Case.

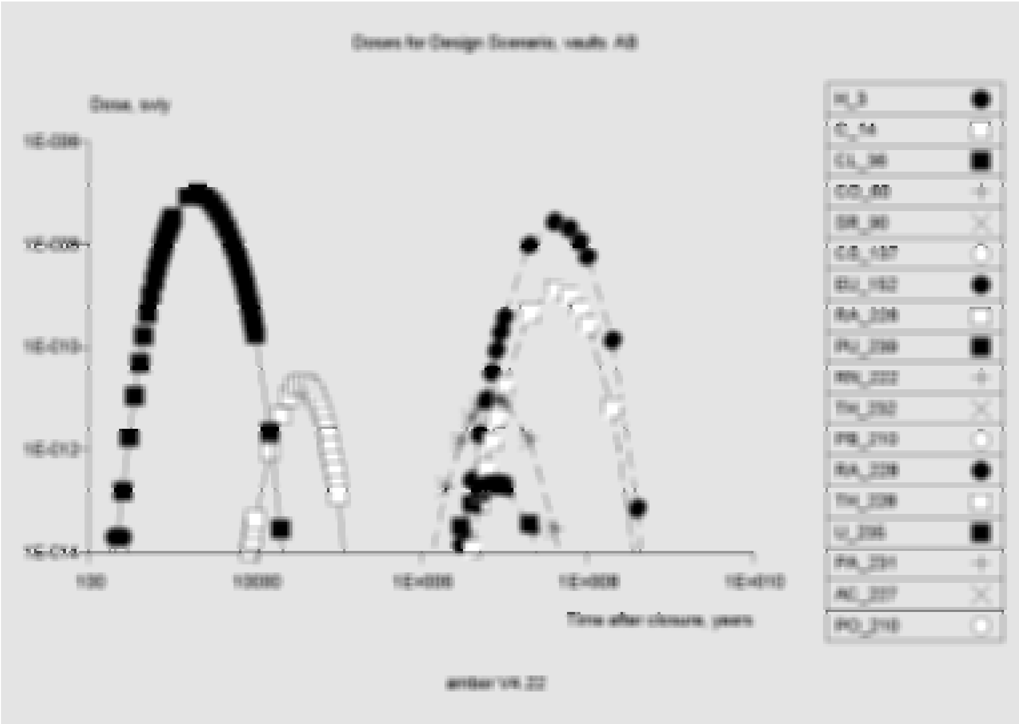


FIG. 53. Dose for Design Scenario, Vaults AB for the RADON Test Case.

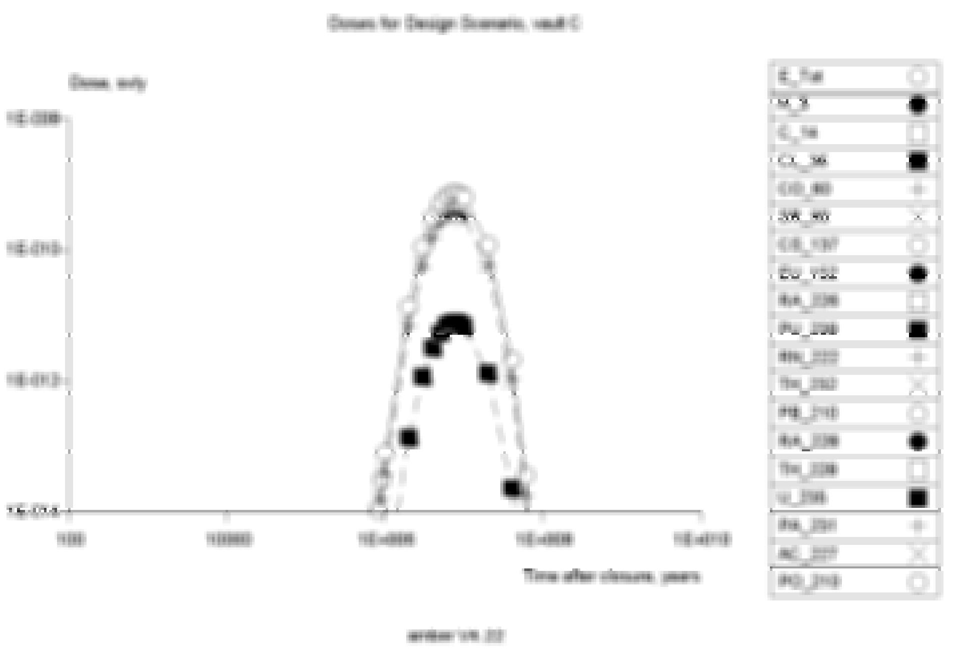


FIG. 54. Dose for Design Scenario, Vaults C for the RADON Test Case.

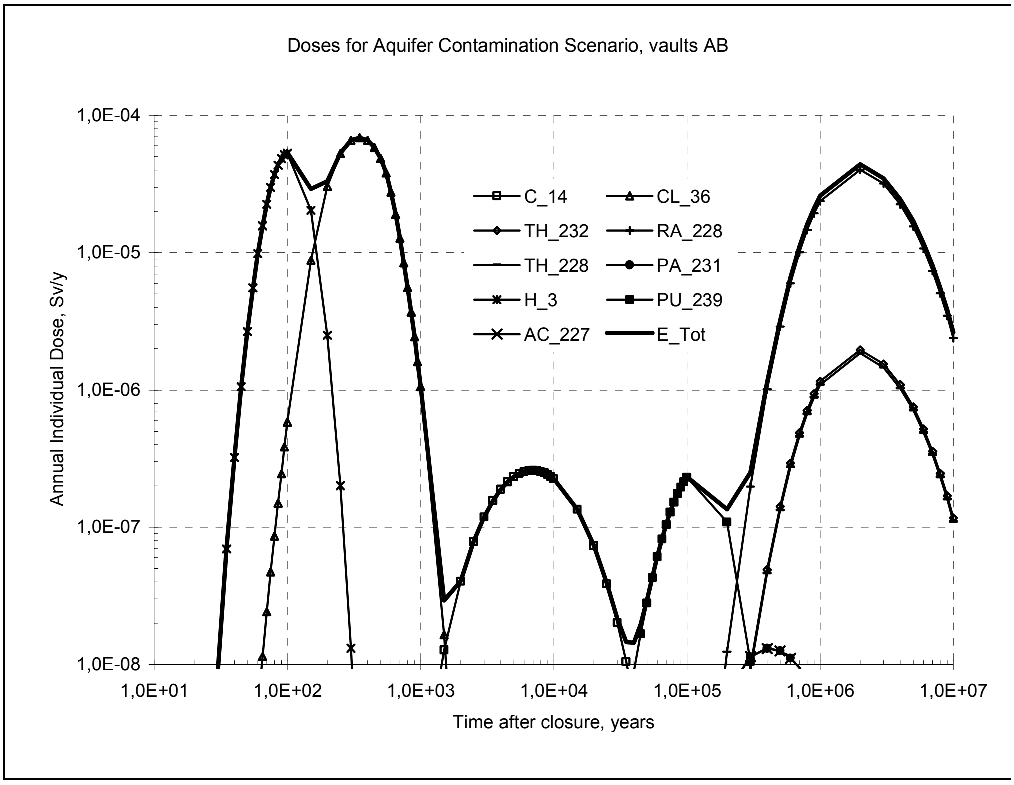


FIG. 55. Doses for Different Radionuclides for Aquifer Contamination Scenario, Vaults AB for the RADON Test Case.

2.8.2. Comparison of results against assessment end points

For the current study, the calculations are rather more conservative than realistic. This report is an initial assessment, and further iterations would be needed for a real disposal facility. The amount of uncertainty will change in the light of new knowledge. Some new data on the site characteristics and the geosphere-biosphere interface could decrease uncertainties and give a more realistic picture of radionuclides leaching and migrating from RADON-type facilities.

2.8.3. Uncertainty analysis

Several kinds of uncertainty occur in modelling any physical system, and a number of these are particularly important in safety assessments. According to the sources from which such uncertainties arise they can be divided into four groups:

— Uncertainty in geological structure and hydrogeological conditions of the site (description uncertainty);
— Uncertainty in the evolution of the disposal system over time (scenario uncertainty);
— Uncertainty in the conceptual, mathematical and computer models used to simulate the behaviour and evolution of the disposal system (e.g. owing to the inability of models to represent the system completely, approximations used in solving the model equations, and coding errors); and
— Uncertainty and variability in the data and parameters used as inputs in the modelling.

Uncertainty in the system description seems to be particularly important for historic facilities. Geological investigations usually take place at the first stage of site development, and data have frequently been lost over the years at such sites. For instance, at Oak Ridge in the USA, a building fire destroyed many inventory records of past disposals. On the other hand, geological descriptions, models of disposal facility behaviour, and general scientific understanding of the behaviour of radionuclides in the environment has developed during the past few decades. Consequently, some data needed today for safety assessment were not studied in the past and are unavailable. Similarly, information that might be important for safety assessments in the future may not be collected now. Such uncertainties have influenced the Design Scenario and alternative scenarios, and the effect can be illustrated by comparing the Design Scenario results for the first and second iterations. To evaluate the uncertainty in hydrogeological conditions, the initial Design Scenario was divided into two cases during the second iteration. These cases were the Design Scenario itself and the Aquifer Contamination variant. In the latter variant, a conservative approach was used when assuming that all infiltrating water goes down to the aquifer and does not form a perched groundwater flow.

Uncertainty in the evolution of the disposal system arises due to the unpredictable nature of system changes in time and due to the unpredictability of future human behaviour. Over long timescales, such as those considered in the RADON Test Case, the natural environment and the engineered waste disposal facility can be expected to change due to natural processes, human actions or interactions between the natural environment and the disposal facility [32]. Even for a well-characterized site, disposal facility and waste, there is uncertainty about the importance or rate of various natural processes, timing and frequency of disruptive events, and human activities. This type of uncertainty can be treated by carrying out safety assessment calculations for a number of scenarios representing possible future states of the site. During the scenario-generation procedure, following identification and classification of FEPs, the general list of events and processes was reduced according to the site description and assessment context. Based on these considerations, some events with a very low probability (e.g. earthquake) are not considered in this study. Some very slow processes, such as climate or geological changes are not explicitly considered as separate scenarios, but their effects can be considered using the set of scenarios evaluated here. During the identification and formulation of the scenarios, expert judgement was used extensively. Moreover, any actual biosphere system can be highly variable as a function of time, and it is not possible to rely on biosphere processes to ensure the safety of disposal. However, some exercises performed previously have shown that the eventual effective dose received by an average member of a small agricultural community is a robust estimator, and the variability of the dose is lower than that of some of the internal parameters (e.g. transfer coefficients). Therefore, the scenarios selected are considered to cover a sufficiently wide range of possible events and pathways for the purpose of an initial assessment. More confidence is given by the fact that these scenarios are consistent with those in the literature [33].

For the current assessment context, the probability of occurrence of the scenario has not been estimated. Use of formal probabilistic approaches to quantify scenario uncertainty has both advantages and drawbacks, which have not been addressed in this test case. Instead, the focus has been on consequence analyses for specified scenarios.

Conceptual model uncertainties represent all uncertainties that arise as a result of assumptions that are made in the course of conducting an assessment. Simplifications are typically made regarding the geometry, boundary conditions, properties, and nature of processes operating on the system. Every choice that is made (e.g. the selection of what process to include) leads to uncertainty. The validity of simplifying assumptions is difficult to estimate due to incomplete knowledge of the system. There is also uncertainty associated with the discretization of the system into separate components. Multiple conceptual models can be used to give some assurance that the results encompass possible system behaviour. It should be noted that significant simplifications to the biosphere were made in the conceptual models in this assessment. Notably, only ingestion of cow products has been considered; sheep, pig, poultry and eggs were excluded. Some processes were omitted as being judged insignificant, such as external irradiation from the atmosphere or animal product contamination due to inhalation.

Uncertainty in the mathematical models arises from approximations required to arrive at solution for the equations used to represent the conceptual model. In many situations there could be an alternative mathematical model, which could be used, and the results will depend upon the model. For this safety assessment quite simple linear mathematical models were used to represent some of complex processes, e.g. linear isotherms to represent the partition of radionuclides between the solute phase and solid phase. The flow in an unsaturated zone has been modelled as a time-average, steady, spatially-uniform infiltration rate, calculated from the total precipitation amount averaged over the year. The degradation of the vaults and containers were approximated by changes in the leaching rate to geosphere. In addition, the same degradation rate for both types of vaults has been assumed, despite the fact that vault C contains more concrete, and leaching processes would likely be different. Additional chemical processes in the special environment in the vault C are also excluded.

The mathematical models in this assessment were implemented using the *computer code* AMBER. This computer tool has been verified and used successfully for assessing the environmental impact from a wide range of different sources of contamination. Thus, the uncertainty related with coding errors associated with the numerical solver is assumed to be negligible. However, the mathematical models for the conceptual models were in some cases simplified to adapt them into AMBER. For example, the radioactive inventory has been considered to be regularly distributed in the disposal facility and one-dimensional models for radionuclide migration were used. Similarly, the use of a compartment model like AMBER tends to introduce numerical dispersion compared to more rigorous numerical methods. On the other hand, more complex or detailed models and calculations do not always give more accurate result, especially if the existing information and data about the disposal facility is insufficient to make more detailed evaluations.

The model uncertainty may be quantified by analysing the results from a set of similar models. An example of model influences on the final result is found in the Radon Gas Scenario. According to the conceptual model used in this study, the thickness of the cap was linearly decreasing over time due to erosion. To illustrate the role of the cap thickness, another scenario was constructed where the thickness of the cap was assumed to be constant. The result of this change is presented in Fig. 56. As seen, the difference between the maximum dose could be about two orders of magnitude for 1.5 m of cap.

However, not all models are so sensitive. Another example is given for Erosion Scenario, which produced the highest dose in the assessment. For this scenario it was assumed that infiltration before the erosion of the cap is lower than for the Design Scenario. If it is assumed that the flow through the facility is the same for both scenarios, the maximum dose for the new model (Erosion modified) is only slightly lower (see Fig. 57).

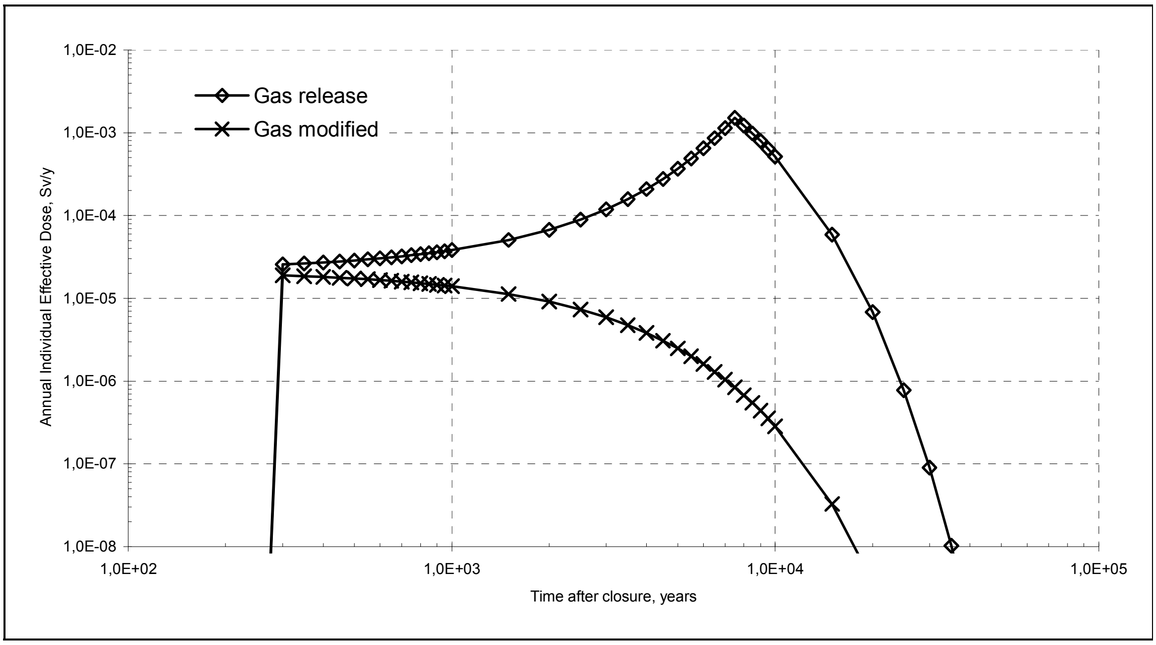


FIG. 56. The Influence of Model Changes for the RADON Test Case Radon Gas Scenario, Vault AB.

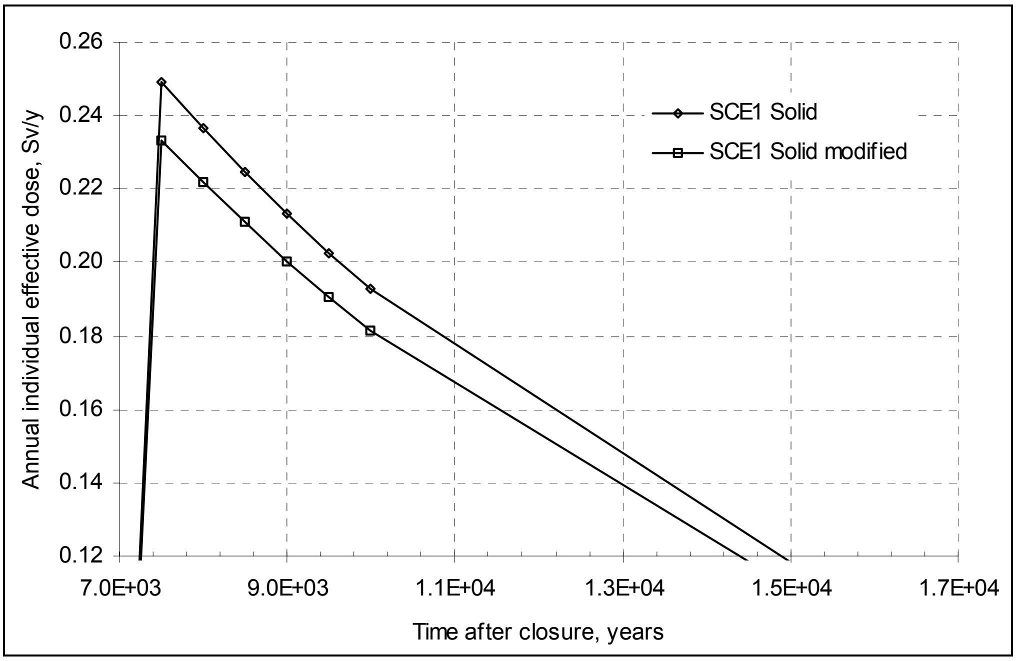


FIG. 57. The Influence of Model Changes for the RADON Test Case, Erosion Scenario, Vault C.

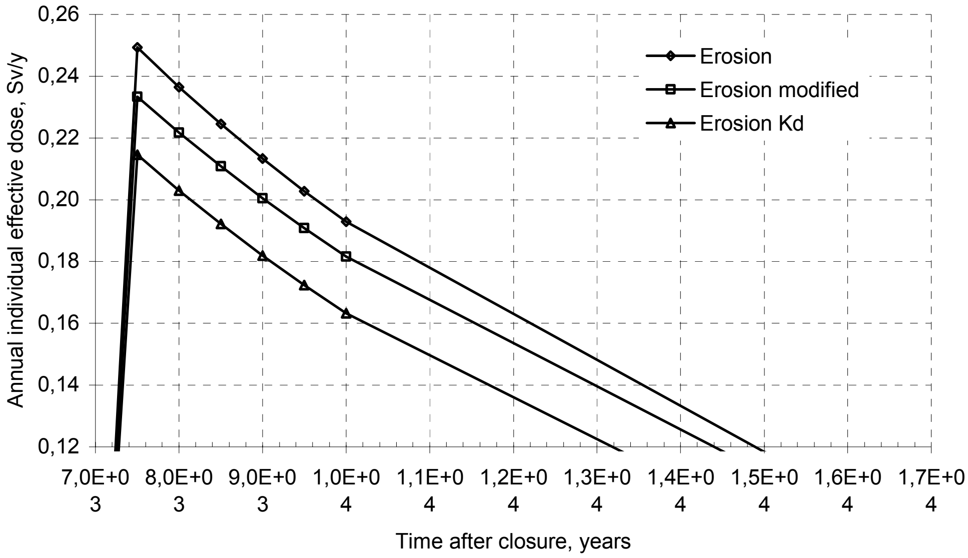


FIG. 58. The Influence of K_d Value to the Individual Annual Effective Dose, for the RADON Test Case Erosion, Vault C, ^{239}Pu.

Parameter uncertainty can be defined as uncertainty that arises in selecting values for parameters in the various models. There are many parameters in this assessment that are uncertain. First, there are insufficient data about the site climatic, geological and hydrological conditions. As a result, such parameters as sorption coefficients, moisture content, river flow rate, river depth and width, hydraulic gradient in the aquifer, and erosion rate are taken from the general literature. Some parameters used need to be specified more accurately, e.g. evaporation or distance between the disposal facility and the river, and between the disposal facility and residences (for Design Scenario). There is also a lack of some information about the facility: e.g. vault dimensions and container parameters. Second, human exposure data (ingestion of water, animal products, occupation time outside, etc.) are taken from [3]. More site-specific information would be useful.

An example to illustrate the role of the key parameters is presented below.

Also further modification of the Erosion Scenario was performed (Erosion Kd). It was assumed that K_d values are 50% of the values used for the original calculations. The results for all three Erosion Scenario cases are presented in Fig. 58. As seen, this new change reduced the dose by much less than a factor of two.

2.8.4. Confidence building

The Results from the RADON Test Case can be compared against results from other assessments to help build confidence, although care must be taken to ensure the compatibility of the comparison. In order to check the values derived from this study, a comparison was undertaken between them and the values derived by another IAEA study [3]. The Human Intrusion: Farming Scenario results were compared against the IAEA Residence on the mixed waste (trench case) scenario under temperate conditions for sand geosphere when the time before the scenario starts is 300 y. When comparing results, there is good agreement (less than one order of magnitude) for all radionuclides, except for ^{60}Co (Table 34). The minor discrepancies arise due to differences in some parameters, e.g. bulk density, between the two studies.

TABLE 34. COMPARISON OF LIMITING CONCENTRATIONS (BQ/KG) FOR THE RADON TEST CASE HUMAN INTRUSION: FARMING SCENARIO (VAULTS AB) AND THE RESIDENCE SCENARIO FROM [3]

Radionuclide	This study	IAEA [3]
H-3	1.82E+13	5.00E+12
C-14	1.51E+06	4.00E+05
Co-60	>1E18	>1E18
Sr-90	5.00E+06	1.00E+06
Cs-137	3.43E+07	9.00E+06
Ra-226	2.95E+03	9.00E+02
Th-232	2.23E+03	6.00E+02
Pu-239	1.12E+05	7.00E+04

Initially, relatively poor agreement is found when comparing the Excavation Human Intrusion: Scenario and the road construction scenario under temperate conditions considered in [3]. The reasons for the discrepancies, about two orders of magnitude, are due to differences in the conceptual and mathematical models used in the two studies. To evaluate the influence of these differences, calculations for the Human Intrusion: Excavation Scenario were performed, using the same occupation time on the contaminated ground and the same model for dust level above the surface as in the IAEA road construction scenario. The results of the calculations are presented in Table 35. The discrepancies in this case were mostly less than one order of magnitude. Some minor disagreements arise for the same reasons as for the Human Intrusion: Farming Scenario.

TABLE 35. COMPARISON OF LIMITING CONCENTRATIONS (BQ/KG) FOR THE RADON TEST CASE HUMAN INTRUSION: EXCAVATION SCENARIO (VAULTS AB) AND THE ROAD CONSTRUCTION SCENARIO FROM [3]

Radionuclide	This study	This study, after modification	IAEA [3]
H-3	1.25E+19	2.07E+18	8.00E+17
C-14	2.11E+10	3.43E+09	1.00E+09
Co-60	>1E+20	>1E+20	9.00E+19
Sr-90	1.51E+11	2.51E+10	1.00E+10
Cs-137	3.10E+09	5.18E+08	3.00E+08
Ra-226	6.52E+05	1.09E+05	6.00E+04
Th-232	7.12E+05	1.19E+04	5.00E+04
Pu-239	4.62E+07	6.72E+06	3.00E+05

2.9. LESSONS LEARNT AND CONCLUSIONS

The RADON Test Case met the objectives defined in the ISAM project. The assessment was conducted according to the ISAM project methodology, and represents an initial attempt to apply such a methodology to a RADON-type disposal facility. As a result, a number of important initial steps have been taken during this exercise.

— It must be recognized that the RADON Test Case was developed under specific conditions and constraints, the most important of which are the following: The assessment was based on a hypothetical mixture of realistic site descriptions with vaults and waste inventories from different sites. Consequently, the specific modelling results should not be interpreted as having significance for any real RADON-type disposal facility. Instead, the value of the test case has been using the ISAM methodology, which can be used at specific real RADON-type disposal facilities.

— Some information on inventory, waste characteristics, etc. was not available and therefore the disposal inventory should be considered illustrative. Specific attention should be paid to the inventory of Pu-239 that needs to be re-evaluated in the performance of a real safety, as it seems that the assumed inventory exceeds the real one typical for assessment RADON-type facilities.

— One of the key outcomes of the RADON Test Case was a rather broad agreement on high-level assumptions and concepts that should be applied in the assessment context, as at the outset of the ISAM project, there was little agreement among participants as to appropriate assumptions for a sensible assessment context. Participants in the RADON, Test Case from a number of countries having RADON-type disposal facilities gathered to discuss these issues. Similarly, when discussions began on the system description part of the assessment, there was considerable discussion among participants about specific conditions that would represent conditions at real RADON-type facilities. It was discovered that there was more variability among practices at these facilities than was previously understood.

— The scenario analysis conducted for the RADON Test Case represents one of the first applications of scenario analysis to these facilities. The high-level ISAM FEPs list is a very useful tool for safety assessment. It was used in a limited way for scenario development, but more as a checklist to audit the scenarios after they were developed.

— Implementation of models to assess the consequences of releases in the RADON Test Case led to a number of observations:

— Conceptual and mathematical modelling can be applied to the calculation of end points (e.g. doses), and also to identify missing data necessary for the safety assessment. This second approach is particularly important for historic RADON-type facilities, at which some types of information are missing. These information gaps exist because some important parameters were not investigated during site selection and operation, also because records and other types of information have occasionally been lost.

— The overall model requires the implementation of a biosphere component including human behaviour, especially when safety criteria in the assessment context are expressed in terms of dose or risk rather than the contaminant concentration in the environment.

— The complexity of each component of the model, particularly those dealing with groundwater flow and transport, depend on the assessment purpose, as well as available data and knowledge of the system. Care must be taken when combining different kinds of models into a joint system.

— Data quality is one of the key points in confidence building. The safety assessment shows that one of the most important pieces of information is the inventory, especially for a historical facility. Flow and sorption properties of surrounding rocks are very important for contamination transport in groundwater although the results of solid release scenarios do not depend significantly on these data. The ISAM project methodology was found to be effective in identifying which data would be most important to obtain.

— Within the RADON Test Case a limited number of scenarios were considered and calculated. In particular, in this test case, solid releases of radionuclides from the near surface facility lead to higher doses than did groundwater releases. Solid releases were modelled as an aftermath of either erosion or human intrusion. Though both cases seem unlikely to occur in present conditions, the results show that these scenarios provide the potential for significant doses once institutional control over the site is lost. It also means that long term study of erosion process at RADON-type facilities may be appropriate to obtain specific data. Each approach for scenario generation could be implemented for appropriate conditions for a specific facility. At the same time it was considered helpful to develop a generic list of scenarios specific to RADON-type facilities. This could be done on the basis of specific features of typical disposal units at RADON-type facilities, taking into account typical geological and hydrogeological conditions at their sites. For example, in the Russian Federation the 16 existing sites could fit in a smaller number of categories. These scenarios should be verified using the FEP screening procedure for each specific facility. Additional scenarios might be developed if needed.

— Two iterations were made and the associated results calculated. The iterations were the result of obtaining new data, and clarification of existing data, which occurred during the period of the ISAM project. These differences are:

— The Design Scenario calculation for the first and second iterations differ from each other in the hydrogeological conditions assumed. Additionally, in the first iteration all disposal units were considered as a single source term with the total activity, while in the second iteration the vaults were considered separately, and the trenches and the borehole were excluded from calculations. Accordingly the activity taken into account in the second iteration was less, but the calculated dose appeared to be higher than in the first iteration. This discrepancy can be explained by the following distinctions between the models: differences in the hydrogeological model, differences in transport modelling, and more detailed biosphere modelling in the second iteration.

— The first iteration of the Design Scenario used a detailed hydrogeological model, including both the unsaturated and saturated layers. By contrast, the second iteration uses simplified conservative models assuming either absolute impermeability of the clay layer aquifer overlying the Aptian or uninhibited movement of infiltrating water into the Aptian aquifer. Transport modelling in the first iteration was based on an assumption that some part of contaminants dissolved in ground water is retained by surrounding rock and cannot be desorbed in the future. In the second iteration the sorption-adsorption mechanism was considered simply as retardation. In this case, activity decrease in the ground water is caused only by natural decay of radionuclides with time.

This investigation is one of the first such analyses conducted for a RADON type disposal facility and the approach was found to be very useful for test case participants to understand the overall disposal system better.

3. BOREHOLE TEST CASE

The Borehole Test Case is based on the BDC (Borehole Disposal Concept) concept, which was developed as part of an IAEA AFRA Technical Corporation (TC) project [36]. The concept, which is still under development, is intended to provide a solution specifically for the disposal of disused radiation sources and therefore must take into consideration the size and number of the sources (i.e. the volume) that need to be disposed. AFRA is an Africa regional project and consequently the purpose of the BDC concept is to provide African countries with a solution for the long term management of their disused sources.

Some small changes and simplifying assumptions were introduced to make the BOSS disposal concept suitable for the Borehole Test Case. This approach provided the opportunity to evaluate additional aspects of a concept that is still under development.

3.1. SPECIFICATION OF ASSESSMENT CONTEXT

3.1.1. Purpose

At each stage in the development of a waste disposal facility, safety assessment is normally required to support management and regulatory decisions, as is new information and data. Furthermore, the scope content and site-specific nature of the safety case normally increase with each phase, as illustrated in Fig. 59. It is recognized that the regulatory safety assessment cycle is an ongoing iterative process.

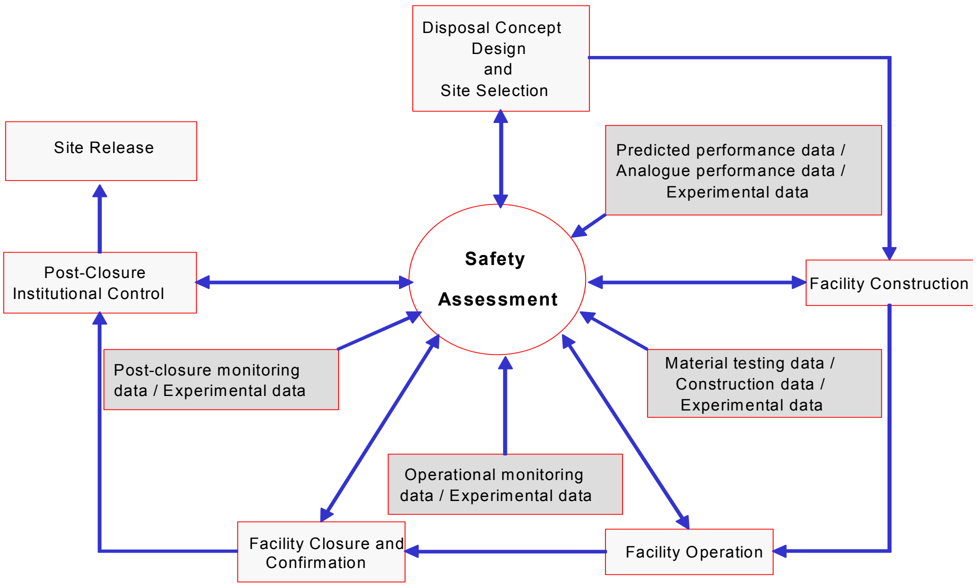


FIG. 59. Relationship between a Radioactive Waste Disposal Site Life Cycle and Safety Assessment.

This safety assessment is the first to be developed following the site selection process. Past assessments have been relatively simple and have not used all of the available data. It is recognized that additional iterations of the safety assessment process are very likely to be required in the future.

The aim of this assessment is to develop the borehole disposal concept further by testing its suitability at the selected site, under specific site and land use conditions. Only currently available information will be used. The most important uncertainties will be identified, with suggestions about further data collection and/or alternative conceptual models that may be the subject of future safety assessment iterations.

Another important objective of the test case is to increase confidence that the site and concept design will be suitable for disused source disposal and that future investment in concept development, site characterization and other activities will be worthwhile.

The safety assessment will illustrate progress towards demonstrating adequate safety (i.e. compliance with the regulatory requirements) but it is too early in the assessment cycle to demonstrate complete compliance with the set of regulatory requirements for authorization of disposals as set out in Section 2.1.3.

The ISAM Borehole Test Case is only to assess post-closure safety The operational safety aspects will not be considered. The assessment considers impacts on humans only; other biota is not considered.

The assessment will only consider radiological impacts; chemical or biological toxicity will not be assessed. It is recognized that this issue may be important, but it is assumed that it would be dealt with in a separate safety assessment aimed at compliance with different environmental regulations.

3.1.2. Target audience

The target audience (stakeholders) for the Borehole Test Case is assumed to be a hypothetical regulatory body and staff involved in producing the safety assessment. Other possible stakeholders such as the public or other interest groups have not been considered at this stage.

3.1.3. Regulatory framework

There is no legal regulatory framework for the safety assessment and consequently the regulatory framework has been developed for the purposes of the ISAM Test Cases. It is not based on the regulations for any particular country but is based on broadly accepted international principles (e.g. IAEA WS-R-1 ICRP 60). In particular, these are not the regulations for South Africa where the hypothetical borehole facility is located.

The provisional requirements in the framework should not be assumed to be a comprehensive set of requirements that would be needed in a comprehensive national regulatory structure, nor are they the only ones that might be adopted. The intent of this report is to assess the potential for the safe disposal of disused sources in a borehole. Consequently, a provisional set of requirements will be assumed for the purposes of this report. The regulatory framework is founded on four basic requirements set out below. Some additional guidance is also provided.

(b) Requirement No. 1 – independence of safety from controls

Following the closure of the disposal facility, the continued isolation of the waste from the accessible environment should not depend on actions by future generations to maintain the integrity of the disposal system.

(c) Requirement No. 2 – effects in the future

Radioactive wastes shall be managed in such a way that estimated impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.

The practical implication of this requirement is that there is no time cut-off limit beyond which impacts need not be considered, and there will be no discounting of doses in the distant future. Nevertheless, it is recognized that calculated doses in the far-distant future may be less relevant than those in the near-term future, and it is expected that qualitative judgement should play a role in determining the meaning of calculated doses. Following closure of the disposal facility, estimated impacts should be constrained to a fraction of the dose limit.

(d) Requirement No.3–- optimization

The radiological detriment to members of the public that may result from the disposal of radioactive waste shall be as low as reasonably achievable (ALARA), economic and social factors being taken into account. The ALARA principles cannot be rigorously applied to post-closure safety, since the notion of population dose is poorly defined for future populations. As a result, ALARA will be applied in an informal, common sense fashion.

(e) Requirement No. 4 – radiological protection criteria

The assessed radiological impact of the disposal facility must be consistent with a dose constraints applied to ensure compliance with the internationally accepted effective dose limit of 1 mSv in any one year [6], excluding natural background radiation and medical procedures. A dose constraint of 0.3 mSv y^{-1} will be applicable for an individual dose to humans for the illustrative purposes of this investigation.

After closure, it is assumed that the site may continue to be managed and be subject to regulation, including licensing or monitoring. However, it is recognized that institutional control relies on the active presence of stable institutions, and that human institutions are transient. Some of the nations in Africa have relatively short histories of institutional memory and control. Consequently, a short control period is chosen, and there will be an assumption of 30 years of active and passive institutional control. Following this time period, it will be assumed that there is no societal memory of the existence of the disposal facility. It should be noted that this institutional control period is quite pessimistic compared to values used in other parts of the world. The effect of adopting a conservative assumption regarding control will be to provide a greater assurance of safety.

3.1.4. Assessment endpoints

The assessment endpoints need to correspond with the regulatory requirements, hence the individual effective dose will be calculated to demonstrate compliance with regulatory requirements No's. 2, 3 and 4 given in Section 3.1.3. A dose constraint of 0.3 mSv y^{-1} will be assumed.

Other useful performance indicators such as radionuclide fluxes emanating from each barrier, radionuclide concentrations in the geosphere and biosphere, etc. may be calculated to compare with background radiation levels.

3.1.5. Assessment philosophy

The assessment will follow an *iterative approach,* which means that one must expect that the safety assessment will have to be repeated two or more consecutive times. The advantage of such an approach is that it allows use of information from the previous iteration to refine the design of the system and the collection of additional data. It also reduces the tendency that the assessment will focus on one component at the expense of others.

The basis of the assessment will be *site-specific prospective evaluations.* Site-specific emphasizes the fact that the assessment should include data from the actual disposal system assessed. Where necessary, existing site-specific data will be supplemented by generic data available from the literature. The intent of the modelling studies is not to predict actual system behaviour in the future, but rather to understand its behaviour better and to reflect the importance of specific components with respect to compliance with regulatory criteria.

Generally, safety assessments of radioactive disposal systems are not an exact procedure. For this reason, a *reasonable assurance* approach will be followed in the assessment. The aim of such an assessment is to reach defensible decisions on the extent to which the disposal system may comply with the regulatory criteria. The safety assessment is seen as a decision-aiding tool to help determine the conditions for which reasonable assurance of compliance with safety objectives can be provided. The results will therefore be largely a function of the data, design and assumptions used in the analysis. Changes in any one of these conditions can change the conclusions of the assessment [37].

A significant amount of information and data are available on the Vaalputs site, while data is lacking on the engineered part of the facility. It would therefore be possible to follow a realistic approach for the safety assessment to a certain level. Where data are lacking, the assessment will be given a conservative bias. However, it must also be recognized that the use of extreme or unreasonable levels of conservatism can lead to unreasonable decisions. Consequently, in practice there needs to be an appropriate balance between conservatism and rigor in the analyses [38].

3.1.6. Assessment timeframe

The regulatory requirement stipulates that there is no cut-off beyond which impacts need not be considered. Therefore, it is recognized that the safety assessment developers need to define and justify the approach to time dependence. It should be noted that this does not mean there is a regulatory requirement for time-dependent modelling, only that the approach taken needs to be adequately justified. The timescales used for quantitative assessment will be justified on the basis of scientific credibility. 10^4 years is proposed as a reasonable timescale for the main quantitative assessment. Simple bounding calculations could be carried out for longer time periods.

Regulatory requirements state that the operating company should not assume more than 30 years of active institutional control of the site following the end of disposal operations. Active control measures include site security fences, environmental monitoring, repair work, etc. The withdrawal of controls by the operating company may be termed ‘site closure’ and marks the start of the post-closure assessment period. After the institutional control period, the site becomes accessible and no records or knowledge of the existence of the site remains.

3.1.7. Disposal system characteristics

The ISAM Borehole Test Case is being developed for a borehole disposal facility with intermediate depth (40 m to 100 m). It was originally proposed that disposal of disused sources above or below the water table would be tested, i.e. in the unsaturated or in the saturated zone. However time constraints only allowed the assessment of disposal in the unsaturated zone.

FIG. 60. Location of Vaalputs in the Northern Cape Province of South Africa.

The facility design, as described more fully in Section 3.2., is based on the BOSS disposal concept and makes provision for the disposal of disused radiation sources. The inventory is typical of one found in an African country and includes short lived isotopes such as ^{192}Ir and long-lived isotopes such as ^{226}Ra.

The hypothetical location of the site has been chosen as Vaalputs located in the District of Namaqualand 90 km south east of Springbok in the Northern Cape Province of South Africa, as shown on the map in Fig. 60. System description information for the Vaalputs geosphere and biosphere is provided in Sections 3.2.2 and 3.2.3 respectively.

Two land use conditions have been assumed for the assessment. The first condition considers continuation of current land use, characterized by small farms and agricultural activity to the extent supported by the local climate. For this purpose the assessment is based on current human behaviour, habits and actions at the site and if necessary analogue sites. Urban and industrial land uses are deemed unlikely due to the geographical location of the site. The second condition is a reversion to traditional human behaviour, characterized by hunter-gatherer land uses. The basis for this condition is that, historically, Namaqualand was inhabited by Bushmen and therefore the possibility exists of a societal change to traditional behaviour after loss of institutional control and any societal memory of the disposal site. Furthermore, a Bushmen reserve currently exists some 500km from the Vaalputs site, where Bushmen live in the traditional hunting way of life.

These two conditions suggest that no attempt is made to evaluate the impact of technological development. Also, no attempt is made to predict advances in human society and institutions, as such predictions would be difficult to justify.

In line with regulatory requirement No.1 (Section 3.1.3), the test case will assume that the continued isolation of the waste from the accessible environment will not depend on actions by future generations to maintain the integrity of the disposal system. Therefore, issues such as retrievability, remedial actions and monitoring after site closure will not be considered.

3.2. DESCRIPTION OF THE DISPOSAL SYSTEM

The disposal system is described in terms of:

— The wastes;
— The engineered and natural barriers expected to contain the waste for a period of time;
— The potentially contaminated geology and surface environment; and
— The geology, surface environment and human behaviour necessary to provide an estimate of the movement and the potential exposure of human beings to the radionuclides on the longer term.

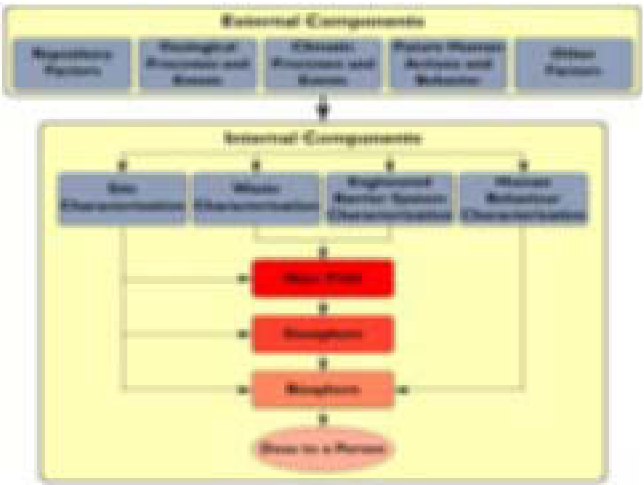


FIG. 61. Representation of the Different Components of a Disposal System, and the Associated Flow of Information.

From a safety assessment perspective, the disposal system provides a description which is necessary to determine how radioactive materials may migrate from the disposal facility; the paths along which it can migrate; and the effect that it ultimately will have on human beings. A conceptual representation of the disposal system, its associated components and the flow of information through the system are shown in Fig. 61. From Fig. 61 it is clear that the disposal system concept provides the necessary information to describe, analyse and evaluate the fate and transport of activity through what is known as the near field, the geosphere and the biosphere. The subsequent results of these analyses facilitate the calculation of doses to human beings, and therefore the potential impact of the radioactive waste disposal facility.

3.2.1. Near field

Waste inventory

The waste inventory is typical of what one would found in an African country and ranges from short lived isotopes such as ^{192}Ir to long-lived isotopes such as ^{226}Ra. It consists of various types of disused radiation sources from medicine, industry and education. The inventory adopted for the Borehole Test Case is that of Algeria, with the addition of the ^{109}Cd and ^{99m}Tc sources from Ghana. The details of the inventory and associated waste characteristics are presented in Table 36.

TABLE 36. THE INVENTORY AND ASSOCIATED WASTE CHARACTERISTICS THAT WILL BE USED FOR THE ISAM BOREHOLE TEST CASE

Isotope	**Half-life (y)**	**No. of Sources**	**Activity per Source (Bq)**	**Total Activity (Bq)**	**Dimensions**	**Application**
^{99m}Tc	6.86E-04	1	4.99E+09	4.99E+09	-	Nuclear Medicine
^{192}Ir	0.202	22	3.70E+12	8.14E+13	3 mm height 3 mm diameter	Gammagraphy
^{57}Co	0.742	4	1.85E+05	7.40E+05	-	Medicine
^{109}Cd	1.27	4	1.11E+08	4.44E+08	-	X ray fluorescence
^{60}Co	5.60	2	3.70E+09	7.40E+09	3.2 mm height 3 mm diameter	Level Gauges
^{137}Cs	30.60	11	2.78E+09	3.05E+10	6 mm height 4 mm diameter	Gamma densitometers
		5	5.55E+10	2.78E+11	6 mm height 4 mm diameter	Well Logging
^{241}Am	412	560	1.85E+05	1.04E+08	6 cm diameter 5ìm thickness	Smoke Detectors
		9	5.55E+05	5.00E+06		
^{226}Ra	1600.00	6	3.70E+06	2.22E+07	10 cm height 3.5 cm diameter	Calibration
		3	1.11E+05	3.33E+05	7 cm height 5 cm diameter	Teaching
^{239}Pu	2.41E+04	1	3.70E+09	3.70E+09	2 x 5 cm diameter ìm thickness	Static Electricity Removal

The purpose of the facility is to dispose disused sources using a borehole disposal concept. The design of the facility should therefore contribute to the general aim of the safety concept for near surface disposal systems. Fundamental aspects to take into consideration in the design of the facility are:

— The dimensions of the borehole allow for the disposal of disused sources in suitable waste packages;
— The design of the borehole take into consideration the operational requirements, e.g. waste emplacements takes place as a matter of routine over the period during which it operates;
— The design minimizes the need for active maintenance after site closure and compliment the natural characteristics of the site to reduce environmental impact; and
— Human intrusion (advertent and inadvertent) into the borehole is difficult.

Conceptually, the disposal concept comprises a borehole drilled down to a depth of several tens of metres, as shown in Fig. 62. The waste can be disposed either above or below the water table.

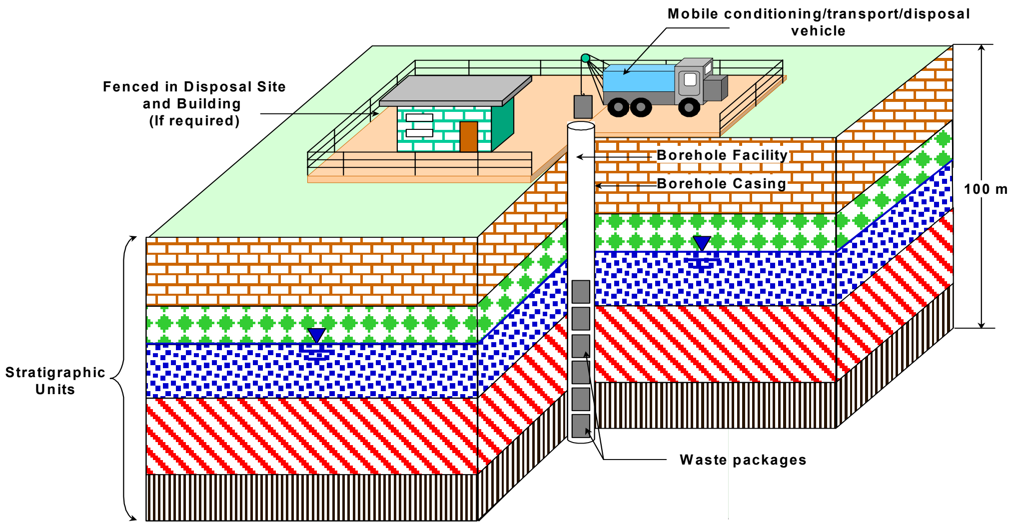


FIG. 62. A Schematic Presentation of the Disposal Facility Area of the Borehole Disposal Concept (Not to scale).

The borehole will be constructed using the percussion drilling method. It is a 305 mm (12 inch) diameter borehole through the weathered zone that is narrowed to 254 mm (10 inch) diameter in the hard rock zone, as sown in Fig. 63. A 300 mm casing will be fitted through the weathered zone to keep loose material from falling in. A 203 mm (8 inch) PVC casing will be fitted to the bottom of the borehole, where it will be driven through a wet cement plug. Due to the possible corrosiveness of the water/soil, the borehole casing will be a PVC. PVC casings are comparable in terms of cost and availability with carbon steel casings. The design might also change for the saturated and unsaturated conditions. To ensure that the disposal volume is dry during the operational period, a bottom plug is provided. The disposal area can be fenced off to limit access, and a temporary site office can be erected.

For the purpose of the test case, it was originally proposed that two types of borehole configurations would be considered. In the first configuration, it is assumed that the disposal zone is completely in the unsaturated zone. Therefore, the borehole only extends down to a depth of 45 m, which is 10 m above the piezometric level. In the second configuration, it was to be assumed that the disposal zone is in the saturated zone. Therefore the borehole extends to a depth of 100 m. In both cases, waste packages (containers) are only stacked in the bottom 10 m of the borehole. However, due to time constraints only the first configuration was considered.

By definition, the borehole will not be fitted with a cap; the top 3 m will be filled with topsoil to conceal the location of the borehole. The concrete backfill will also serve as a plug.

Waste package description

The waste packages play a very important role in the safety of the borehole disposal concept. It's primary function as an engineered barrier is to provide practically complete confinement of the radionuclides in the disposed sources for a predetermined period, after which the waste package is likely to degrade, allowing direct contact of the sources with the near field components and groundwater. The near field components may control the release of radionuclides for a further period, after which all activity will be available for transport

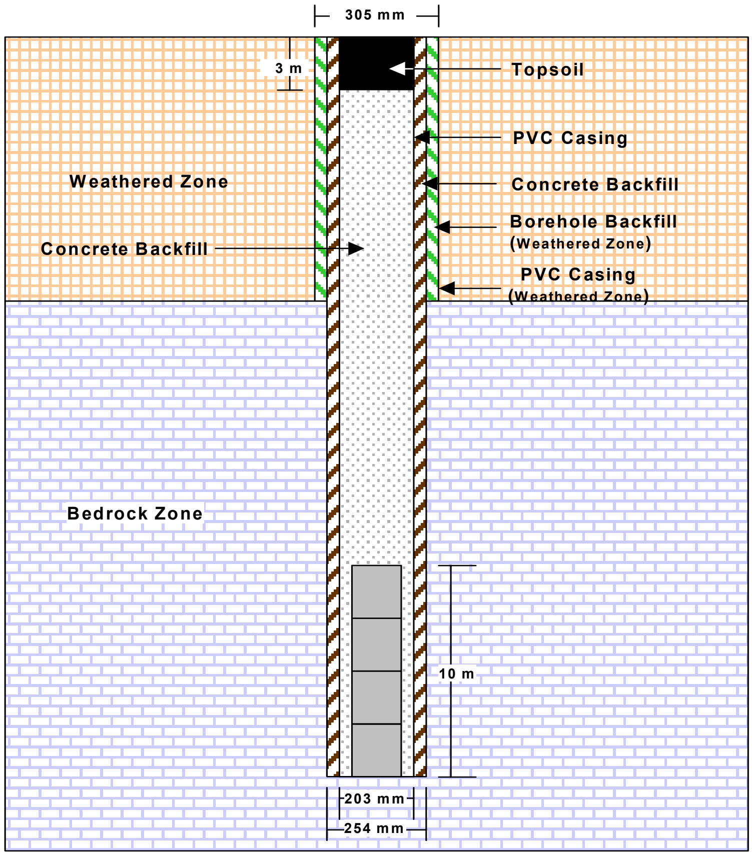


FIG. 63. The Design of the Borehole Assessed in the Borehole Test Case.

through the natural barrier (geosphere) to the accessible environment (biosphere). The secondary function of the waste package is to facilitate conditioning, handling, transportation and disposal.

^{226}Ra is the most demanding isotope that needs to be disposed and consequently a reference waste packages will be defined suitable for ^{226}Ra to evaluate the safety of the disposal system.

The container material proposed for the reference design is stainless steel, which offers many attractive properties. Compared to, for example carbon steel, they are more resistant to corrosion and do not need any protective coating. However, they are not free of corrosion problems, particular in the presence of chloride and sulphate ions. Type 304 stainless steel was used for the conditioning of the radium sources. For consistency, the disposal containers for the borehole concept will also be assumed to be Type 304 stainless steel.

Stainless steel is expected to be passivated under high-pH conditions, and the general corrosion and pitting corrosion rates are expected to be low. Crevice corrosion, however, cannot be excluded, particularly in groundwater with high chloride content. An estimate of 0.3 to 1.0 µm y^{-1} for a general corrosion rate of stainless steel under alkaline anaerobic conditions could be used.

The proposed backfill for the waste is cement, which plays several key roles in the performance of the concept. First, it provides a barrier between the capsule and aggressive chemicals (primarily chloride) that may initiate corrosion on the capsule. Corrosive attack on the passivation layer of the steel is possible only once the outer container is breached and chloride migrates through the cement. Secondly, it provides chemical buffering of the waste disposal system, which may intrinsically limit the release of the radium wastes. Thirdly, it provides a physical, chemical, and hydrological barrier through which leached radium must pass before release into the surroundings.

The spent sources are introduced into a cementitious waste form, which in turn is contained in a Type 304 stainless steel container of 114.3 mm outside diameter, 250 mm in length and a wall thickness of 3.04 mm. An example of the container is presented in Fig. 64.

The sealed sources, which may be broken and leaking will be placed in a type 304 stainless steel capsule. The annular space will be occupied by air. The capsule has a height of 110 mm, with a diameter of 21.3 mm. The wall thickness of the capsule is 2.77 mm. The capsule will only be applicable for the disposal of Ra, the other isotopes will be placed directly in the concrete.

Waste package emplacement configuration

Once the waste package is closed, it is ready for disposal. The waste package emplacement configuration in the borehole is presented in Fig. 64. It consists of a layer of cement (375 mm) cast in the borehole, followed by the waste package. The borehole is then backfilled up to a depth of 375 mm on top of the package. Each emplacement configuration is thus in the order of 1 m and, therefore, 10 such units can potentially fit into a borehole facility.

The disposal facility design will start with a simple design that can be improved should the safety assessment indicate that it is a critical issue. The maximum activity that will be accepted in a container must also be determined from the safety assessment. For the purpose of this assessment and simplicity, it will be assumed that the long-lived isotopes such as ^{226}Ra will not be mixed with the other shorter-lived isotopes within the same container. In other words each isotope will go into a package so that the packages will contain a homogeneous inventory. However, the longer-lived containers will be stacked in the same borehole as the other isotopes with the isotopes with the longer half-lives stacked deeper in the borehole.

A concrete/bentonite-concrete backfill will be used to fill the space between the container and the borehole casing and between the borehole and the wall. *No credit will be taken for the backfill*, because its integrity cannot be ensured in a small diameter borehole. The container might even be touching the borehole casing in situations where the borehole is not drilled straight.

FIG 64. A Stainless Steel Container and Lid Similar to the One Used in the Borehole Disposal concept.

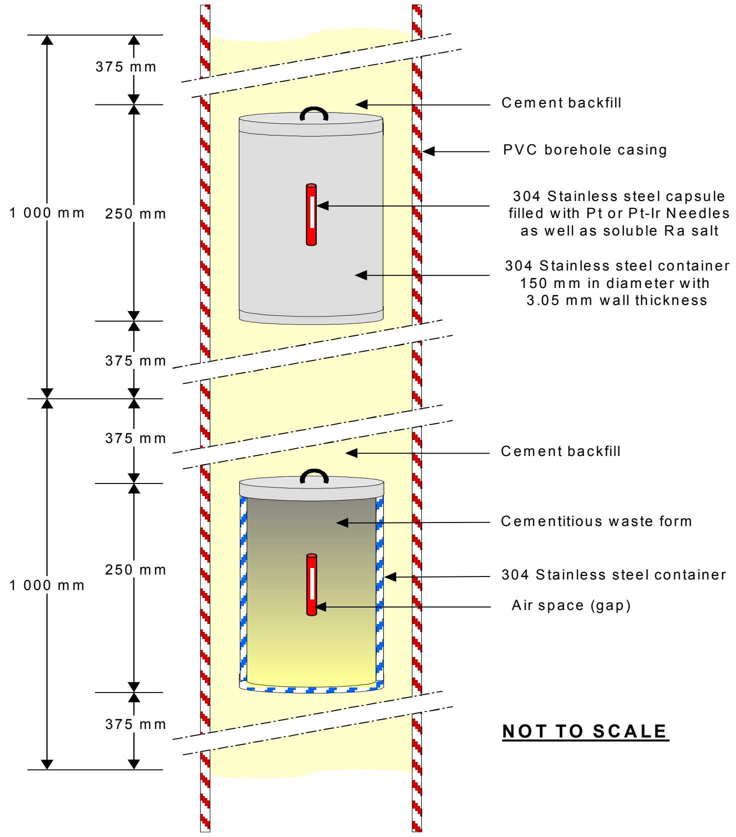


FIG. 65. Schematic Description of the Waste Emplacement Configuration for the Borehole Disposal Concept.

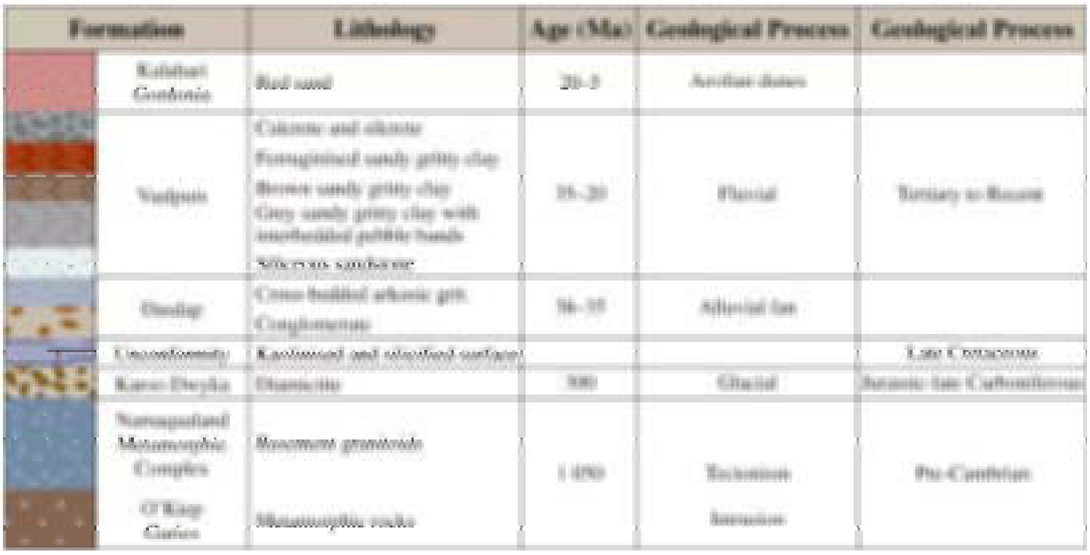
3.2.2. Geosphere

Geology

Locally Vaalputs is situated on the Precambrian Crystalline rocks of the Namaqualand Metamorphic Complex. As shown in Fig. 66, the crystalline rocks form the basement of this complex, which are covered by younger sedimentary rocks. Metamorphism transformed the original sedimentary and volcanic rocks to granite-gneisses and metavolcanics.

Basement rocks

The basement rocks belongs to the pre-tectonic Garies Subgroup of the O'Okiep Group and consists of light coloured biotite gneiss and quartzo-feldspathic rocks. The Vaalputs granite-gneiss is fine to medium crystalline with a uniform pinkish colour, with small amounts of garnet and biotite. Clearly visible in Fig. 66 is the extensively large-scale tectonism, which led to the folded, thrusted and fractured bedrock.



Formation		Lithology	Age (Ma)	Geological Process	Geological Process
	Kalahari Gordonia	Red sand	20-3	Aeolian dunes	
	Vaalputs	Calcrete and silcrete Ferruginised sandy gritty clay Brown sandy gritty clay Grey sandy gritty clay with interbedded pebble bands Siliceous sandstone	35-20	Fluvial	Tertiary to Recent
	Dasdap	Cross-bedded arkosic grit Conglomerate	56-35	Alluvial fan	
	Unconformity	Kaolinised and silicified surface			Late Cretaceous
	Karoo Dwyka	Diamictite	300	Glacial	Jurassic late Carboniferous
	Namaqualand Metamorphic Complex	Basement granitoids	1 050	Tectonism	Pre-Cambrian
	O'Kiep Gneiss	Metamorphic rocks		Intrusion	

FIG. 66. Geological Succession at Vaalputs.

The basement rocks were also intruded by granites, which caused extensive re-melting. The fractured basement rocks at Vaalputs are important because the local aquifer is situated in the weathered and hard bedrock. In fact, the Norabees granite largely constitutes the basement rock underlying the radioactive waste disposal site.

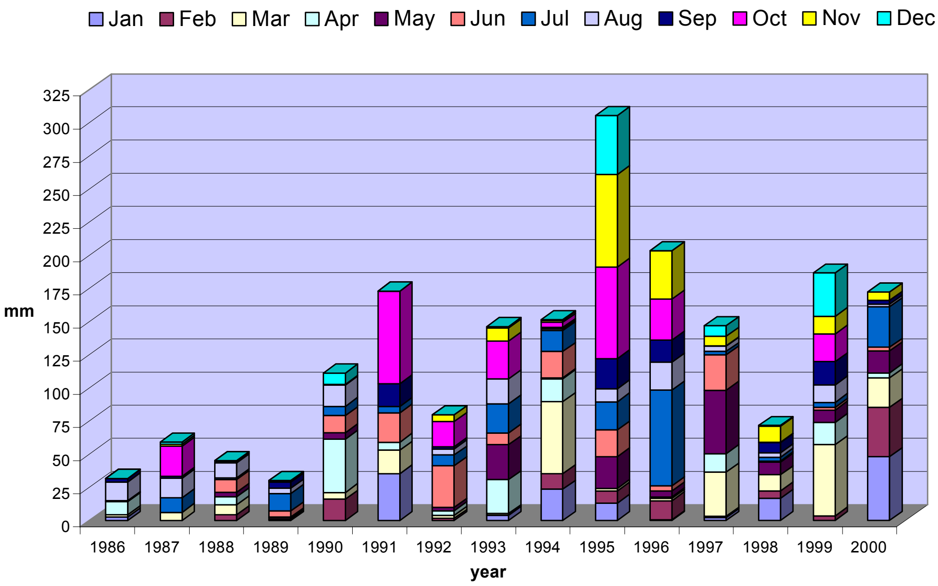


FIG. 67. Monthly and Annual Rainfall FIG.s as Measured at Vaalputs between 1986 and 1998.

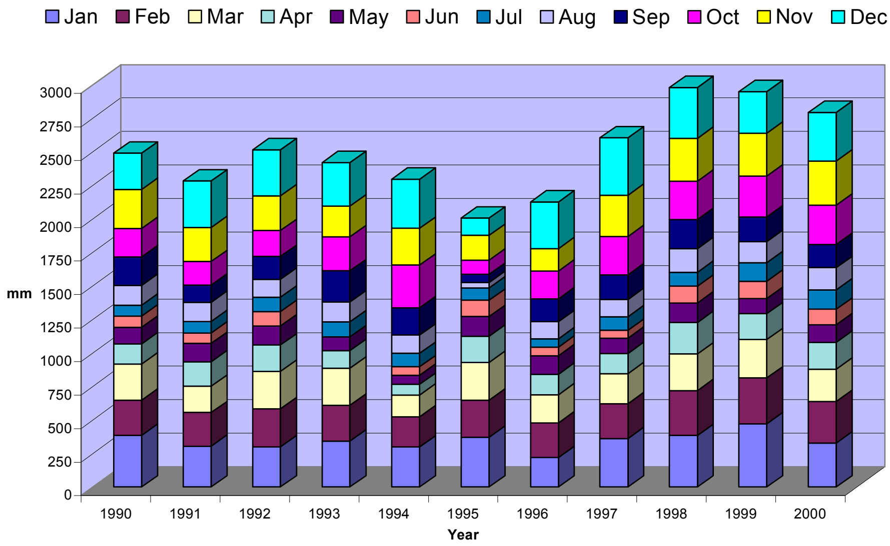


FIG. 68. Monthly and Annual Pan Evaporation FIG.s as Measured at Vaalputs between 1990 and 1998.

The karoo sedimentary rocks

The Dwyka Tillite Formation is the only formation of the Karoo Sequence present in the vicinity of Vaalputs, and overlies the basement rocks. The Karoo rocks outcrop east of Vaalputs as a thin layer that is poorly exposed. The Dwyka Formation forms the base of the Karoo Sequence and in the Vaalputs area, it consists of massive clast rich arenaceous and clast poor argillaceous diamictite, bedded diamictite, basement breccia, dropstones and fine to coarse grained sandstones. Remnants of the Dwyka Formation are preserved in local fault-bounded basins.

Tertiary sedimentary rocks

Following the Karoo rocks are the much younger sedimentary rocks of the Dasdap and Vaalputs formations. These deposits are in the order of 10 m thick. The Dasdap Formation was formed by a large alluvial fan that occurs south of Vaalputs and consists of conglomerate, sandstone and cross-bedded arkosic grits. These sediments overlie an unconformity consisting of a kaolinised and silicified surface.

The Vaalputs Formation consists of sediments that accumulated in the Vaalputs Basin. This formation is comprised of aeolian sand, calcretized sandy, gritty clay and red to greyish fluvial gritty, sandy clay containing gravel and quartz pebbles. Calcite veins cut through the whole Vaalputs sequence and are deeper than 7 m. These veins resulted from infilled fractures. The Vaalputs Formation is overlain by northeast trending red Kalahari sand dunes, of the Gordonia Formation. These dunes conform to underlying geological structures. In the vicinity of the disposal site, the Vaalputs Formation overlies the Norabees Granite suite. Lithologically from the base upward the surface deposits consists of:

— 10 m to 15 m of in situ developed kaolinitic/montmorillonitic clay derived from the underlying basement (*white clay*);
— 15 m to 20 m fluvial red/brown to greyish clayey grit (*red clay*);
— 1 m to 5 m of calcrete with some silcrete nodules (*calcrete*); and
— 0.5 m to 1 m of loose and partially ferruginised aeolian sand (*sand*).

A vertical cross-section through the clay and silt sized fractions (< 45 μm) of the surface deposits constitute up to 39% of the brown clay. The mean volumetric composition of the clay fraction is 46% smectite, 32% illite and 21% kaolinite. The smectite and kaolinite content generally increase with depth at the expense of illite but smectite, however, increases at a higher rate than kaolinite. In the vicinity of basic igneous bodies, smectite predominates and koalinite is virtually absent.

Intrusive rocks

During the tectonic periods of folding and faulting, weak zones developed in the earth's crust. Igneous rocks intruded in the form of magma along these weak zones. Intrusive rocks like granite, pegmatite, norite, diorite, enderbite, charnockite and granitoids intruded approximately at the same period as the tectonic events. The granitic intrusions are the same age as the tectonism (syntectonic) of the Spektakel and Koperberg Suites. At Vaalputs, it is known as the Stofkloof granite. The Norabees granite intruded in the form of a massive sill, which underlie the Vaalputs area. Partial melting has taken place at the contact zones with the host rock. It is in the form of a large syncline that dips at an angle of 5^o to the east.

Other important syntectonic intrusives in the basement are charnokite, diorite, norite and pegmatites. Intrusions of Karoo dolerite in the form of dykes, sills and basalt are also present in the Vaalputs area. Late Cretaceous (65 to 70 Ma) kimberlite pipe intrusions that followed structural weak zones in the crust, occur in the area. One such a kimberlite pipe occurs on the southern boundary of Vaalputs.

Structural geology and seismology

Five deformational events have been recognized in the Namaqualand Metamorphic Complex, with the result that the structural geology at Vaalputs is very complex. Various fault zones bisect the rock mass below the site. The Vaalputs structural Sub-Terrane is bounded by the Kamiebees Shear Zone in the north and by the Platbakkies Shear Zone in the south, as shown in Fig. 69. The Vaalputs Sub-Terrane has an eliptic shape with an east-west axis of 50 km and a north-south axis of 25 km. The Kamiebees Shear Zone can be followed for a distance of 150 km on the aeromagnetic map, while the Platbakkies Shear Zone can be traced for 100 km. The Vaalputs Sub-Terrane was interpreted as a large-scale wrench fault zone.

The Vaalputs Fault has a northeast direction and is considered to be a steep structure in which noritoids have intruded. These noritoids have distinct magnetic anomalies. The Garing Fault Zone represents some of the secondary faults and fractures that formed as a result of wrenching. The secondary faults and fractures are strongly developed in a north-west trend. A second conjugate set of secondary faults and fractures at Vaalputs has a northeast trend. The Garing Fault Zone persists for more than 30 km and dips steeply to the northeast. Core and percussion boreholes that were drilled into this fault zone revealed that it is permeable in some locations where water production boreholes were drilled and annealed in other locations.

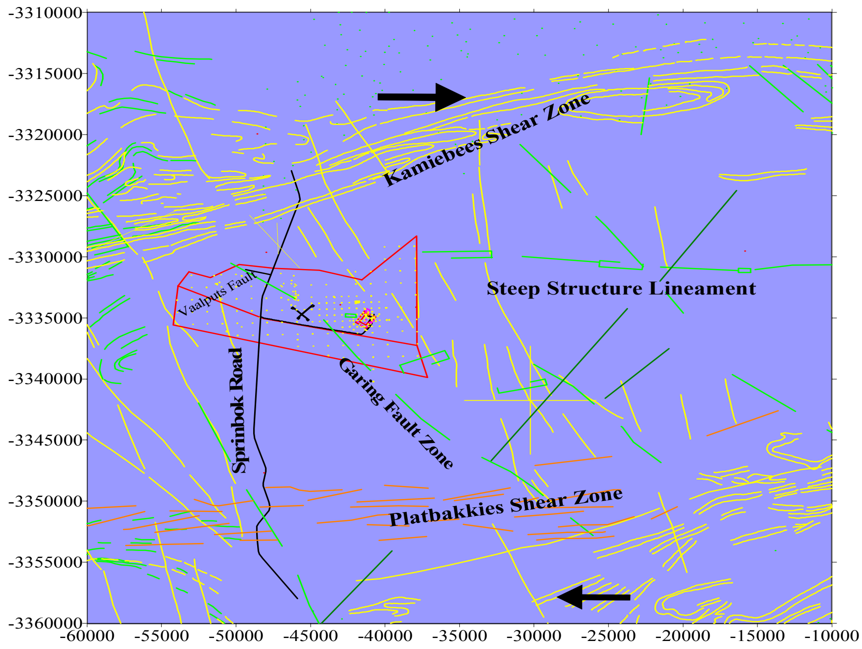


FIG. 69. Regional Structural Geological Delineation of Vaalputs and Surroundings.

The Vaalputs area is situated on a seismic cluster. Two linear weak zones, namely the Kuboos-Bremen line and the Platbakkies Shear Zone, is just south of Vaalputs. Seismic activity tends to occur along these zones and consequently the Platbakkies Shear Zone is considered as an active fault. A number of small seismic events and one of magnitude 3.4 were recorded at Vaalputs. During 2001 an earthquake measuring 4.3 was recorded 50 km from Vaalputs. The largest known earthquake with a magnitude of 7 was recorded in 1956; its epicenter was near Port Nolloth, which is north-west of Vaalputs. The possibility exists that fracture (faults) zones may be rejuvenated or new fractures could be initiated by the seismic activity.

Hydrogeology

The unsaturated zone

Indications are that there is only one *confined* aquifer at Vaalputs. Waterstrikes in the boreholes drilled in the vicinity of Vaalputs varied between 50 m and 100 m, which serves as an indication of the unsaturated thickness. The zone consists of the weathered overburden of between 15 m and 30 m with fractured Norabees granite and associated rocks constituting the remaining strata. The geometry of the unsaturated zone consisting thus off irregular layers of sand, red clay, white clay, calcrete, and weathered and fresh granite, with thicknesses as presented in Section 3.2.2.

Volumetric soil moisture content

The movement of soil water through unsaturated soils is directly dependent on the volumetric moisture content (θ), which varies between 0.1 and 0.3 in the vicinity of the disposal site. Down to a depth of 9 m, the average measured volumetric moisture content is just below 0.2.

Van genuchten parameters

Coefficients of the Van Genuchten equation were determined for various soil samples taken from the different strata. The results are presented in Table 37. Saturated hydraulic conductivity values are presented in Table 38.

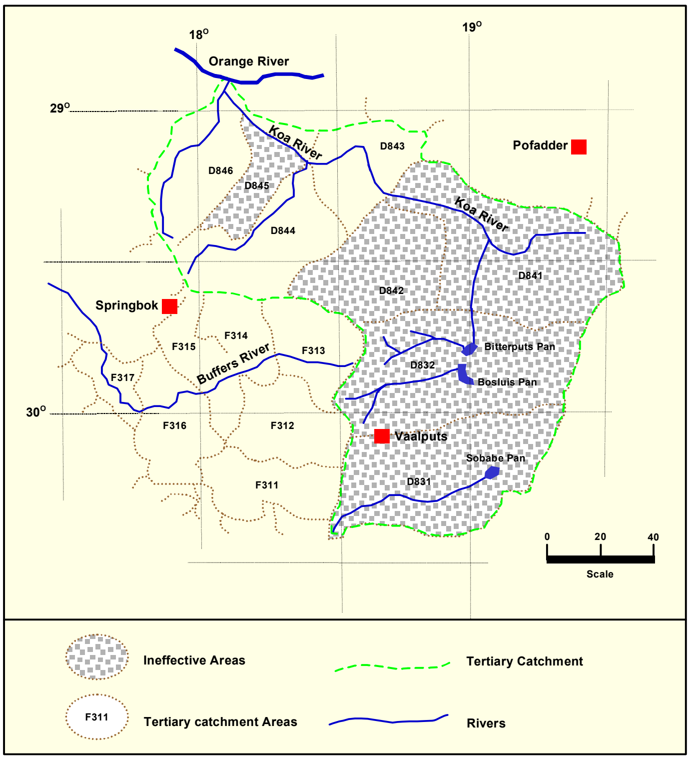


FIG. 70. Regional Tertiary and Quaternary Sub-catchment Boundaries. Run-off from the enclosed drainage basins does not reach the major river system or ocean, but may cause local stream flow or contribute to local pans, marshes or leis and possible to the aquifer.

TABLE 37. COEFFICIENTS OF THE VAN GENUCHTEN EQUATION OF SOIL SAMPLES TAKEN AT VAALPUTS

Sample	Soil Type	α (m^{-1})	N	θ_r	θ_s
W35,00S08	White Kaolinitic Clay	1.3155	3.1156	0.1409	0.300
W35,00S08	Yellow Brown Clay	4.6501	1.4872	0.1474	0.275
W42,05S13	Yellow Brown Clay	0.5017	4.2411	0.1565	0.313
W37,05S05	Yellow Brown Clay	2.1103	1.4196	0.1861	0.290
AFW42,05S10	Ferruginous Sand	37.0623	1.10035	0.000	0.230
AFW40,05S05	Calcrete	8.8998	1.1412	0.0665	0.187
AFW32,05S03	Weathered Granite	9.43965	1.17984	0.08743	0.267
AFW35,00S08	White Clay	21.7609	1.1064	0.0190	0.209
AFW35,00S13	Weathered Granite	1.4220	1.5212	0.0851	0.192
6	Loose Red Sand	7.6415	1.6054	0.0230	0.260
Sites 9/13–20/7	Sandy Gritty Clay	2.5323	1.5400	0.1618	0.304

TABLE 38. SATURATED HYDRAULIC CONDUCTIVITY FOR SOIL SAMPLES FROM VAALPUTS

Sample	Description	Depth (m)	Saturated Hydraulic Conductivity (m.s^{-1})
AFW42S10	Ferruginous Sand	0.0 – 2.0	2.90×10^{-7}
AFW35S05	Sandy Clay	8.0 – 9.0	3.06×10^{-8}
AFW37,5S03	Ferruginous Sand	2.0 – 3.0	1.28×10^{-8}
AFW32,05S03	Weathered Granite	16.5 – 16.98	7.95×10^{-8}
AFW35S08	Coarse Sandy Clay	8.0 – 9.0	4.29×10^{-8}
AFW35S08	White Clay	20.9 – 21.6	1.96×10^{-8}
AFW32,00S13	Weathered Granite	20.0 – 20.5	6.00×10^{-8}
9/16	Sandy Gritty Clay	-	1.14×10^{-7}
20/7	Sandy Gritty Clay	-	1.16×10^{-7}

The saturated zone

The most important aquifer in the area is located in the fractured Norabees granite suite and associated rocks, which underlie the disposal site. Fault zones, which structurally control the aquifer, are both permeable and impermeable, depending on the location. The resultant effect is that the aquifer is divided into compartments. Some of the fault or fracture zones act therefore as conduits and some as groundwater flow barriers. It can therefore be assumed that the aquifer consists of two zones. The weathered granite forms the upper zone and general has a higher hydraulic conductivity than the underlying fractured hard granite zone. The fractured granite zone consists of a matrix with a low hydraulic conductivity and the fractures with a higher hydraulic conductivity.

Piezometric levels and gradients

The topography at Vaalputs has an important influence on the regional piezometric head elevation. The presence of an escarpment with a high relief on the western part causes steep groundwater gradients in that part. However, most of Vaalputs including the area of the disposal facility is situated on a very flat plateau, which results in very flat gradients at the disposal site. According to the piezometric gradients, the general groundwater flow direction would be from the high in the southwest towards the lowest location in the drainage system, which is the Koa Valley, northeast of Vaalputs. The regional gentle groundwater gradients cause low groundwater flow velocities.

On a local scale the piezometric gradients and flow directions may change. Fracture (fault) zones have an influence on the piezometric elevation, because changes in the hydraulic conductivity between fracture and matrix zones causes changes in the piezometric head distribution. The piezometric elevation northeast of the site is higher than that in the south. This is also the part of the aquifer that is more fractured and permeable. The higher elevation of piezometric heads could be due to the fact that the fracture systems receive recharge. Large differences are therefore possible if the regional and local scale piezometric head distribution is compared, mainly because of influences of the fracture zones and aquifer compartments on a local scale.

Aquifer parameters

Aquifer tests were conducted at Vaalputs during the pre-operational investigations. From these tests, the hydraulic parameters could be determined. Four boreholes adjacent to the disposal site were tested. The pumping tests lasted between 16 h to 48 h. The tests were analysed with the Cooper-Jacob method, which yields reliable transmissivity values for fractured aquifers. The details of the pumping tests are summarized in Table 39.

TABLE 39. INFORMATION ON PUMPING TESTS CONDUCTED AT VAALPUTS

Borehole no.	**Transmissivity ($m^2.d^{-1}$)**	**Storage**	**Yield Tested ($m^3.h^{-1}$)**
GWB1	0.55	-	1.25
GWB3	30	2.0×10^{-4}	13.75
GWB5	29	1.6×10^{-5}	13.75
PBH16	26	6.0×10^{-5}	2.38
Average	21	9.2×10^{-5}	7.78

The transmissivity values reveal that the fracture systems have a general high hydraulic conductivity. Pumping tests reflect the characteristics of the fracture systems, because only water yielding boreholes could be pump tested. The storativity values are very low and representative of the fracture systems. From the pumping tests and the blow out yields recorded during percussion drilling, it seems that the more permeable fracture zones is situated in the northern and north-western sides of the site. The transmissivity values decreases towards the southeastern side.

Fracture analysis

Fracture system in the unsaturated zone

There is evidence of a fracture system in the unsaturated zone which might cause an increase in the soil moisture flow rate through the unsaturated zone, especially during high precipitation and infiltration events. The fractures form preferential flow paths that facilitate the flow of soil moisture at a rate much faster than the unsaturated matrix.

Fracture systems in the saturated zone

The saturated aquifer consists of matrix blocks of granite-gneiss and anorthosite separated by fracture zones. The matrix blocks contain joints that can be considered as micro-fractures (due to its very low permeability). The hydraulic characteristics of the unweathered granite-gneiss and anorthosite are very similar and no distinctions (in terms of groundwater flow) will be made between these two lithological units. The fractures may occur either as discrete fractures or as fracture (shear) zones. Fracture zones consist of a large number of smaller interconnected fractures. These fracture zones may contain mylonite (fine-grained remnants of fractured rock due to faulting) or weathered material. The weathered material and mylonite may reduce the permeability of fracture zones in places.

Geophysical techniques have been used to characterize the position and size of fracture systems in the saturated zone below Vaalputs. Water was struck in 15 of the 37 monitoring percussion boreholes drilled around the site, all of which occurred in fracture zones. Acoustic scans were carried out for some of the water yielding boreholes to reveal the orientations of the fracture zones. The resulting images are shown in Fig. 71 and Fig. 72, which reveals that some of the fractures are discrete, while others are zones formed by a large number of smaller fractures. The fracture orientations also vary from sub-horizontal to sub-vertical.

From the rose diagram in Fig. 73, showing the trends of the lineaments at Vaalputs, there are four main fracture orientations. The main trends of lineaments (interpreted as fracture zones) are north-west to southeast with a second set northeast to south-west. On the structural map of Vaalputs shown in Fig. 74, a few lineaments (the third set) that strike north-south can be seen. The fourth fracture orientation is sub-horizontal. These lineaments are interpreted as fault and fracture zones. The major set is much stronger developed that the other subsets. Therefore, the aquifer will have a strong anisotropy for groundwater flow. In Fig. 74, a regional trend of the lineaments on the Vaalputs farm can be seen. Some of the fracture zones (faults) are continuous for large distances. These are typically the large-scale fault zones. The smaller scale fracture zones are discontinuous and often terminate against other fractures. This occurs where a younger fault zone cuts another fault zone off. Parallel fracture zones are generally linked by cross-cutting fault zones.

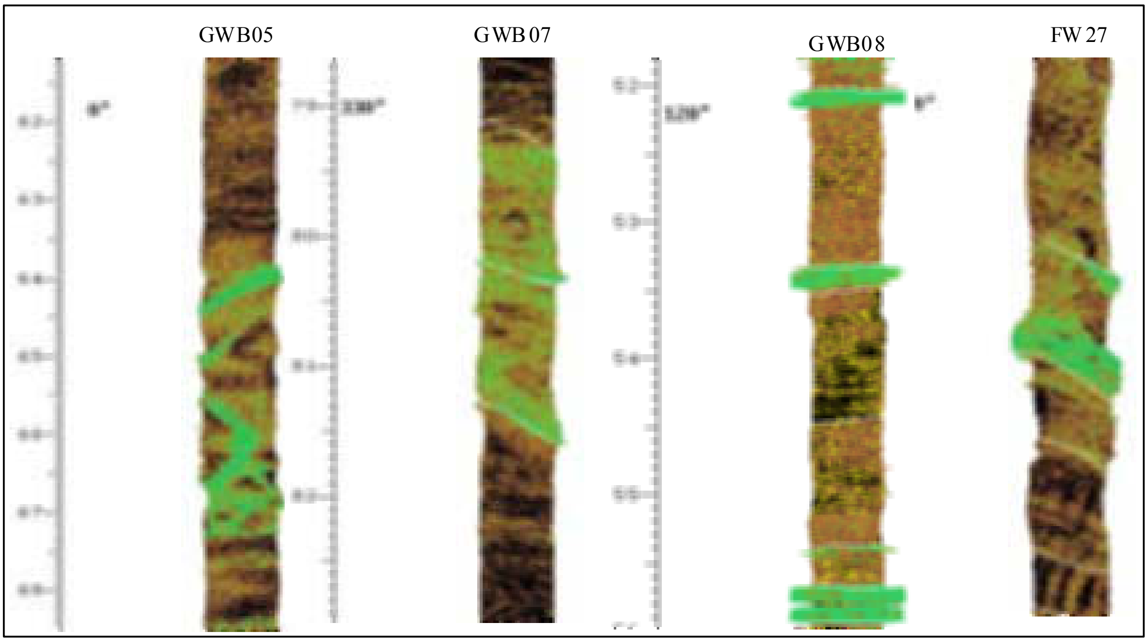


FIG. 71. Acoustic Scanner Images of Fractures (Shown in Green) in Some of the Percussion Drilled Boreholes around Vaalputs.

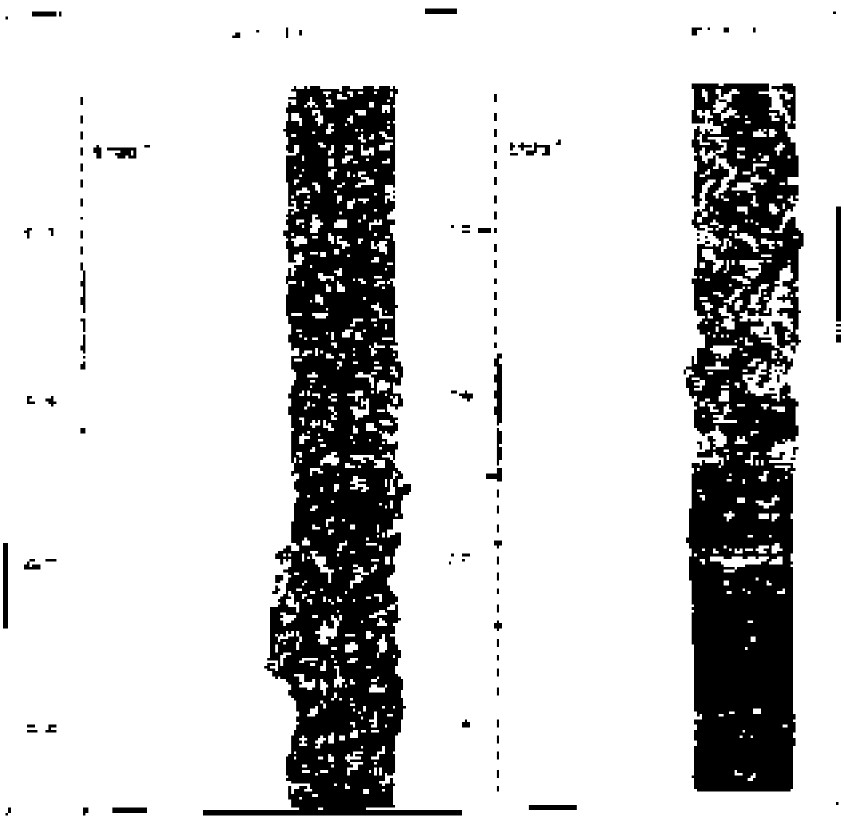


FIG. 72. Acoustic Scan Image of a Sub-vertical Fracture in a Borehole at Vaalputs.

FIG. 73. Rose Diagram Showing the Trends of the Lineaments at Vaalputs.

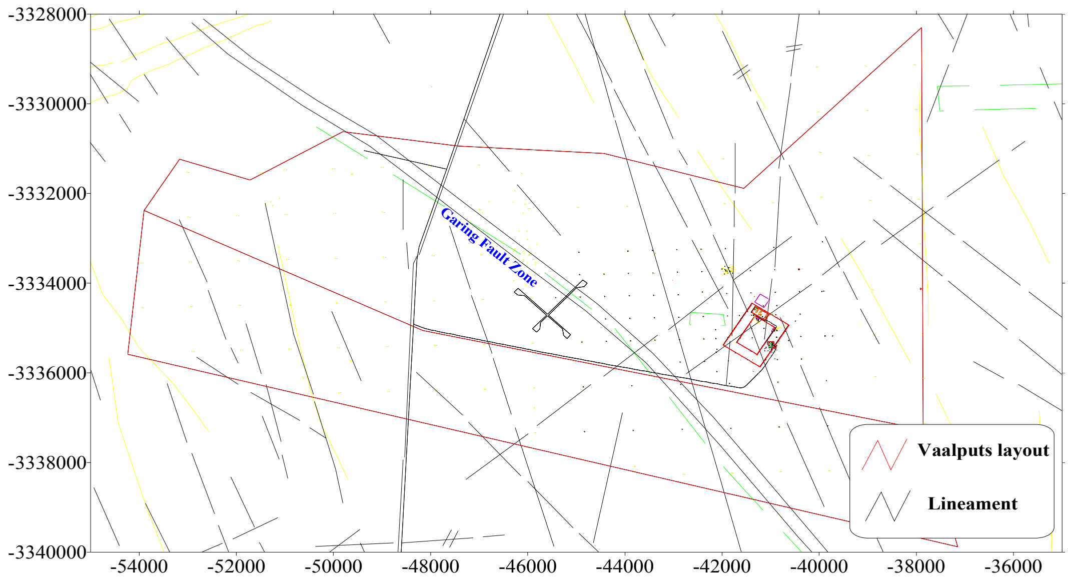


FIG 74. A Regional Trend of the Lineaments on the Vaalputs Farm.

Hydrogeochemistry

A regional groundwater survey has been conducted at Vaalputs and its surroundings. The survey indicated that the regional pH ranges between 6.5 and 8.4 with an average of 7.06. The pH decreases slightly from the area near Garing (northeast of the airfield) to the southeast and southwest. The groundwater temperature ranges between 18 ^{o}C to 26 ^{o}C, with a regional increase in temperature from southwest to northeast.

The average electrical conductivity is 4,770µs cm^{-1}, which yields a total dissolved solids content of 3,100 mg l^{-1}. The electrical conductivity (TDS) has a low in the centre of Vaalputs near Garing and it increases to the west and east. At the proposed location of the facility, the electrical conductivity ranges between 4,500 µS cm^{-1} to 5,500 µS cm^{-1}.

The groundwater changes from a bicarbonate character to a sulphate and chloride character from the recharge to the discharge zones. This chloride and sulphate character in the groundwater sequence is observed towards Bosluis Pan in the Koa Valley, which is the discharge location. The origin of the chloride in the groundwater is due to the high chloride content of the unsaturated zone and the rocks that constitutes the aquifer. The average chloride content in the Vaalputs area is 1,505 mg $l.c.^{-1}$, which is representative of an arid environment. The Vaalputs groundwater is also characterized by a relatively high sulphate content. The average sulphate concentration is 379 mg $l.c.^{-1}$, and the distribution follow the same pattern as the chloride.

3.2.3. Biosphere

Site location and demography

Vaalputs is located in the district of Namaqualand 90 km south east of Springbok in the Northern Cape Province, 200 km from the Namibian border, as shown on the map in Fig. 60.

At present there is almost no permanent human habitation within 20 km of the site. The nearest is Rooifontein, which is 25 km away, while Springbok, which is the largest town, is 90 km away.

Relief

Vaalputs is situated on the edge of the western side of the escarpment that divides the inland and coastal plains in South Africa. As shown in Fig. 75, the site is bordered by rugged, mountainous terrain on the west and the flat plains of the Bushmanland plateau, with an elevation of approximately 1,000 mamsl on the east. The disposal facility is situated on this plateau. Vaalputs forms part of an elevated 2500 km^2 area, which is topographically higher than the surrounding plateau. This high elevation of the Vaalputs area in relation to the plateau ensures that there is not a great enough catchment area that can cause flood situations.

The plateau area has only a slight undulating topography that is characterized by low fossil dunes with a northeasterly trend. Locally at the site the topographical differences it not more than 1 m to 2 m. The drainage courses are largely inactive and frequently end in depressions or pans. The interdune troughs may, however, constitute local ephemeral drainages having a gradient of approximately 1:500, along which minor ponding has been noted.

The geomorphological history of the Vaalputs region is exceedingly complex and a record of aggridational and degradational cycles. Within the central dune field, surface sedimentary accumulations are at present no more than 30 m thick and are probably of mid-Tertiary age, which reflects the remarkable geomorphological stability of the region. However, the area is in a late deflationary stage, the effects of which are occurring extremely slowly and sheet erosion by water is insignificant as borne out by the lack of erosion features such as incision and channelling.

Although sand and dust storms are common phenomena in the region, in particular those created by the dry easterly berg winds during the winter months, they carry loads of sand and dust from the interior and thereby balancing any removal that may occur on site. Therefore, although wind erosion does occur, their degradational effect is minimal because the sand is too coarse to be transported by wind.

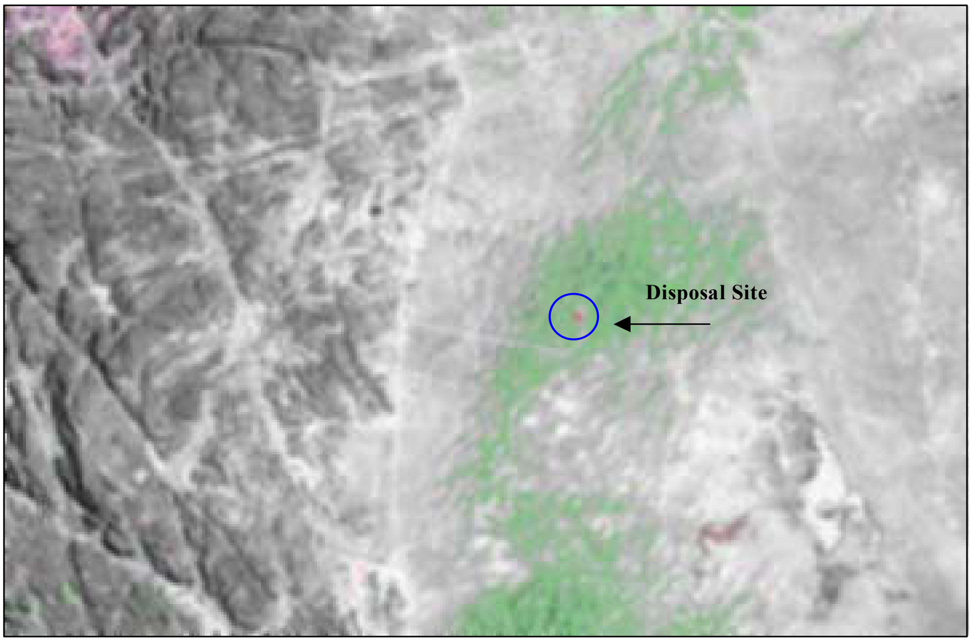


FIG. 75. Spacemap of the Vaalputs Area, Showing the Regional Topographic Relief of the Site and Environments.

Meteorology

Vaalputs is situated on the Bushmanland plateau, on the border of two well defined rainfall regions namely Bushmanland and Namaqualand. Bushmanland is mainly in the summer rainfall area, which experiences convective rainfall and Namaqualand in the winter rainfall area, which experiences cyclonic and orographic rainfall. The Vaalputs site is therefore affected by the rainfall pattern of both regions and is the main reason for the high variability in rainfall. Coastal lows and cold fronts periodically pass over Vaalputs bringing little or no precipitation as a result of the orographic influences of the Kamiesberg, and the rain, which does fall on Vaalputs, is usually from the convective storms that occasionally occur in summer. The western part of the Southern African continent is also known for its dry arid and semi desert conditions. Significant differences between summer and winter temperatures, as well as day and night temperatures are typical of the arid regions.

Ambient temperature

There are fairly large variations in both seasonal and diurnal temperatures at Vaalputs. For the Vaalputs area the summer (February) mean daily temperature is approximately 23.5°C, as opposed to the winter (July) mean daily temperature of approximately 8.9°C. The summer mean daily maximum temperature for the warmest month is 39.3°C, as opposed to the winter mean daily minimum temperature for the coldest month of –2.4°C. The mean annual temperature for Vaalputs is 16.7°C, and the mean annual range of temperature is 14.5°C. The absolute maximum temperature at Vaalputs for a observation period of six years (1994 to 1999) is 40ºC as opposed to the absolute minimum temperature of –4.8ºC for the same period.

Soil temperature

Average monthly soil temperatures are measured at 22 cm and 60 cm. The 22 cm temperature, which follows the same trend as the ambient temperature with a time lag of a few hours, varies between 11°C and 31°C. The 60 cm temperature, which follows the same trend but with less variation, varies between 12°C and 30°C. Indications are that from about a 1.5 m depth, the temperature starts to follow a seasonal trend only.

Rainfall

The variability of the rainfall pattern at Vaalputs is typical of an area that is situated on the border of two rainfall regions. Some seasons it is more under the influence of the summer rainfall area and other seasons under the influence of the winter rainfall area. If one takes into account the changing rainfall occurrence due to more global effects that influence the whole sub continent (like drought and flood cycles), it is very difficult to identify any prevailing or expected rainfall pattern in the area. Vaalputs is located in a transition zone between the winter and summer rainfall areas with winter rainfall somewhat dominant, as shown in Table 40. The long term annual average rainfall is 80 mm, which increased to 125 mm for the period 1986 to 2000, as shown in Fig. 67. The minimum of 30 mm was measured in 1989 with a maximum of 305 mm in 1995. The bulk of the rainfall can be accounted for in single, rare, heavy showers, while hail is seldom recorded in this area. A year's rainfall might occur in a few hours. The maximum amount of rainfall at Vaalputs was 72.2 mm during July 1996.

TABLE 40. THE MEAN MONTHLY RAINFALL AND PAN EVAPORATION AS RECORDED AT THE WEATHER STATION AT VAALPUTS.

Month	Mean Rainfall (mm) (1986 to 2000)	Mean Pan Evaporation (mm) (1990 to 2000)
Jan	9.7	328.56
Feb	7.1	268.78
Mar	14.7	241.28
Apr	9.6	164.00
May	10.0	124.17
Jun	11.1	78.11
Jul	14.4	93.78
Aug	9.2	131.39
Sep	6.5	175.50
Oct	17.8	226.17
Nov	11.0	254.11
Dec	6.5	326.00

Evaporation

The monthly and annual pan evaporation averages are presented in Table 40 and Fig. 68 as measured at the Vaalputs weather station between 1990 and 1998. This pattern shows a clear seasonal trend. Wind is playing the most important role in evaporation with temperature a secondary role. The stronger wind and higher temperatures are therefore responsible for the higher values measured towards summer time. The potential evaporation is very high, with an annual average pan evaporation of 2,412 mm.

Surface drainage

Three drainage systems meet on the Vaalputs farm. The first are the Koa River Basin, which drains the area to the north and northeast, the second is the Buffels River Basin in the west and the third is the Olifants River Basin that drains the south and south-west. Vaalputs is situated in the Koa River palaeo drainage system. Topographical and piezometric level data suggest that the Koa River drainage system is not well developed and most stream courses terminate in local pans. One such a pan called Bosluispan, which is located southeast of the disposal site, as shown in Fig. 69. The Buffels and Olifants Rivers are still active. Also shown in Fig. 69, is a further sub-division of the tertiary sub-catchments into quaternary sub-catchments. In the Koa River, mean annual run-off is restricted to the quarternary sub-catchments in the lower part of the valley, where steeper slopes facilitate run-off. The upper part of the valley, in which the disposal site is located, constitutes ineffective drainage areas or enclosed basins. Run-off from these areas does not reach the major river system or the ocean. It may, however, cause local streamflow or contribute to local pans, marshes or vleis, from where it can infiltrate to the aquifer.

Soil chemistry

Soils taken from the disposal zone can be described as a sequence of palaeosoils formed under arid conditions of low rainfall and high evaporation. The main characteristics of this type of soil are the poor removal of leached soluble salts and the subsequent accumulation of calcium carbonate. The results of a macro water soluble salt analyses carried out on a soil sample is presented in Table 41, while the results of chemical analyses done on sediment samples taken from experimental trenches, are presented in Table 42.

TABLE 41. THE RESULTS OF A MACRO WATER SOLUBLE SALT ANALYSES DONE ON A SOIL SAMPLE TAKEN FROM A AUGER BOREHOLE AT VAALPUTS.

Depth (m)		**0 – 0.7**	**0.7 - 2.4**	**2.4 - 5.6**	**5.6 – 9.0**	**9.0 - 10.2**
Type of soil		**LRS**	**CS and BSGC**	**BSGC**	**BSGC**	**WC**
PH		8.5	8.5	8.4	8.3	7.8
Anions Mg.kg^{-1} soil	**CO_3**	120	170	70	60	0
	HCO_3	620	560	520	500	460
	SO_4	200	190	180	110	210
	Cl	200	220	480	720	880
	F	10	9	22	20	21
Cations mg.kg^{-1} soil	**Na**	440	380	580	680	800
	K	36	58	44	54	50
	Ca	48	54	36	38	41
	Mg	19	18	18	18	21

LRS Loose Red Sand **BSGC** Brown Sandy Gritty Clay **CS** Calcretized Sand **WC** White Clay

TABLE 42. THE RESULTS OF CHEMICAL ANALYSES DONE ON SEDIMENT SAMPLES TAKEN FROM EXPERIMENTAL TRENCHES AT VAALPUTS

Depth Zone (m)	0 - 0.5	2.0 - 8.0		
Rock Unit	Sand	BSGC	RSC	GSC
Sand %	86.7	47.2	67.7	75.5
Silt %	3.7	16.4	6.6	7.9
Clay %	9	36.4	25.7	16.6
PH	6	7.0	7.2	7.3
Conductivity ms.m^{-1}	17.0	870	1190	780
Extractable Ca meq %	1.17	9.92	7.9	3.95
Extractable Mg meq %	0.28	8.68	2.15	3.34
Extractable K meq %	0.3	1.7	1.09	0.65
Extractable Na meq %	Trace	7.16	7.26	2.97
Cation Exchange Capacity (CEC)	3.07	25.21	1.98	9.95
Ca/Mg Ratio	4/1	1/1	4/1	1/1
Inferred ESP %	1	19	43	20
CEC/Clay Ratio	0.31	0.69	0.5	0.59

The Vaalputs ecosystem

The natural plant and animal life in and around the Vaalputs resembles that of a semi-desert environment. Both natural fauna and flora, while a combination of natural and domestic fauna and flora can be found in the Vaalputs region.

Natural botanical survey

The plant life at Vaalputs is a major determinant of the animal variation it supports. The main veld type at Vaalputs is classified as false succulent Karoo type. The botanical distributions depend on the soil type and geology, and are strongly influenced by the climate. In a botanical survey, 160 species of vascular plants have been identified, which include 12 grasses, 20 geophytes and approximately 40 succulents.

The vegetation was identified as eleven communities that belong to four groups. Three of the communities are associated with calcrete and calcareous soils, three communities with saline soils, two communities on shallow soils overlying basement or dorbank, two on soils mixed with some Aeolian sand, and one community is associated with deeper, strongly acid Aeolian sand. The eleven plant communities recognized at Vaalputs are indicated in Table 43. From a survey around the site it can be said that *Stipagrostis brevifolia* occurs mainly on deeper sand underlain by gritty clay (more moist conditions), *Stipagrostis ciliata* on a little shallower sand underlain by calcareous material (drier conditions) and *Stipagrostis obtuse* in shallow sand and calcareous material (dry conditions). In all these sub-veld types, shrubs such as *Euphorbia dregeana*, *Lyceum* species and several others can be found.

TABLE 43. THE ELEVEN PLANT COMMUNITIES AND FOUR GROUPS IDENTIFIED AT VAALPUTS

Community	Name
APTOSIMUM DEPRESSUM Communities on calcareous and saline soils	*Aptosimum depressum* - *Salsola tuberculata* dwarf/low open shrub land community. *Aptosimum depressum - Ruschia muricata - Zygophyllum retrofractum* low semi-open shrub land community. *Aptosimum depressum - Ruschia muricata* low semi-open to moderate closed shrub land community. *Aptosimum depressum - Psilocaulon ciliatum* dwarf semi-open shrub land community. *Aptosimum depressum - Psilocaulon ciliatum - Ruschia (Ruschia levynsiae)* dwarf semi-open shrub land community. *Aptosimum depressum - Psilocaulon planisepalum - Salsola zeyheri* low semi-open shrub land community
EBERLANZIA ARMATA Communities on shallow soils	*Eberlanzia armata* low open to semi-open shrub land community. *Eberlanzia armata – Ruschia robusta* low open to semi-open shrub land community.
STIPAGROSTIS BREVIFOLIA Communities on soils mixed with aeoloan sand	*Aptosimum depressum - Ruschia robusta* low/short open grassy shrub land community. *Aptosimum depressum – Lycium spp*. Complex short open grassy shrubland community.
STIPAGROSTIS CILIATA VAR. CAPENSIS Community on deeper, strongly acid Aeolian sand	*Stipagrostis ciliata var. capensis – Asthenatherum glaucum* low open grassland community.

Zoological survey

A study has been conducted at Vaalputs to determine the occurrence of mammals and arthropods, their density distribution and habits. Some of the animals influence the dose to man through consumption of the animal (diet) and the burrowing animals impose an intrusion hazard. The mammal species that were trapped on Vaalputs constitute eight orders, eighteen families and thirty species. These mammals represent the smaller wildlife like rodents, jackals and rabbits that were able to co-exist with domestic farming.

Animals trapped in these regions are expressed in terms of trapping success, which is the number of trappings in a 12 hour period, as indicated in Table 44.

TABLE 44. TRAPPING RESULTS OF HABITATS SAMPLED AT VAALPUTS

Habitat	Trap Success	No of species.	Species
Koppie-plains	2.9	2	*Elephantulus, Aethomys namaquensis*
Granite-koppies	10	1	*Aethomys namaquensis*
Valleys between koppies	4.9	4	*Elephantulus, Gerbillurus, Aethomys namaquensis*
Calcrete flats	1.9	2	*Elephantulus, Gerbillurus*
Rocky outcrops	2.8	3	*Macroscelides, Gerbillurus, Aethomys*
Red-brown sand	1.2	2	*Gerbillurus, Malacothrix*

Together with the mammal survey, a soil transfer survey was conducted to determine the burrowing characteristics of these animals. One rodent species at Vaalputs, *Paratomys brantsii*, is known to form large colonies with extensive burrow systems. In a study of a 50 m × 50 m area, five species were identified, with an average number of one burrow in 14.2 m^2 in which the total amount of soil that was transferred was 5.44×10^5 cm^3 in ten weeks or 2.8×10^{-5} $m^3.m^{-2}.d^{-1}$.

The other animals that were formally studied were the ant, termite and scorpion species (*fossorial arthropods*). The investigated species included the common harvesting ant (*Messor barbatus*), harvesting ant (*Pheidole capensis*), black pugnaceous ant (*Anoplolepsis steingroeveri*), Scorpionidae (*Opisthothalmus*), the snouted harvester termite (*Trinervitermes trinervoides*) and the common harvester termite (*Hodotermes mossambicus*). The results showed that a high density of *fossorial arthropods* inhabit the disposal site, while the termite *Hodotermes mossambicus* posses the greatest intrusion threat. It constructs an extensive and deep tunnel and nest system and it is capable of excavating large quantities of soil, at a rate of approximately 0.9 kg m^{-2} d^{-1}. It has a preference for denuded and soft areas. A single excavated nest reached 3.72 m depth and the tunnel that is used to obtain water from the soil went even deeper. An example of their tunnel system is shown in Fig. 76.

FIG. 76. Sub-vertical Tunnel Hole of the Termite Hodotermes Mossambicus at Vaalputs.

The maximum depth that these tunnels reach is not known, although it was observed that the termites could tunnel through the very hard calcrete layer, using the fractures. It also occupies a pivotal position in the food chain due to its biomass, dense numbers and the fact that it is a source of food for birds, mammals, reptiles and arthropod fauna. A summary of the known natural and domestic animals in the Vaalputs region are given in Table 44 and Table 45.

Domestic Fauna	Characteristics
Sheep	Graze mainly on the natural grass and rock salt, corn and lucerne may supplement the diet.
Goats	Eats natural grass, desert bush, corn, sorghum and rock salt.
Cattle	Eats natural grass, corn, sorghum and rock salt.

3.2.4. Background radiological characteristics

The amount of solar radiation received at any particular location is influenced by factors such as altitude, topography (slope and aspect), sunshine duration (season), and moisture in the atmosphere, cloud cover and dust content. The average annual duration of bright sunshine at Vaalputs (percentage of possibility) is approximately 80%. Topographic variations in radiation are of little significance on Vaalputs due to the low relief of the area. The radiant flux densities over the Vaalputs area vary from between 130 x 10^5 J m^{-2} day^{-1} during winter and 290 x 10^5 J m^{-2} day^{-1} during summer.

At the altitude of the Vaalputs site (approximately 1 000 m) the contribution of cosmic radiation to the absorbed dose rate (energy absorbed by a unit mass of a substance from the exposed radiation per year) in air is 0.35 mGy y^{-1} (35 mrem y^{-1}) and the dose equivalent rate (absorbed dose average over a tissue/organ multiplied by a radiation weighting factor to take account of the effectiveness of the type of radiation in inducing health effects) is 0.38 mSv y^{-1} (38 mrem y^{-1}).

The principal primordial radionuclides are ^{238}U, ^{232}Th and ^{40}K, and concentrations of these radionuclides vary over a wide range depending on the geological composition of the underlying material. The external radiation flux is determined by the composition of the surface soil layer to the depth of some 50 cm.

The total absorbed dose from external sources for the Vaalputs environment averages around 1.25 mGy y^{-1} with 28 % contributed by cosmic radiation and 72 % by soil radiation. The effective dose equivalent (the sum total of the weighted equivalent doses for all exposed tissues in an individual) of this absorbed dose is 1.35 mSv y^{-1}. Although individual values are variable, the standard deviation of this measured dose is ± 0.19 mGy (95% confidence limit) and reflects the natural variation in primordial radionuclides in the Vaalputs environment.

In addition to external doses, internal doses are accrued from inhalation and ingestion of these primordial radionuclides or their decay products, with particular importance to ^{40}K. Due to homeostatic control on the potassium concentrations in the body, the internal radiation dose from ^{40}K is constant and independent of environmental concentrations. The average effective dose equivalent is 0.2 mSv y^{-1}. Other radionuclides of importance are ^{222}Rn gained through inhalation, and ^{226}Ra, ^{228}Ra and ^{210}Po gained through ingestion.

The ^{222}Rn concentrations were determined by the U/Ra concentrations in surface materials and values of approximately 3 Bq m^{-3} are to be expected in the Vaalputs area. If the equilibrium with the Rn-daughters is 0.5, this will result in an effective dose equivalent of 0.13 mSv y^{-1}. The highest potential exposure is from the use of the local Norabees granite as building material, which may result in radon concentrations of 1 to 2 orders of magnitude above the natural levels. Exposure, however, depends on factors such as occupancy and ventilation and cannot readily be predicted. On average, indoor exposure to Rn-daughters is an order of magnitude higher than outdoor exposure. An average dose of 0.7 mSv y^{-1} due to radon is accepted internationally.

Intake through the drinking of borehole water is considered to be the major pathway in the area around Vaalputs. Concentrations of natural uranium in these borehole waters varies from 2 μg l^{-1} to 250 μg l^{-1} with an average value of 50 μg l^{-1} U. ^{226}Ra is the main contributor to radiation dose in the U-decay series. Measured values of ^{226}Ra in borehole water from the Vaalputs area vary widely, from less than 0.01 Bq l^{-1} to 5.7 Bq l^{-1}, with a mean of 0.4 Bq l^{-1} from 30 boreholes. Using this 0.4 Bq l^{-1} ^{226}Ra concentration together with an annual water consumption for adults of 800 l and a conversion factor of 2.8 x 10^{-7} Sv Bq^{-1}, the dose contribution from ^{226}Ra in drinking water is 0.09 mSv y^{-1}.

3.3. DEVELOPMENT AND JUSTIFICATION OF SCENARIOS

The purpose of scenario generation and justification in the post-closure safety assessment of radioactive waste disposal systems is to address the uncertainties associated with the evolution of the system as a function of time. Various methodologies and approaches exist that can be used for this purpose, several of which are described in Volume I. The scenario generation approach that will be followed in a safety assessment depends on various factors such as the purpose of the assessment, and the level of information available and the regulatory framework.

3.3.1. Definition of exposure scenarios

In Section 3.1.1 it was stated that the purpose of the safety assessment is, amongst others, to evaluate the borehole disposal concept under specific site and land use conditions. The site conditions for the Borehole Test Case, (Section 3.2) involves the implementation of the borehole disposal concept in saturated and unsaturated conditions in a semi-arid environment. The first land use condition for the Borehole Test Case, as described in Section 3.1.7, considers the continuation of current land use patterns, which is characterized by small farms and agricultural activities to the extent supported by the local climate. The second condition is a reversion to traditional human behaviour, characterized by hunter-gatherer land uses. With these conditions as part of the assessment context, it was decided to follow a simplified approach to scenario generation and justification. The following two exposure scenarios were consequently defined for the Borehole Test Case assessment:

— Member of public (farmer) with an abstraction well (with variants on the distance of the well from disposal borehole; and
— Member of public (hunter-gatherer) eating termites.

From these scenarios it is clear that two critical groups are of concern. The first scenario considers a present day farmer and the second a reversion to a more traditional hunter-gatherer life style. In addition to these two scenarios, a third scenario was added for consideration, namely:

— Inadvertent human intrusion.

The remaining effort as part of the scenario generation and justification process was directed towards providing an audit trail of factors to be considered in the consequence analysis of these scenarios, and towards the development of the necessary conceptual models for the consequence analysis.

3.3.2. Screening of the ISAM FEPs list

From Fig. 61 it is clear that the components of a disposal system can be conveniently divided into two classes: internal and external components. The internal components are those components that are situated within the spatial and temporal boundaries of the system, while the external components are situated outside these boundaries. These components can often be further divided into a number of subsystems or components, which are linked to one another through various internal and external features, events and processes (FEPs). With the exposure scenarios to be considered in the Borehole Test Case defined, the next step followed was to screen the ISAM FEPs list (see Volume I) using the assessment context and system description for factors important to the safety assessment. The resulting FEPs list is presented in Table 46.

TABLE 46. ISAM FEP LIST SCREENED FOR THE BOREHOLE TEST CASE

0	**ASSESSMENT CONTEXT**
0.01	Impacts of concern – yes
0.02	Timescales of concern –yes
0.03	Spatial domain of concern –yes
0.04	Repository assumptions - yes
0.05	Future human action assumptions – yes
0.06	Future human behaviour (target group) assumptions – yes
0.07	Dose response assumptions – yes
0.08	Aims of the assessment – yes
0.09	Regulatory requirements and exclusions – yes
0.10	Model and data issues - yes
1	**EXTERNAL FACTORS**
1.1	REPOSITORY ISSUES
1.1.01	Site investigation -yes
1.1.02	Excavation/construction -yes
1.1.03	Emplacement of wastes and backfilling –yes
1.1.04	Closure e.g. capping –yes
1.1.05	Records and markers, repository – yes, but only for 30 years
1.1.06	Waste allocation – yes
1.1.07	Repository design –yes
1.1.08	Quality control –yes
1.1.09	Schedule and planning – no, not significant to what is being carried out
1.1.10	Administrative control, repository site – yes, but only for 30 years
1.1.11	Monitoring of repository – no, no impact on performance
1.1.12	Accidents and unplanned events – yes (could impact on container integrity)
1.1.13	Retrievability – no, assumed not to be required.
1.2	GEOLOGICAL PROCESSES AND EFFECTS
1.2.01	Tectonic movements and orogeny – no, given the location of the site
1.2.02	Deformation, elastic, plastic or brittle – no, given the location of the site
1.2.03	Seismicity – no, seismicity will not have a direct effect unless there is an active fault running through the borehole. Effect of seismic event can be considered in 1.2.10 if required
1.2.04	Volcanic and magmatic activity-no, site context
1.2.05	Metamorphism – no
1.2.06	Hydrothermal activity – no
1.2.07	Erosion and sedimentation – no, geomorphological evidence suggests that area is very stable
1.2.08	Diagenesis – no
1.2.09	Salt diapirism and dissolution – no
1.2.10	Hydrological/hydrogeological response to geological changes – maybe, probably no. Revisited and said no and include under 2.2.04. Later said: maybe yes,

because of hydrological properties of aquifer may change after an earthquake. This needs to be considered further

1.3	CLIMATIC PROCESSES AND EFFECTS
1.3.01	Climate change, global – yes, implicit inclusion in its effect on local and regional climate
1.3.02	Climate change, regional and local – yes
1.3.03	Sea level change – no, site too far from sea to be affected
1.3.04	Periglacial effects – no, even with climate change
1.3.05	Glacial and ice sheet effects, local – no, see 1.3.04
1.3.06	Warm climate effects (tropical and desert) – yes
1.3.07	Hydrological/hydrogeological response to climate changes – yes
1.3.08	Ecological response to climate changes –yes
1.3.09	Human response to climate changes- no, given the assessment context that there is no change in human activities. This Test Case is not sensitive to population changes since we are considering individual doses.
1.3.10	Other geomorphological changes – no, note stability of the region
1.4	FUTURE HUMAN ACTIONS
1.4.01	Human influences on climate – no, given the limited impact of climate change at the site
1.4.02	Motivation and knowledge issues (inadvertent/deliberate human actions) – yes, inadvertent
1.4.03	Un-intrusive site investigation – no, not relevant for the borehole concept
1.4.04	Drilling activities (human intrusion) – yes
1.4.05	Mining and other underground activities (human intrusion) – maybe, even given that the low mineral resource potential of the area
1.4.06	Surface environment, human activities – no, see below
1.4.06.01	Surface Excavations – no, below depth of normal intrusion
1.4.06.02	Pollution – no significant impact envisaged
1.4.06.03	Site Development – no, below depth of normal intrusion
1.4.06.04	Archaeology – no, below depth of normal intrusion
1.4.07	Water management (wells, reservoirs, dams) - yes
1.4.08	Social and institutional developments – no, see assessment context re present day conditions
1.4.09	Technological developments – no, see assessment context re present day technology
1.4.10	Remedial actions – no, cautious to assume no remediation
1.4.11	Explosions and crashes - no, very low probability
1.5	OTHER
1.5.01	Meteorite impact – no, very low probability, non-radiological consequences significantly greater
1.5.02	Miscellaneous and FEPs of uncertain relevance –no
2	**DISPOSAL SYSTEM DOMAIN: ENVIRONMENTAL FACTORS**
2.1	WASTES AND ENGINEERED FEATURES

2.1.01 Inventory, radionuclide and other material – yes
2.1.02 Waste form materials and characteristics - yes
2.1.03 Container materials and characteristics– yes
2.1.04 Buffer/backfill materials and characteristics– yes
2.1.05 Engineered barriers system e.g. caps– yes
2.1.06 Other engineered features materials and characteristics– yes
2.1.07 Mechanical processes and conditions (in wastes and EBS) – yes
2.1.08 Hydraulic/hydrogeological processes and conditions (in wastes and EBS) – yes
2.1.09 Chemical/geochemical processes and conditions (in wastes and EBS) – yes
2.1.10 Biological/biochemical processes and conditions (in wastes and EBS) – yes (termites)
2.1.11 Thermal processes and conditions (in wastes and EBS) – yes
2.1.12 Gas sources and effects (in wastes and EBS) – yes
2.1.13 Radiation effects (in wastes and EBS) – yes
2.1.14 Nuclear criticality – no, not sufficient activity
2.1.15 Extraneous materials – no, none assumed
2.2 GEOLOGICAL ENVIRONMENT
2.2.01 Excavation disturbed zone, host rock – yes
2.2.02 Host lithology – yes
2.2.03 Lithological units, other – yes
2.2.04 Discontinuities, large scale (in geosphere) –yes (including existing faults)
2.2.05 Contaminant transport path characteristics (in geosphere) – yes
2.2.06 Mechanical processes and conditions (in geosphere) – no, not relevant for near surface borehole
2.2.07 Hydraulic/hydrogeological processes and conditions (in geosphere) – yes
2.2.08 Chemical/geochemical processes and conditions (in geosphere) – yes
2.2.09 Biological/biochemical processes and conditions (in geosphere) – yes
2.2.10 Thermal processes and conditions (in geosphere) –no given that considering it for the near field
2.2.11 Gas sources and effects (in geosphere) – maybe, radon gas impacts might need to be considered
2.2.12 Undetected features (in geosphere) – maybe, could consider presently undetected faults.
2.2.13 Geological resources – maybe, see 1.4.05
2.3 SURFACE ENVIRONMENT
2.3.01 Topography and morphology – yes
2.3.02 Soil and sediment - yes
2.3.03 Aquifers and water-bearing features, near surface –yes
2.3.04 Lakes, rivers, streams and springs – no, assume doses will be lower than from water borehole
2.3.05 Coastal features – no, site context
2.3.06 Marine features - no, site context

2.3.07 Atmosphere - yes due to transport capacity of wind
2.3.08 Vegetation - yes
2.3.09 Animal populations -yes
2.3.10 Meteorology – yes
2.3.11 Hydrological regime and water balance (near-surface) – yes
2.3.12 Erosion and deposition – no
2.3.13 Ecological/biological/microbial systems - yes
2.3.14 Animal/plant intrusion leading to vault/trench disruption -yes
2.4 HUMAN BEHAVIOUR
2.4.01 Human characteristics (physiology, metabolism) –yes
2.4.02 Adults, children, infants and other variations – yes
2.4.03 Diet and fluid intake – yes
2.4.04 Habits (non-diet-related behaviour) – yes
2.4.05 Community characteristics – yes
2.4.06 Food and water processing and preparation – no, cautious to assume no prep/treatment
2.4.07 Dwellings – yes/maybe, consistent with radon calculations
2.4.08 Wild and natural land and water use –yes
2.4.09 Rural and agricultural land and water use (incl. fisheries) –yes
2.4.10 Urban and industrial land and water use – no, due to human activity assumptions in assessment context and the fact that the aquifer will not support a high well density given the relatively poor water quality
2.4.11 Leisure and other uses of environment – no, see human activity assumptions
3 RADIONUCLIDE/CONTAMINANT FACTORS
3.1 CONTAMINANT CHARACTERISTICS
3.1.01 Radioactive decay and in-growth –yes
3.1.02 Chemical/organic toxin stability – no, given the scope of ISAM (only interested in radionuclides)
3.1.03 Inorganic solids/solutes – no, see 3.1.02
3.1.04 Volatiles and potential for volatility – maybe
3.1.05 Organics and potential for organic forms - no, see 3.1.02
3.1.06 Noble gases – yes
3.2 CONTAMINANT RELEASE/MIGRATION FACTORS
3.2.01 Dissolution, precipitation and crystallisation, contaminant - yes
3.2.02 Speciation and solubility, contaminant- yes
3.2.03 Sorption/desorption processes, contaminant- yes
3.2.04 Colloids, contaminant interactions and transport with – maybe, perhaps bounded by other processes
3.2.05 Chemical/complexing agents, effects on contaminant speciation/transport – maybe
3.2.06 Microbial/biological/plant-mediated processes, contaminant – yes
3.2.07 Water-mediated transport of contaminants – yes
3.2.08 Solid-mediated transport of contaminants – yes

3.2.09 Gas-mediated transport of contaminants - yes
3.2.10 Atmospheric transport of contaminants -yes
3.2.11 Animal, plant and microbe mediated transport of contaminants – yes
3.2.12 Human-action-mediated transport of contaminants – yes
3.2.13 Foodchains, uptake of contaminants in – yes
3.3 EXPOSURE FACTORS
3.3.01 Drinking water, foodstuffs and drugs, contaminant concentrations in – yes
3.3.02 Environmental media, contaminant concentrations in –yes
3.3.03 Non-food products, contaminant concentrations in –yes
3.3.04 Exposure modes –yes
3.3.05 Dosimetry – yes
3.3.06 Radiological toxicity/effects – yes (risk)
3.3.07 Non-radiological toxicity/effects – no, not considering non-radioactive contaminants
3.3.08 Radon and radon daughter exposure- yes

Although the Level 0 FEPs (Assessment Context) are not FEPs by definition, they still remain factors influencing the assessment and therefore should be included in the list.

The Level 1 FEPs (External Factors) represents the external factors and are often referred to as scenario generating FEPs. The Level 1.1 FEPs (Repository Issues) are all applicable to the Borehole Test Case, except 1.1.09 (Schedule and Planning), 1.1.11 (Monitoring of Repository) and 1.1.13 (Retrievability). Most Level 1.2 FEPs (Geological Processes and Effects) were screened out as not applicable. The exception is 1.2.10 (Hydrological/hydrgeological responds to geological change), which was screened out at first, but later added to make provision for the response of the aquifer to an earthquake. From this perspective the exclusion of 1.2.03 (Seismicity) should be revisited. The Level 1.3 FEPs that were included are limited to climate changes (1.3.01 and 1.3.02) and their influences on the total system (1.3.06, 1.3.07, 1.3.08, 1.3.09). Other than FEPs related to inadvertent human intrusion (1.4.02, 1.4.04 and 1.4.05), the Level 1.4 FEPs is not applicable to the Borehole Test Case, because of the limited future land used assumptions applicable to the assessment. All Level 1.5 FEPs were screened out as irrelevant.

The Level 2 FEPs (Disposal System Domain: Environmental Factors) represents internal factors associated with the waste and engineered features as well as the site and human behaviour characteristics. The Level 2.1 FEPs (Waste and Engineered Features) were all included, except 2.1.14 (Nuclear criticality) because of insufficient activity in the inventory and 2.1.15 (Extraneous material), because the inventory does not contain any exotic or unidentified materials. The Level 2.2 FEPs (Geological Environment) are related to the FEPs in the geosphere. Two FEPs in this category were considered unimportant for the Borehole Test Case. The first is 2.2.06 (Mechanical processes and conditions in the geosphere), because it was felt to be irrelevant for the borehole disposal concept, particularly at the depth of disposal. The second is 2.2.10 (Thermal processes and conditions in the geosphere), which is excluded because thermal processes within the near field (2.1.11) is included, while it is not expected that thermal activity originating within the geosphere will influence the Test Case. The only Level 2.3 FEPs (Surface Environment) not applicable to the Borehole Test Case are those associated with coastal (2.3.05) and marine features (2.3.06), because of the site location, as well as 2.3.12 (Erosion and deposition). The depth of disposal makes this FEPs irrelevant within the Borehole Test Case assessment context. The land use conditions as discussed in the assessment context helped to screen some of the Level 2.4 FEPs (Human Behaviour). In particular 2.4.10 (Urban and industrial land and water use), and 2.4.11 (Leisure and other users of environment) are not within the Borehole Test Case assessment context. In addition, the assumption is made that no food and water processing and preparation (2.4.06) will be carried out.

The Level 3 FEPs (Radionuclide/Contaminant Factors) can also be considered as internal FEPs, which are directly associated with the contaminant characteristics, its migration factors and the possible exposure modes. Of importance to note is that only radiological impact are determined in the Borehole Test Case, which means that 3.1.02 (Chemical/organic toxin stability), 3.1.01 (Inorganic solids/solutes) and 3.1.05 (Organics and potential for organic forms) can be eliminated from the Level 3.1 FEPs (Contaminant characteristics). Not one of the Level 3.2 FEPs (Contaminant release/Migration factors) could be screened from the FEPs list with confidence, while under the Level 3.3 FEPs (Exposure modes), it was only 3.3.07 (Non-radiological toxicity/effects) that was excluded, because only radiological impact are considered in the Borehole Test Case.

3.3.3. Source-pathway-receptor analysis

In Section 3.3.2, the FEPs relevant to the natural, and human evolution (change of habits) of the system evolution were identified for the Borehole Test Case. The next step followed was to use this information and to perform a source-pathway-receptor analysis for the exposure scenarios defined in Section 3.3.1. The advantage is that site-specific issues are addressed directly and conceptual model development will flow directly out of the analysis.

Source

An initial assumption was made that the source is in the unsaturated zone. This means that the top of the waste is at 35 m, while the base is at 45 m below surface. The water table at Vaalputs is more or less at 55 m, which implies that there is a 10 m thickness of unsaturated zone beneath the disposed waste.

A schematic representation of the sources in the borehole disposal concept and the flow of activity through the different components of the system are presented in Fig. 77. For disused Ra sealed sources the activity first has to move through the air gap, after which corrosion of the stainless steel capsule will cause failure and subsequent movement of activity into the cement backfill. Corrosion will again be responsible for the failure of the stainless steel container, with subsequent movement of activity into the concrete backfill of the borehole.

A discussion on pitting and crevice corrosion rates led to the assumption that the rate is 0.3 µm y^{-1} to 1 µm y^{-1}. After 2000 years (with a range of 1000 years to 5000 years) failure of the above system will allow access of water to the source. The waste is dissolved in water and available for transport through the geosphere.

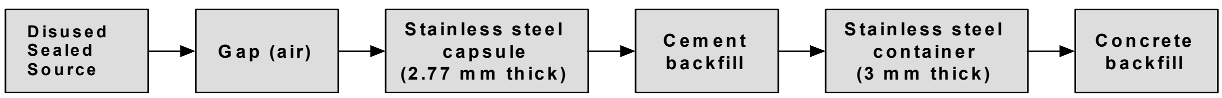


FIG. 77. Schematic Representation of the Movement of Activity through the Source of the Borehole Disposal Concept.

Pathway

For any of the source activity to reach the receptors, three pathways are of potential importance, namely a downward pathway, an atmospheric pathway, and upward pathway. The downward liquid pathway is induced by precipitation and the consequent infiltration and percolation of soil moisture through the unsaturated zone. Some of this soil moisture will be lost through the soil surface through evapotranspiration, causing an upward movement in the topsoil layer. Scientific evidence shows that capillary rise only occurs in the top 3 m of the soil profile. This will results in a net infiltration and percolation of water though the unsaturated zone. The disturbed zone caused by the drilling of the borehole might enhance infiltration. A net infiltration rate of 1 mm y^{-1} to 3 mm y^{-1} was assumed for the Borehole Test Case assessment. Under the processes of advection and diffusion, transports the radionuclides released from the source will occur through the remaining 10 m of unsaturated soil to the saturated zone. Flow and transport through the saturated zone takes place, followed by abstraction of contaminated water from a borehole. The borehole water is then used for agricultural and household purposes. This results in a number of secondary pathways to consider e.g. drinking (human and animal), irrigation (of animal feed and crops), and food and animal consumption for each critical group.

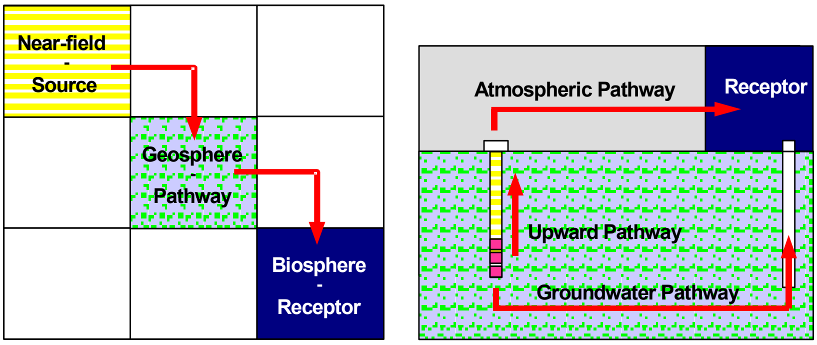


FIG. 78. Schematic Representation of the Source-pathway-receptor Analysis for the Borehole Test Case.

For the atmospheric pathway, it was decided that it is unlikely that there will be a significant diffusive flux due to the thick clay rich cover. However, a scoping calculation could be undertaken for gas, especially since the borehole might act as a conduit. The assumption could also be made that a house could be located on top of the borehole but then it might prevent the downward migration pathway because it will prevent infiltration and is discounted. An additional pathway is the upward non-gas pathway. This movement could be due to a number of reasons. Firstly, liquid diffusion to the soil surface with particulate emission and air transport and deposition onto plants and soil at the receptors could occur. Plant uptake of activity will occur at the point of upward movement and at the point of deposition.

Secondly termites have been identified as a burrowing animal that could influence the integrity of the system. They excavate contaminated soil to the surface. This could cause external radiation to the receptors. During excavation, activity accumulates in the termites after which the receptors will be exposed to radiation if they eat the termites as a source of protein.

Thirdly, inadvertent human intrusion, the pathway will be limited to a new borehole being drilled into the contaminated zone around the disposal borehole, after which the receptors are exposed to the excavated solid material through various secondary pathways.

Receptor

From the definition of the exposure scenarios it is clear that three groups of receptors are of concern for the Borehole Test Case.

The first group considers a present day farmer and his family making a living using groundwater abstracted from a water borehole, which is assumed 10 m away from the disposal borehole. This water is used for household purposes (e.g. drinking) and for agricultural purposes (irrigation, livestock water supply). The farmer makes a living from the land and also feeds his livestock from the land. Various ingestion, inhalation and external pathways to the farmer are therefore of concern.

The next receptor group are those who eat the termites that have excavated contaminated soil. This receptor group, which is traditional hunter-gatherers, will be exposed to radiation through ingestion of contaminated termites and externally comprised of from the contaminated soil while harvesting the termites. Traditionally they do not use borehole water and also do not grow farm products. The contaminated termites and soil are therefore the only exposure pathway for this group.

The final receptor group is comprised of those persons responsible for inadvertent intrusion. For the Borehole Test Case the normal intrusion pathways such as excavations are irrelevant because the depth of disposal is below the normal depth of intrusion. The inadvertent intrusion that will be considered is related to the drilling of a borehole into the contaminated plume. The probability of a perfect hit into the waste packages is very low and consequently will not be considered. The receptor group for this scenario consists of the drilling contractors responsible for the drilling of the borehole. These contractors will be exposed to external radiation from the core samples and internal exposure from inhaling the contaminated dust. The purpose of the drilling could be various reasons but would not influence the receptor group.

3.4. FORMULATION AND IMPLEMENTATION OF MODELS

With the exposure scenarios defined, the next step in the safety assessment process is to formulate and implement the necessary models to perform the consequence analysis. Two types of models have to be to developed, namely conceptual and mathematical models. The conceptual model is a simplified conceptualisation of the real world system and amongst others, may consists of a written description, a flow diagram or a schematic representation. The mathematical model consists of the mathematical equations (governing equations) describing to processes taking place in the disposal system.

The models and associated data developed for the scenario defined in Section 3.3 are discussed below. For the conceptual model development, an interaction matrix approach was followed, combined with the use of the screened ISAM FEPs. This approach provided an audit trail for the processes considered in the assessment.

Note, however, that due to a time and resource constraints, all the defined scenarios did not received equal attention. Models were developed and calculations were undertaken for the farmer scenario (Section 3.4.2) and the hunter gather scenario (Section 3.4.3).

3.4.1. Total system model development

Before attempting to develop conceptual and mathematical models for the individual components of the total system for each scenario (the near field, geosphere and biosphere), an attempt was made to develop a conceptual model for the total system (i.e. a high level conceptual model). The interaction matrix used for this purpose can therefore also be considered as a high level matrix.

In developing an interaction matrix it is possible to develop two types of matrix. The first considers the influence of element A on element B, i.e. the interaction between element A and element B. The second type of matrix considers the transfer of activity from element A to element B. The former can exclude the waste package (i.e. source term) and the dose to the exposure group and essentially is a mass balance that considers how water, solid and gas moves around the system. The latter approach includes the source term and doses. In developing a total system interaction matrix, the first attempt was to try and combine both approaches into one matrix to save time.

The Leading Diagonal Elements (LDE) identified for the interaction matrix are: waste package, unsaturated zone, saturated zone, soil, atmosphere, flora, fauna, human activities, exposure group.

(i) As used here the *waste package* refers to both the waste and the waste form, i.e. the conditioned waste in an outer container.

(ii) The *unsaturated zone* includes to the region between the ground surface and the water table but excluding the plant rooting zone (soil).
(iii) The *saturated zone*, on the other hand, refers to the region below the water table. The capillary fringe is ignored in this definition.
(iv) *Soil* refers to the region from the ground surface to the base of the rooting zone of cultivated plants. A maximum of 1 m is assumed for the soil region.
(v) *Atmosphere* refers to the gaseous layer above the soil.
(vi) *Flora* refers to all the plants, including gum tree, lucerne, grass, prickly pear, corn, desert bush and fig tree for the area of concern.
(vii) *Fauna* refers to all the animals, which include rabbits, rats, snake, aardvark, sheep, termite, goat, ostrich, springbok, gemsbok, poultry and wild birds.
(viii) *Human activities* that will be considered are the farming of animals and crops, irrigation, ingestion and inhalation for the farmer scenarios. For the hunter-gatherer scenario the activities will be limited to the harvesting of termites and ingestion. For the intrusion scenario the activities that will be considered include drilling of boreholes, handling of core samples and inhalation of dust.
(ix) *Dose to exposure group(s)* refers to the dose calculated for different member of public. For the farmer scenario, various age groups could be considered with doses via ingestion, inhalation and external irradiation/immersion. For the hunter-gatherer scenario various age group can again be considered, with doses via ingestion and external irradiation of the older age groups. For the human intrusion scenario it is only necessary to consider adults with doses via inhalation and external irradiation.

Some processes take place within the LDEs that needs to be recognized. This includes:

(i) Corrosion (sulphate attack, chloride attack), leaching, dissolution, diffusion, advection, sorption, decay and in-growth, chemical speciation, solubility limitation;
(ii) Diffusion, advection, sorption, decay and in-growth, chemical speciation;
(iii) Diffusion, advection, sorption, decay and in-growth, chemical speciation;
(iv) Diffusion, advection, sorption, decay and in-growth, chemical speciation, water erosion, wind erosion;
(v) Wind advection and dispersion, precipitation, temperature, radon progeny attachment to air borne particulate, decay and in-growth but only for radon progeny;
(vi) Biomass production, translocation; and
(vii) Production, transfer of contaminants to human.

The resulting total system interaction matrix including the Off-Diagonal Elements (ODE) is presented in Table 47. A few points to note are the following:

— It is assumed that the consequences of gum tree root intrusion (2.6) and intrusion of termites (2.7) into the unsaturated zone is small compared with direct intrusion into waste packages [See (1.6) and (1.7)].
— The saturated zone is assumed to be too deep for the gum tree roots or the termites to penetrate [See (1.6) and (1.7)].
— Water abstraction (3.8) – it is assumed that the farmer did not drill the borehole.

To check that all relevant FEPs had been included in the interaction matrix, the location of each FEP in the matrix was mapped onto the FEP list. This allowed a double check of the initial screening of FEPs and the documentation and explanation of any changes. The resulting FEPs list is presented in Table 48.

TABLE 47 THE TOTAL SYSTEM INTERACTION MATRIX AS COMPILED FOR THE BOREHOLE TEST CASE.

	1	2	3	4	5	6	7	8	9
1	**Waste Package**	Diffusion, advection (include radon)				Gum tree root uptake	Excavation by termites		
2	Percolation	**Unsaturated zone**	Advection, Diffusion, Dispersion	Diffusion, Gas advection		Gum tree root uptake	Excavation by termites		
3			**Saturated zone**					Water supply	Ingestion Immersion
4		Infiltration		**Soil**	Suspension, Gas diffusion, Evaporation	Root uptake, Rain splash	Ingestion		Ingestion, External irradiation
5				Deposition (wet and dry), Infiltration	**Atmosphere**	Deposition (wet and dry)	Inhalation		Inhalation
6	Gum tree root intrusion	Gum tree root intrusion		Death and decay	Transpiration	**Flora**	Ingestion		Ingestion
7	Intrusion by Termites	Intrusion by Termites		Bioturbation, Fertilisation	Exhalation, Flatulence	Fertilisation	**Fauna**		Ingestion
8			Water abstraction	Ploughing, Irrigation (drip)		Cultivation, Harvesting	Rearing, Hunting	**Human activities**	Exposure mechanisms
9									**Dose to Exposure Group(s)**

TABLE 48. ISAM FEP LIST SCREENED FOR THE BOREHOLE TEST CASE WITH REFERENCE TO THE TOTAL SYSTEM INTERACTION MATRIX.

0	**ASSESSMENT CONTEXT**
0.01	Impacts of concern – yes, see assessment context for details
0.02	Timescales of concern –yes, see assessment context for details
0.03	Spatial domain of concern –yes, see assessment context for details
0.04	Repository assumptions - yes, see assessment context for details
0.05	Future human action assumptions – yes, see assessment context for details
0.06	Future human behaviour (target group) assumptions – yes, see assessment context for details
0.07	Dose response assumptions – yes, see assessment context for details
0.08	Aims of the assessment – yes, see assessment context for details
0.09	Regulatory requirements and exclusions – yes, see assessment context for details
0.10	Model and data issues – yes, see assessment context for details
1	**EXTERNAL FACTORS**
1.1	REPOSITORY ISSUES
1.1.01	Site investigation –yes, assume that site investigation programme does not impact on the safety of the site.
1.1.02	Excavation/construction –yes, cautiously assume that the disposal borehole intercepts a fracture.
1.1.03	Emplacement of wastes and backfilling –yes, assume no credit taken for backfill.
1.1.04	Closure e.g. capping –yes, assume no credit taken for closure measures. Note that need to describe the cap design. Top of “cap” will be at grade and will be 3 m thick. May wish to iterate on closure design on the basis of the initial assessment results, e.g. design against termites.
1.1.05	Records and markers, repository – yes, but only for 30 years, thereafter no credit taken
1.1.06	Waste allocation – yes, noted that we need to clarify the waste allocation since so far we have not considered this in detail. It has been suggest that we should consider 10 packages, with an isotope per package. JvP suggested that we focus on waste packages that will fit into the current design. It was felt worthwhile to try and keep the inventory discussed on Monday. Someone should come up with the list of radionulcides and waste allocation outside this meeting. We should aim for 10 packages over a 10 m depth with an isotope per package, although this will be double checked outside the meeting.
1.1.07	Repository design –yes, see disposal facility design for details. See scenario description from Tuesday for information re depth of borehole and depth of waste.
1.1.08	Quality control –yes, assume good quality control in general but note that no credit taken for backfill (possibly due to waste contacting side of borehole)
1.1.09	Schedule and planning – no, not significant to what we are doing

1.1.10 Administrative control, repository site – yes, but only for 30 years

1.1.11 Monitoring of repository – no, no impact on performance. Might have some monitoring but only for 30 years. Heated discussion re the purpose of monitoring post closure, is it for public relations or will data be used for assessing/checking the safety of the facility? It was agreed that monitoring is important for public confidence building. For this assessment, not significant

1.1.12 Accidents and unplanned events – yes (could impact on container integrity), but not considered in this scenario

1.1.13 Retrievability – no, assumed not to be required.

1.2 GEOLOGICAL PROCESSES AND EFFECTS

1.2.01 Tectonic movements and orogeny – no, given the location of the site

1.2.02 Deformation, elastic, plastic or brittle – no, given the location of the site

1.2.03 Seismicity – no, seismicity will not have a direct effect unless there is an active fault running through the borehole. Effect of seismic event can be considered in 1.2.10 if required

1.2.04 Volcanic and magmatic activity-no, site context

1.2.05 Metamorphism – no

1.2.06 Hydrothermal activity – no

1.2.07 Erosion and sedimentation – no, geomorphological evidence suggests that area is very stable

1.2.08 Diagenesis – no

1.2.09 Salt diapirism and dissolution – no

1.2.10 Hydrological/hydrogeological response to geological changes – maybe, probably no. Revisited and said no and include under 2.2.04. Later said: maybe yes, because of hydrological properties of aquifer may change after an earthquake. This needs to be considered further. Yes, can include in sensitivity/uncertainty analysis. Need to check with geologist re the possible impacts of seismic pumping. Perhaps it can be included under 2.2 factors.

1.3 CLIMATIC PROCESSES AND EFFECTS

1.3.01 Climate change, global – yes, implicit inclusion in its effect on local and regional climate, see 1.3.02

1.3.02 Climate change, regional and local – yes, consider through calculations with a range in precipitation, calculations could be deterministic or probabilistic. Might need to consider the temporal effects of climate change

1.3.03 Sea level change – no, site too far from sea to be affected

1.3.04 Periglacial effects – no, even with climate change

1.3.05 Glacial and ice sheet effects, local – no, see 1.3.04

1.3.06 Warm climate effects (tropical and desert) – yes, but will assume that annual averages will be sufficient. Will high magnitude, low frequent events be used in deriving the “annual” average? Yes

1.3.07 Hydrological/hydrogeological response to climate changes – yes, see 1.3.02 (note need to couple to other relevant parameter)

1.3.08 Ecological response to climate changes –yes, see 1.3.02 and 1.3.07

1.3.09 Human response to climate changes - no, given the assessment context that there is no change in human activities. This test case is not sensitive to population changes since individual doses are considered. Discussion as to whether the “no” should be “yes” especially given that have got ecological change. No fundamental change in habits, but perhaps allow changes in magnitude. Overall decide to change to YES, but only in so far as it changes the amounts of food ingested. No fundamental change in habit.

1.3.10 Other geomorphological changes – no, note stability of the region

1.4 FUTURE HUMAN ACTIONS

1.4.01 Human influences on climate – no, given the limited impact of climate change at the site

1.4.02 Motivation and knowledge issues (inadvertent/deliberate human actions) – yes, inadvertent for intrusion scenario. No for farmer and hunter gatherer scenarios.

1.4.03 Un-intrusive site investigation – no, not relevant for the borehole concept

1.4.04 Drilling activities (human intrusion) – yes for human intrusion scenario. No for farmer scenario other than drilling the well in the first place, and no for hunter gatherer scenario.

1.4.05 Mining and other underground activities (human intrusion) – maybe for intrusion scenario, even given that the low mineral resource potential of the area - no for farmer scenario other than drilling the well in the first place

1.4.06 Surface environment, human activities – no, see below

1.4.06.01 Surface Excavations – no, below depth of normal intrusion

1.4.06.02 Pollution – no significant impact envisaged

1.4.06.03 Site Development – no, below depth of normal intrusion

1.4.06.04 Archaeology – no, below depth of normal intrusion

1.4.07 Water management (wells, reservoirs, dams) – yes

1.4.08 Social and institutional developments – no, see assessment context re present day conditions

1.4.09 Technological developments – no, see assessment context re present day technology

1.4.10 Remedial actions – no, cautious to assume no remediation

1.4.11 Explosions and crashes - no, very low probability

1.5 OTHER

1.5.01 Meteorite impact – no, very low probability, non-radiological consequences significantly greater

1.5.02 Miscellaneous and FEPs of uncertain relevance –no

2 DISPOSAL SYSTEM DOMAIN: ENVIRONMENTAL FACTORS

2.1 WASTES AND ENGINEERED FEATURES

2.1.01 Inventory, radionuclide and other material – yes, 1.1

2.1.02 Waste form materials and characteristics – yes, 1.1

2.1.03 Container materials and characteristics– yes, 1.1

2.1.04 Buffer/backfill materials and characteristics– yes, 2.2 (but no credit taken) (some discussion re whether the canister is assumed to touch the wall of the borehole. It was agreed to assume that the container is centred)

2.1.05 Engineered barriers system e.g. caps– yes, 1.1, 2.2

2.1.06 Other engineered features materials and characteristics– yes, 2.2

2.1.07 Mechanical processes and conditions (in wastes and EBS) – yes, 1.1, 2.2

2.1.08 Hydraulic/hydrogeological processes and conditions (in wastes and EBS) – yes, 1.1, 1.2, 2.1, 2.2

2.1.09 Chemical/geochemical processes and conditions (in wastes and EBS) – yes, 1.1, 1.2, 2.1, 2.2

2.1.10 Biological/biochemical processes and conditions (in wastes and EBS) – yes (termites), 1.6, 1.7, 2.6, 2.7, 6.1, 6.2, 7.1, 7.2

2.1.11 Thermal processes and conditions (in wastes and EBS) – yes, - consider that we should check the inventory to see if this is an important FEP – ideally this should be done as part of side calculation work.

2.1.12 Gas sources and effects (in wastes and EBS) – yes, 1.1, 1.2

2.1.13 Radiation effects (in wastes and EBS) – yes, 1.1, 2.2

2.1.14 Nuclear criticality – no, not sufficient activity

2.1.15 Extraneous materials – no, (Consider that this FEP needs to be clarified/improved/deleted)

2.2 GEOLOGICAL ENVIRONMENT

2.2.01 Excavation disturbed zone, host rock – yes, 2.2

2.2.02 Host lithology – yes, 2.2

2.2.03 Lithological units, other – yes, 2.2, 3.3

2.2.04 Discontinuities, large scale (in geosphere) –yes (including existing faults), 2.2, 3.3

2.2.05 Contaminant transport path characteristics (in geosphere) – yes, 2.1, 2.2, 2.3, 2.4, 3.3, 3.8, 8.3

2.2.06 Mechanical processes and conditions (in geosphere) – no, not relevant for near surface borehole

2.2.07 Hydraulic/hydrogeological processes and conditions (in geosphere) – yes, 2.1, 2.2, 2.3, 2.4, 3.3, 3.8, 8.3

2.2.08 Chemical/geochemical processes and conditions (in geosphere) – yes, 2.1, 2.2, 2.3, 2.4, 3.3, 3.8, 8.3

2.2.09 Biological/biochemical processes and conditions (in geosphere) – yes, 2.6, 2.7, 6.2, 7.2

2.2.10 Thermal processes and conditions (in geosphere) –no given that considering it for the near field

2.2.11 Gas sources and effects (in geosphere) – maybe, radon gas impacts might need to be considered, - now change to yes, 2.2, 2.4

2.2.12 Undetected features (in geosphere) – maybe, could consider presently undetected faults. – no change to yes, 2.2, 3.3

2.2.13 Geological resources – maybe, see 1.4.05 , no for farming scenario and hunter gatherer scenario

2.3 SURFACE ENVIRONMENT

2.3.01 Topography and morphology – yes, 4.4

2.3.02 Soil and sediment - yes, 4.4

2.3.03 Aquifers and water-bearing features, near surface –yes, 3.3

2.3.04 Lakes, rivers, streams and springs – no, assume doses will be lower than from water borehole

2.3.05 Coastal features – no, site context

2.3.06 Marine features - no, site context

2.3.07 Atmosphere - yes due to transport capacity of wind, 5.5

2.3.08 Vegetation - yes, 6.6,

2.3.09 Animal populations –yes, 7.7

2.3.10 Meteorology – yes, 5.5

2.3.11 Hydrological regime and water balance (near-surface) – yes, 4.4, 5.5, 6.6, 8.8, 2.1, 4.2, 5.4, 6.5, 4.5, 4.6, 8.4

2.3.12 Erosion and deposition – yes, but note no net erosion/deposition but allow for resuspension and deposition, 4.4, 4.5, 5.4, 5.6

2.3.13 Ecological/biological/microbial systems - yes, 6.6, 7.7, 8.8

2.3.14 Animal/plant intrusion leading to vault/trench disruption –yes, 1.6, 1.7, 2.6, 2.7, 6.1, 6.2, 7.1, 7.2

2.4 HUMAN BEHAVIOUR

2.4.01 Human characteristics (physiology, metabolism) –yes, assume that have ICRP reference human characteristics, high level FEP

2.4.02 Adults, children, infants and other variations – yes, assume that have 5 age groups, high level FEP

2.4.03 Diet and fluid intake – yes, 3.8, 3.9, 4.9, 6.9, 7.9

2.4.04 Habits (non-diet-related behaviour) – yes, 8.3, 8.4, 8.6, 8.7

2.4.05 Community characteristics – yes, self contained group,

2.4.06 Food and water processing and preparation – no, cautious to assume no prep/treatment

2.4.07 Dwellings – yes/maybe, consistent with radon calculations

2.4.08 Wild and natural land and water use –yes, 3.8, 8.3, 8.6, 8.7, (maybe say that farmer has 20% of food intake from wild foodstuffs) Some discussion concerning the use of soil, flora and fauna as resources (e.g. building materials, skins, etc). It was decided that the impacts would be significantly smaller than other pathways

2.4.09 Rural and agricultural land and water use (incl. fisheries) –yes, 8.4, 8.6, 8.7, 2.4.10 Urban and industrial land and water use – no, due to human activity assumptions in assessment context and the fact that the aquifer will not support a high well density given the relatively poor water quality

2.4.11 Leisure and other uses of environment – no, see human activity assumptions.

3 RADIONUCLIDE/CONTAMINANT FACTORS

3.1 CONTAMINANT CHARACTERISTICS

3.1.01 Radioactive decay and in-growth –yes, 1.1, 2.2, 3.3, 4.4, 5.5

3.1.02 Chemical/organic toxin stability – no, given the scope of ISAM (only interested in radioactive contaminants)

3.1.03 Inorganic solids/solutes – no, see 3.1.02

3.1.04 Volatiles and potential for volatility – maybe – yes because considering radon, 1.1

3.1.05 Organics and potential for organic forms - no, see 3.1.02

3.1.06 Noble gases – yes, as 3.1.04

3.2 CONTAMINANT RELEASE/MIGRATION FACTORS

3.2.01 Dissolution, precipitation and crystallisation, contaminant – yes, 1.1, 2.2, 3.3, 4.4

3.2.02 Speciation and solubility, contaminant- yes, 1.1, 2.2, 3.3, 4.4

3.2.03 Sorption/desorption processes, contaminant- yes, 1.1, 2.2, 3.3, 4.4

3.2.04 Colloids, contaminant interactions and transport with – maybe, perhaps bounded by other processes – decided not to consider it as an explicit process in mathematical models, could consider via Kd sampling – ensure low Kd value for Pu for lower limit. It is recognized that colloids can exist.

3.2.05 Chemical/complexing agents, effects on contaminant speciation/transport – maybe – yes, will consider pH effect of disposal facility system, 1.1

3.2.06 Microbial/biological/plant-mediated processes, contaminant – originally selected as yes, but decided to change this to "no" on second reading of the FEP definition.

3.2.07 Water-mediated transport of contaminants – yes, 1.2, 2.3, 2.4, 4.4

3.2.08 Solid-mediated transport of contaminants – yes, 4.4, 4.5, 4.6, 5.4, 5.6

3.2.09 Gas-mediated transport of contaminants – yes, 1.2, 2.3, 2.4, 4.5

3.2.10 Atmospheric transport of contaminants –yes, 4.4, 4.5, 5.5, 5.6

3.2.11 Animal, plant and microbe mediated transport of contaminants – yes, 1.6, 1.7, 2.6, 2.7, 4.6, 4.7, 5.7, 6.4, 6.6, 6.7, 7.4, 7.5, 7.6, 7.7

3.2.12 Human-action-mediated transport of contaminants – yes, 3.8, 8.3, 8.4, 8.6, 8.7

3.2.13 Foodchains, uptake of contaminants in – yes, 4.6, 4.7, 5.6, 5.7, 6.7, 7.6

3.3 EXPOSURE FACTORS

3.3.01 Drinking water, foodstuffs and drugs, contaminant concentrations in – yes, It was thought that the FEP needed to be clarified, 3.3, 6.6, 7.7

3.3.02 Environmental media, contaminant concentrations in –yes, 4.4, 5.5

3.3.03 Non-food products, contaminant concentrations in – yes, - in closer examination of this FEP an extra possible pathway was identified: burning the gum tree. It was thought that the impact was low and would be bounded by other calculations, only one tree at a time can be contaminated.

3.3.04 Exposure modes –yes, 3.9, 4.9, 5.9, 6.9, 7.9

3.3.05 Dosimetry – yes, 3.9, 4.9, 5.9, 6.9, 7.9

3.3.06 Radiological toxicity/effects – yes (risk?), 3.9, 4.9, 5.9, 6.9, 7.9

3.3.07 Non-radiological toxicity/effects – no, not considering non-radioactive contaminants

3.3.08 Radon and radon daughter exposure- yes, 5.9

With the interaction matrix complete and all the relevant FEPs identified, it is possible to develop the conceptual model in terms of the radionuclide migration and exposure pathways for the total system. Note that in the conceptual model it is assumed that contaminated irrigation water does not infiltrate into the unsaturated zone. Instead it is cautiously assumed that the radionuclides accumulate in the soil.

3.4.2. Farmer scenario

Near field model development

In principle the near field for the borehole disposal concept can be considered as the waste packages, the concrete backfill, the borehole itself and the disturbed or damaged zone. The near field plays a very important role in the performance of the concept and provides almost complete confinement of activity from the geosphere.

In this section the work that has been undertaken relating to of near field model development is discussed. It is based on the model used to calculate the release of ^{226}Ra from the near field.

Conceptual model

For any release of activity to occur, corrosion of the outer stainless steel container has to start, keeping in mind that some passivation of the container will occur due to the concrete backfill. Kozak *et al*. [36] evaluated the general corrosion of a stainless steel container under borehole conditions, and concluded that the container is unlikely to fail due to general corrosion within 10 000 years after closure. A more credible failure mechanism for the stainless steel is crevice corrosion at the welds. Such corrosion is considered to permit releases through a small fraction of the total surface area of the container. Chloride ions have to diffuse through the cement backfill matrix and then start crevice corrosion of the capsule that contains the disused source. Due to gas generation in the capsule, resulting from ^{226}Ra decay, the pressure in the capsule increases but not to such levels that would cause the failure of the container due to pressure build-up. The capsule starts to fail due to corrosion and some advective flow causes the capsule to fill or causes contact of water with the waste. It is assumed that the radium needles are broken and failed. Transport of activity through the waste form through advection and diffusion will commence. For the purposes of this analysis, the container is assumed to be initially breached by crevice corrosion at between 100 years to 300 years after emplacement. The breach is assumed to open a fraction of between 0.001 to 0.01 of the container.

For sources other than ^{226}Ra a similar conceptual model can be used, but without pressure increase and some different model parameter values.

Mathematical model

The release of activity from the stainless steel container is evaluated using the following basic assumptions. First, it is assumed that the disused source is encapsulated in the grout matrix without its shielding or other encapsulation. In considering the disposal of disused sources, this assumption is likely to be very conservative. It is assumed that the concentration of contaminant at the surface of the disused source is controlled by elemental solubility. It is further assumed that the grout in the container is well formed, and that transport through it is governed by Fickian diffusion. In this case the flux is given by:

where

$$j_i = -D_e \nabla C_i \quad (42)$$

where:

j_i is the flux of contaminant i through the grout [Bq m^{2}y^{-1}];
D_e is the effective diffusion coefficient of the contaminant in the grout matrix [m.y^{-1}];
C_i is the aqueous concentration of contaminant i [Bq.m^{-3}].

Assuming that the concentration at the surface of the source is at its solubility limit, and that the concentration at the crevice is zero, and for the sake of simplicity assuming one-dimensional radial diffusion, the release rate [Bq y^{-1}] from the container is given by:

$$Q_i = \pi r_c^2 L f D_e C_s / (r_c - r_s) \quad (43)$$

where

r_c is the radius of the container [m];
r_s is the radius of the source;
L is the length of the container [m];
F is the fraction of the container that fails by crevice corrosion;
C_s is the solubility limit for the contaminant [Bq.m^{-3}].

That is, the release rate will be constant until the inventory is exhausted. For a non-decaying contaminant, this occurs when:

$$T = a_0 / q_i \quad (44)$$

Here, a_0 is the initial activity of the waste [Bq], and q_i is the ensuing constant release rate [Bq.y^{-1}].

For a decaying contaminant with decay constant λ[y^{-1}], the inventory becomes exhausted when:

$$T = \frac{1}{\lambda}\ln[1 + \frac{\lambda a_0 e^{-\lambda t_b}}{q_i}] = \frac{1}{\lambda}\ln[1 + \frac{\lambda a_0 e^{-\lambda t_b}(r_c - r_s)}{\pi L f D_e c_s r_c^2}] \quad (45)$$

Here, t_b is the time at which the breach occurs [y].

Assuming that this release is uniformly dispersed radially in the borehole, this release leads to a concentration in the borehole of:

$$C_i = q_i / V_{bore} = f D_e c_s r_c^2 / (r_c - r_s) \theta_{bore} r_{bore}^2 \quad (46)$$

where

V_{bore} is the volume of the aqueous phase in the borehole plug (m^3);
θ_{bore} is the moisture content in the borehole plug (–);
r_{bore} is the radius of the borehole (m).

In this formulation of the equations, sorption is not explicitly expressed. Instead, it is included implicitly by the choice of effective diffusion coefficient.

Geosphere model development

The geosphere for the Borehole Test Case consists of the unsaturated and saturated zones in the vicinity of the near field to the point of the receptors. To develop conceptual and mathematical models for the geosphere, several continuous assumption were introduced in terms of a simplified conceptual models and model parameters to enhance the infiltration capacity of the system.

The first assumption is that termites made their nest right on top of the disposal borehole. This is considered to be a realistic scenario, because termites would prefer any soft soil spot. In this case they would target the disturbed area that is covered with topsoil. It is furthermore assumed that a single termite hole follows the trace of the borehole in an attempt to reach the water table. It is also assumed that the borehole penetrated a permeable fracture zone (0.2 m wide) just before it terminates at 45 m below surface. When the termites reach the bottom of the borehole, they follow the soft and damp fracture zone to the water table. The termites at Vaalputs use fractures to penetrate the hard calcrete layer. It is also assumed that after the hole is dug, the termite hill on top of the borehole is destroyed by an Aardvark, which leaves a depression right on top of the borehole. Rainwater will collect in this depression and increase infiltration.

An extended assumption is that a Gum tree is growing next to the borehole and that root invasion of the backfill material and the area around the waste packages takes place. Root uptake of radionuclides takes place.

In addition to the termite hole, it is also assumed that a fracture exits from the surface and cuts right through the disposal zone down to the water table. This fracture continues in the saturated zone to the abstraction. A schematic representation of these assumptions is presented in Fig. 79.

Conceptual model

Following a precipitation event, some moisture will infiltrate into the topsoil layer, from where most will evaporate back into the atmosphere. A fraction will also be returned back to the atmosphere by the vegetation, while a small fraction will infiltrate into the deeper soil layers and the fracture zone. The fracture zones at Vaalputs extend through the overlying red sand through the disposal zone and down into the saturated zone. At the destroyed termite hill ponding will occur, which will enhance infiltration through the existing, abandoned termite tunnel. The flow in the termite tunnel and the fracture zone will depend on the saturation, although flow occurs even if these zones are only partially saturated. The water flows past the waste packages, transports the radionuclides emanating from the waste packages by advection, dispersion and diffusion via the fracture zone and termite tunnel to the water table. Along the flowpath, decay occurs and the radionuclides adsorb on the fracture walls. The fracture zone is intersected by a sub-horizontal fracture zone, which in turn is penetrated by a water supply borehole located 10 m away from the disposal borehole. Groundwater abstraction from the water supply borehole causes the plume to move in that direction and the contaminated water is pumped out for use as drinking water and for irrigation.

The resulting conceptual model in compartment format is illustrated in Fig. 80. Included in the conceptual model are some of the input parameters needed for the geosphere analysis, as well as some of the transport processes that will be considered.

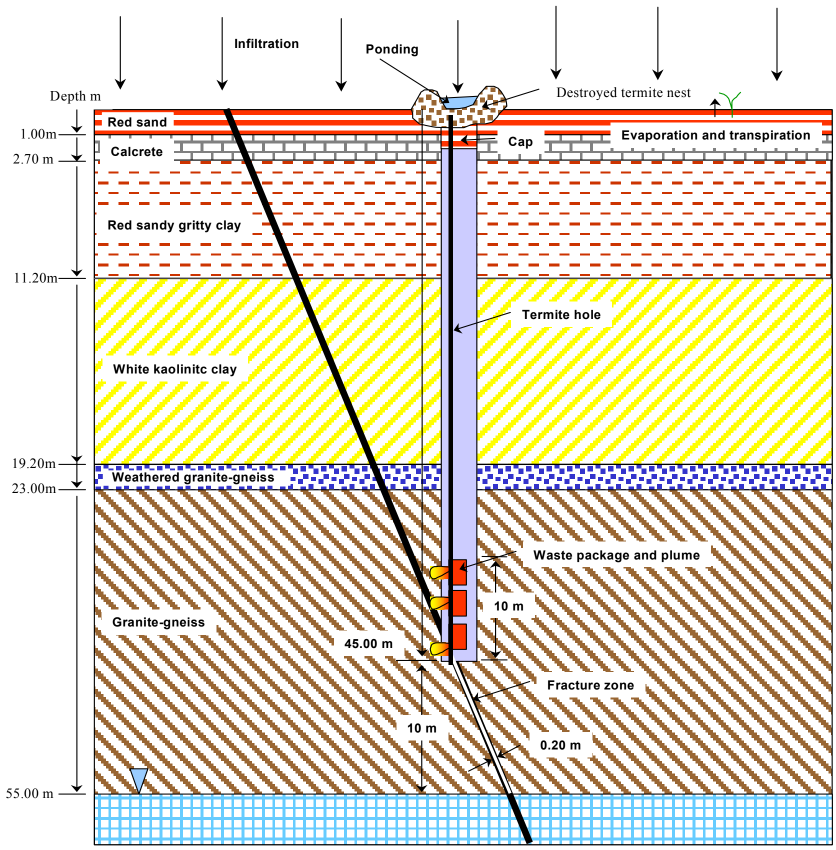


FIG. 79. Schematic Representation of the Assumptions for the Geosphere Model Development for the Borehole Test Case *Safety Assessment.*

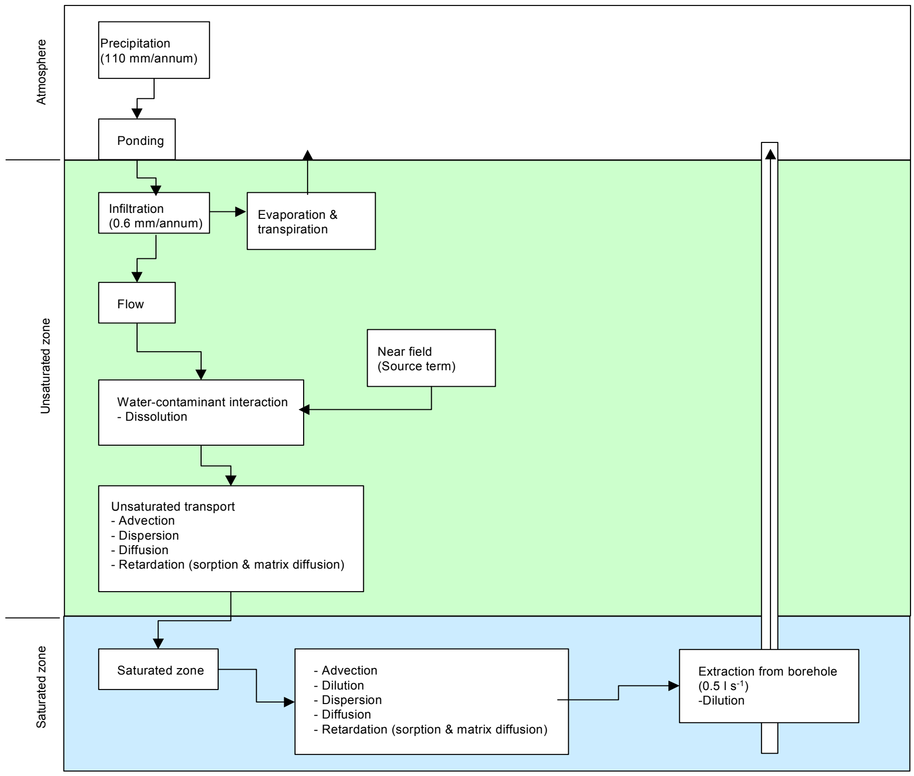


FIG. 80. The Geosphere Conceptual Model for the Borehole Test Case Safety Assessment, in Compartment Format.

The geosphere interaction matrix compiled in Table 49 is an attempt to reflect the assumptions and condition in the geosphere as described above. This means that it primarily describes the processes and conditions for the farmer scenario, in which water is abstracted from a borehole 10 m away from the disposal borehole.

Mathematical model

An analytical approach to derive radionuclide concentrations in borehole water was followed for the Borehole Test Case. The procedure involved the following steps:

- Source Term: Radionuclide concentration time series at the bottom of the borehole;
- Unsaturated zone flow and transport;
- Mixing at the water table; and
- Saturated zone transport to water borehole.

$$q = I = -K(\theta)\left(\frac{\partial \psi}{\partial z} - 1\right) \tag{47}$$

where

q is the Darcy flux in "z" direction (m y^{-1});
I is the recharge, or infiltration (m);
$K(\theta)$ is the hydraulic conductivity at moisture content, θ (m y^{-1});
ψ is the matrix potential (m);
z is the depth co-ordinate, z is positive downward (m);
$\partial\psi/\partial z$ is the matrix potential gradient (–).

Assuming that the matric potential is uniform, Equation (47) can be expressed as:

$$q = K(\theta) \tag{48}$$

The pore water velocity (v, m y^{-1}) is expressed as:

$$\boldsymbol{v} = \frac{\boldsymbol{q}}{\boldsymbol{n_e}\,\boldsymbol{R}} \tag{49}$$

where

n_e is the effective porosity (–);
R is the retardation (–).

The retardation R is given by:

$$\boldsymbol{R} = 1 + \frac{\rho_b}{\boldsymbol{n}} \tag{50}$$

where

ρ_b is the bulk density (kg m^{-3});
K_d is the distribution coefficient (m^3 kg^{-1}).

Assuming that the effective porosity is equal to the soil water content, the pore water velocity for a radionuclide (advective velocity) can be calculated using Equations (49) and Equation (48). The relationship between the hydraulic conductivity and soil water content must be available. Using the van Genuchten relationship in Equation (51) and Equation (42) below, the soil water content corresponding to the infiltration rate is obtained.

$$\boldsymbol{K}(\theta) = \boldsymbol{K_{sat}}\,\boldsymbol{S}^{1/2}\left[1-\left(1-\boldsymbol{S}^{1/\boldsymbol{m}}\right)^{\boldsymbol{m}}\right]^2 \tag{51}$$

TABLE 49. THE GEOSPHERE INTERACTION MATRIX AS COMPILED FOR THE BOREHOLE TEST CASE.

	1	2	3	4	5	6	7	8	9	10	11
1	**Atmosphere**	Deposition (wet & dry)	Rain/ Infiltration	Rain/ infiltration	Rain/ infiltration	Rain/ infiltration	Inhalation				
2	Transpiration	**Gum tree**	Root intrusion		Root intrusion			Root intrusion/ uptake			
3		Fertilisation Death & decay	**Soil**	Flow	Flow	Flow	Ingestion	Flow			
4	Gas migration		Gas migration	**Unsaturated Fracture**	Flow	Flow	Advection, Dispersion Diffusion Adsorption Matrix diffusion	Dissolution Advection Dispersion Diffusion Adsorption	Advection Dispersion Diffusion Adsorption Matrix diffusion	Advection Dispersion Diffusion Adsorption	
5		Root death & decay	Evaporation	Dissolution Advection Dispersion Diffusion Adsorption	**Unsaturated matrix**	Flow	Flow	Advection Dispersion Diffusion Adsorption Matrix diffusion	Advection Dispersion Diffusion Adsorption		
6	Gas migration		Alter hydraulic properties	Alter hydraulic properties	Alter hydraulic properties	**Termite hole**	Access to subsurface	Dissolution Advection Dispersion Diffusion Adsorption	Advection Dispersion Diffusion Adsorption Matrix diffusion	Advection Dispersion Diffusion Adsorption	
7	Death & decay		Tunneling/ Bioturbation	Tunneling/ bioturbation	Tunneling/ bioturbation	Size, depth	**Termites**	Ingestion	Ingestion	Ingestion	
8		Root uptake		Dissolution Advection Dispersion Diffusion Adsorption	Dissolution Advection Dispersion Diffusion Adsorption	Dissolution Advection Dispersion Diffusion Adsorption	Access to water via borehole Excavation	**Near field/plume**	Advection Dispersion Diffusion Adsorption	Advection Dispersion Diffusion Adsorption	
9									**Saturated Matrix**	Advection Dispersion Diffusion Adsorption	Advection Dilution Dispersion Diffusion Adsorption
10				Transfer	Diffusion	Excavation	Water supply		Advection Dispersion Diffusion Adsorption Matrix diffusion	**Saturated Fracture**	Advection Dilution Dispersion Diffusion Adsorption
11									Extraction	Extraction	**Well**

$$\boldsymbol{S} = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{52}$$

where

K_{sat}	is the saturated hydraulic conductivity (m y^{-1});
S	is the relative saturation (–);
θ_r	is the residual pore water content (–);
θ_s	is the saturated pore water content (–);
m	is the 1-1/n where n is an empirical curve-fitting parameter.

The time of travel of radionuclide to the water table can then be expressed as:

$$\boldsymbol{T} = \frac{\boldsymbol{d}}{\boldsymbol{v}} \tag{53}$$

Where d is the distance to the water table (m). The radionuclide concentration at the water table can then be expressed as:

$$\boldsymbol{C_{wt}} = \boldsymbol{C_s}\, \boldsymbol{e}^{-\lambda \boldsymbol{T}} \tag{54}$$

where

C_{wt}	is the concentration at the water table (Bq m^{-3});
C_s	is the concentration at the source (bottom of borehole) (Bq m^{-3});
λ	is the decay coefficient (y^{-1}).

To calculate the mixing of contaminated soil water with uncontaminated groundwater at the water table, it is first necessary to calculate the depth of the radionuclide plume development on the water table, which can be expressed as follows:

$$H = (2\alpha_v L)^{1/2} + B\left(1 - \exp\left(-\frac{I}{V_l \rho B}\right)\right) \tag{55}$$

where

H	is the mixing depth (m);
L	is the length scale of source facility in the direction of flow (m);
α_v	is the vertical dispersivity (m);
B	is the thickness of the saturated zone (m);
I	is the recharge rate (m y^{-1});
V_l	is the linear pore velocity in the saturated zone (m y^{-1});
ρ	is the porosity (–).

The first part of the above equation gives the mixing due to vertical dispersion, and the second, due to advection. The second part of the equation could be neglected if the saturated zone thickness is unknown. Equation (56) below accounts for the dilution due to mixing in deriving the radionuclide concentration in the groundwater beneath the facility.

$$C_0 = C_{wt}\left(\frac{I}{I + Q_l}\right)\left(\frac{W}{H}\right) \tag{56}$$

where

C_0 is the groundwater concentration, source term for saturated zone transport (Bq m^{-3});

Q is the Darcy flux in the saturated zone (m y^{-1});
W is the width of facility lateral to the saturated zone flow direction (or square-root of the facility area foot-print on the water table) (m).

To derive the receptor borehole water concentrations (i.e. analyse the saturated zone transport), an analytical one-dimensional transport equation is proposed. This transport equation requires the linear flow velocity (pore velocity), which is computed as the potential gradient times the hydraulic conductivity divided by the effective porosity. The one-dimensional solute transport equation is given by:

$$\boldsymbol{R}\frac{\partial \boldsymbol{c}}{\partial \boldsymbol{t}} = \boldsymbol{D}\frac{\partial^2 \boldsymbol{c}}{\partial \boldsymbol{x}^2} - \boldsymbol{v}\frac{\partial \boldsymbol{c}}{\partial \boldsymbol{x}} - \lambda \boldsymbol{c} \tag{57}$$

while the initial and boundary conditions is given by:

$$\boldsymbol{c}(\boldsymbol{x},\boldsymbol{o}) = 0 \tag{58}$$

$$\boldsymbol{c}(\boldsymbol{o},\boldsymbol{t}) = \boldsymbol{C}_j \quad \text{for } \boldsymbol{t}_j \le \boldsymbol{t} < \boldsymbol{t}_{j+1} \tag{59}$$

$$\frac{\partial \boldsymbol{c}}{\partial \boldsymbol{x}}(\infty,\boldsymbol{t}) = 0 \tag{60}$$

where

c is the concentration (Bq m^{-3});

R is the retardation factor given by: $R = 1 + \frac{\rho_b k_d}{n}$ (-);

ρ_b is the bulk density (kg m^{-3});
k_d is the distribution coefficient m^3 Kg^{-1});
n is the porosity (–);
v is the average pore-water velocity (m y^{-1});
D is the dispersion coefficient given by: $D = \alpha\, v + D^*$ (m^{2}y^{-1});
v is the dispersivity (m);
$\boldsymbol{D}^*$ is the molecular diffusion (m^{2}y^{-1});
α is the first-order decay constant (y^{-1});
t is the time (y);
x is the space coordinate (m);
j is the time index ($j = 1, \quad , N$);
N is the total number of time steps.

The analytical solution of Equation (57) subject to boundary conditions shown below, is published by van Genuchten and Alves (1982), and is given by:

$$\boldsymbol{c}(\boldsymbol{o},\boldsymbol{t}) = \boldsymbol{C}_j$$

$$\frac{\partial \boldsymbol{c}}{\partial \boldsymbol{x}}(\infty,\boldsymbol{t}) = 0$$

$$\boldsymbol{c}(\boldsymbol{x},\boldsymbol{t}) = \boldsymbol{C}_a \boldsymbol{B}(\boldsymbol{x},\boldsymbol{t}) \tag{61}$$

where

$$B(x,t)=\frac{1}{2}e^{(v-u)x/2D}erfc\left[\frac{Rx-ut}{2(DRt)^{1/2}}\right]+\frac{1}{2}e^{(v+u)x/2D}erfc\left[\frac{Rx+ut}{2(DRt)^{1/2}}\right] \tag{62}$$

$$u = v\left[1+\frac{4\mu D}{v^2}\right]^{1/2} \tag{63}$$

Equation (61), however, is not applicable when the boundary is variable in time. To account for the time variability, the principle of superposition is used. First, the boundary concentration is redefined as a series of step functions:

$$c(0,t)=\left[C_1+\sum_{j=2}^{j=M}(C_j-C_{j-1})\right]\text{ for } t_M < t < t_{M+1} \tag{64}$$

The concentration at any point in space and time is then obtained by summing the contribution of individual steps $(C_j - C_{j-1})$ with the time t in Equation (62) set to $\Delta t_j=t-t_j$:

$$c(x,t)=\sum_{j=2}^{N}\left[\left(C_j-C_{j-1}\right)\left\{\frac{1}{2}e^{(v-u)x/2D}erfc\left[\frac{Rx-u\Delta t_j}{2(DR\Delta t_j)^{1/2}}\right]+\frac{1}{2}e^{(v+u)x/2D}erfc\left[\frac{Rx+u\Delta t_j}{2(DR\Delta t_j)^{1/2}}\right]\right\}\right]$$

$$+C_1\left\{\frac{1}{2}e^{(v-u)x/2D}erfc\left[\frac{Rx-u\Delta t_1}{2(DR\Delta t_1)^{1/2}}\right]+\frac{1}{2}e^{(v+u)x/2D}erfc\left[\frac{Rx+u\Delta t_1}{2(DR\Delta t_1)^{1/2}}\right]\right\}$$

$$-C_N\left\{\frac{1}{2}e^{(v-u)x/2D}erfc\left[\frac{Rx-u\Delta t_{N+1}}{2(DR\Delta t_{N+1})^{1/2}}\right]+\frac{1}{2}e^{(v+u)x/2D}erfc\left[\frac{Rx+u\Delta t_{N+1}}{2(DR\Delta t_{N+1})^{1/2}}\right]\right\} \tag{65}$$

where

$\Delta t_j = t - t_j$ is the time since the concentration;

$c(o,t) = C_j$ is imposed at the boundary.

It is important to note here that the application of the principle of superposition to the equation at hand is valid because Equation (57) is linear with respect to concentration *c (x, t)*.

Implementation in software

The GoldSim model was used in the mathematical implementation of the conceptual model of the groundwater pathway for the farmer scenario. GoldSim is a visual object oriented program for performing dynamic probabilistic simulations to support decision making in engineering and business, developed by Golder Associates [39]. The assessment model for the farmer scenario was built to simulate:

The release of radionuclides from the waste packages in the borehole;

— Their transport through the unsaturated zone to the water table;
— Through the saturated zone to a borehole near the site; and
— The dose to the farmer who uses borehole water for drinking, and consumes sheep, poultry, and eggs that are contaminated by the borehole water.

GoldSim's Contaminant Transport Module [40] was used to build the near field (source term) and the geosphere transport components of the assessment model. The dose assessment component of the model was developed using various built-in GoldSim objects, referred to as elements that perform specific mathematical functions. A brief description of GoldSim's features and how the framer scenario assessment has been implemented in the model is presented in Appendix F.

Assessment data

Inventory

The radionuclide inventory evaluated in this assessment excludes the radionuclides with short half-lives from the initial borehole inventory presented in Table 50, this included ^{99}Tc(m), ^{192}Ir, ^{57}Co, ^{109}Cd, and ^{60}Co. The daughter products of the three decay chains in Fig. 81 with half-lives and activities as presented in Table 50, were considered in the assessment.

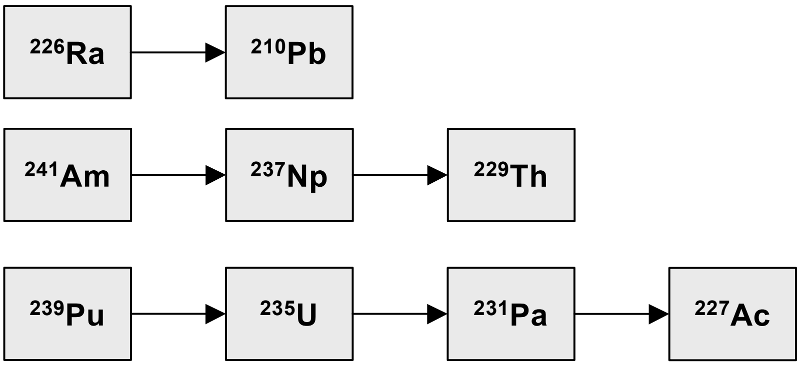


FIG. 81. Radionuclides and their associated daughter products that were considered in the farmer scenario of the Borehole Test Case.

TABLE 50. INVENTORY OF RADIONUCLIDES EVALUATED IN THE FARMER SCENARIO OF THE BOREHOLE TEST CASE

Radionuclide	Half-live (y)	Activity (Bq)
^{137}Cs	30	3.09E+11
^{241}Am	433	1.09E+08
^{237}Np	2.14E+06	0.0
^{233}U	1.59E+05	0.0
^{229}Th	7.34E+03	0.0
^{226}Ra	1.6E+03	2.25E+07
^{210}Pb	22.3	0.0
^{239}Pu	2.41E+04	3.70E+09
^{235}U	7.04E+08	0.0
^{231}Pa	3.29E+04	0.0
^{227}Ac	21.8	0.0

Recharge

Recharge was estimated from the available precipitation data by an unsaturated zone flow analysis, because of a lack of estimates or measurements of recharge at the Vaalputs site. The estimates were based on following assumptions:

— Infiltration at the ground surface is a given percentage of precipitation;
— Recharge is equal to infiltration; and
— Flow is steady-state and one-dimensional.

The mathematical model used to calculate the steady state groundwater flow and associated travel times of the radionuclides is presented in Equations (47) to (53) in Section 3.4.2.

Following the above procedure, a steady-state recharge distribution was derived assuming that five percent of the annual precipitation infiltrates the ground surface and becomes recharge. As shown in Table 51, a short record of annual precipitation exists for Vaalputs. The mean annual recharge rate is estimated to be approximately 6.3 mm y^{-1}. It is assumed to be normally distributed with a standard deviation of 1 mm y^{-1} (the standard error of the mean, which accounts for uncertainty). The minimum and the maximum of the distribution were set at 2.3 mm y^{-1} and 10 mm y^{-1} respectively.

The parameters defining the soil moisture retention characteristics for a sandy soil type are given in Table 52. For the given recharge distribution, the soil moisture content distribution was derived through Monte Carlo simulations. The resultant moisture content distribution had the following parameters: mean, 6.11E-02; standard deviation, 1.00E-02; minimum, 3.40E-02; maximum, 1.00E-01.

TABLE 51. VAALPUTS PRECIPITATION DATA (IN MM) AS MEASURED BETWEEN 1986 AND 1998

Year	**Precipitation (mm)**
1986	71.9
1987	59.2
1988	45.2
1989	30.2
1990	111.2
1991	173.0
1992	79.5
1993	146.1
1994	151.4
1995	305.1
1996	203.4
1997	146.8
1998	103.7
Mean	**125.1**
Standard Deviation	**75.1**

TABLE 52. MOISTURE RETENTION CURVE CHARACTERISTICS OF SAND, AS USED IN THE BOREHOLE TEST CASE ASSESSMENT

Parameter	Distribution	Mean	Standard Deviation	Minimum	Maximum
Saturated Conductivity ($cm.s^{-1}$)	Uniform	-	-	2.0E-05	2.0E-02
Residual Moisture	Lognormal	4.5E-02	1.0E-02	1.5E-02	7.5E-02
Saturation Moisture	Lognormal	0.43	6.0E-02	0.25	0.5
Van Genuchten α (cm^{-1})	Lognormal	0.145	2.9E-02		
Van Genuchten n	Lognormal	2.68	2.9E-01	1.81	3.55

Disposal geometry

The radionuclide inventory is assumed to be evenly distributed into ten stainless steel containers stacked vertically one meter apart in a borehole. The container is a type 304 stainless steel tube with a diameter of 114 mm, a height of 250 mm and a wall thickness of 3.04 mm. A stainless steel capsule containing the sources (a 110 mm long tube with a diameter of 21.3 mm) is placed into the steel container, and back filled with cement. The containers are placed into a borehole with a PVC casing. The top of the borehole will have a diameter of 305 mm in the weathered zone and a diameter of 254 mm below. The casing diameter will be 300 mm in the weathered zone and 203 mm below. The borehole will go down 45 m from the ground surface, with its bottom 10 m above the water table. Although a concrete/bentonite backfill will fill the space between the borehole and the container, no credit is taken for the backfill in this analysis.

The cell element used to represent the stainless steel container in the model is estimated to have 2.55 kg of concrete (ignoring the steel capsule inside, and a porosity of 0.5 and a density of 2000 $kg.m^{-3}$ for concrete) and 1.5E-03 m^3 of water (assuming a moisture content of 0.06 when the container is breached).

Solubility and distribution coefficients

Radionuclide specific solubility and distribution coefficients (K_d) are treated probabilistically. For simplicity, they are assumed to have uniform distributions, the parameters of which are shown in Table 53. Solubility limits are adopted from various references providing data on radionuclide solubility in cementatious waste forms for aerobic, high pH conditions that would prevail in the unsaturated media at the Vaalputs site [41, 42]. The K_d values are adopted from Yu *et. al*. [43], which contain data supporting the United States Department of Energy's Residual Radioactive Material Guidelines (RESRAD) dose assessment program. The expected values of the K_d distributions shown in Table 53 are for a sandy type material. Since there are no consistent set of K_d values available from cementatious materials with high pH conditions typical of the borehole environment at the Vaalputs site, K_d values for a sandy material are used instead, leading to a conservative analysis. The minimum and maximum value of the K_d distributions are assumed to cover a range equal to the expected value of the distribution.

TABLE 53. SOLUBILITY LIMITS AND DISTRIBUTION COEFFICIENTS USED IN THE FARMER SCENARIO OF THE BOREHOLE TEST CASE

Radionuclide	Solubility ($mg.l^{-1}$)		K_d - Sand ($m^3.kg^{-1}$)	
	Min	**Max**	**Min**	**Max**
^{137}Cs	3.26E+02	3.26E+03	1.40E-01	4.20E-01
^{241}Am	2.77E-04	2.77E-01	9.50E-01	2.85E+00
^{237}Np	8.39e+00	8.39E+03	2.50E-03	7.50E-03
^{233}U	2.70E-03	2.70E+02	1.75E-02	5.25E-02
229Th	1.57E-02	1.57 E+00	1.60E+00	4.80E+00
^{226}Ra	2.90E-03	2.90E-01	2.50E-01	7.50E-01
^{210}Pb	5.40E-05	1.35 E+00	1.35E-01	4.05E-01
^{239}Pu	2.71E-04	2.71E-01	2.75E-01	8.25E-01
^{235}U	2.70E-03	2.7E+02	1.75E-02	5.25E-02
^{231}Pa	2.63E+00	7.89E+04	2.75E-01	8.25E-01
^{227}Ac	2.01E-02	2.01E+03	2.25E-01	6.75E-01

Container degradation

Kozak *et al*. [36] has determined that steel containers are unlikely to fail due to corrosion within 10000 years after closure, given the borehole conditions at Vaalputs site. For this assessment, it is assumed conservatively that containers will breach completely during a period of 300 to 600 years after closure. The time of failure of containers is assumed to have a uniform distribution.

Transport parameters

The site characterization at Vaalputs has confirmed that most of the flow in the unsaturated and saturated zones is through the high conductivity fracture zones. The conceptual model for flow and transport therefore considers the existence of a fracture tube, from ground surface to the water table, filled with sand, through which radionuclides are transported. To simplify the geometry, it is assumed further that the borehole will perform as a high permeability fracture zone once the concrete/bentonite backfill in the borehole degrades to its constituent elements of sand and gravel. Likewise, contaminated water reaching the water table is assumed to move through a high permeability fracture tube to the receptor well. This fracture tube is also filled with sand. The media and transport parameters characterising these fracture zones as Pipe elements in GoldSim are listed in Tables 54 and Table 55. These are assumed to have constant values (no uncertainty) and treated deterministically. However, the solubility limits and K_d values are treated probabilistically. Their distributions are same as the distributions used in the source term model. The receptor was assumed to pump water from the well annually at a rate of 91.25 m^3 [42].

TABLE 54. PHYSICAL MEDIA PROPERTIES USED IN THE FARMER SCENARIO OF THE BOREHOLE TEST CASE

Media	Sand	Grout
Bulk Density (kg.m^{-3})	1 600	2 000
Porosity	0.43	0.5
Tortuosity	0.2	0.2

TABLE 55. TRANSPORT MEDIA PROPERTIES USED IN THE FARMER SCENARIO OF THE BOREHOLE TEST CASE

Property	**Unsaturated Zone**	**Saturated Zone**
Length (m)	10	10
Area (m^2)	0.05	0.05
Perimeter (m)	0.8	0.8
Dispersivity (m)	0.5	0.1
Infiltration medium	Sand	Sand

Dose assessment parameters

The dose coefficients, which are assumed constants, are given in Table 56. The transfer factors for poultry are from Kennedy and Strenge [42]. The poultry transfer factors are assumed lognormally distributed with the median values shown in Table 57. A geometric standard deviation of 3 is assumed. An upper limit of geometric standard deviation for beef cattle is reported to be 3.8. The transfer factors for sheep are also taken from Kennedy and Strenge [42]. The sheep transfer factors are assumed to be log-normally distributed with the median values shown in Table 57. A geometric standard deviation of 4 is assumed. The intake rate distributions for water, mutton, poultry and eggs are shown in Table 58.

TABLE 56. INGESTION DOSE COEFFICIENTS USED IN THE FARMER SCENARIO OF THE BOREHOLE TEST CASE

Radionuclide	**Dose Coefficient (Sv.Bq^{-1})**
^{137}Cs	1.30E-08
^{241}Am	2.00E-07
^{237}Np	1.11E-07
^{233}U	5.10E-08
^{229}Th	6.13E-07
^{226}Ra	2.80E-07
^{210}Pb	1.89E-06
^{239}Pu	2.50E-07
^{235}U	4.73E-08
^{231}Pa	7.10E-07
^{227}Ac	1.21E-06

TABLE 57. TRANSFER FACTORS USED IN THE FARMER SCENARIO OF THE BOREHOLE TEST CASE

Radionuclide	Sheep	Poultry	Egg
	(d.kg^{-1})		
^{137}Cs	2.00E-02	4.00E+00	4.90E-01
^{241}Am	3.50E-06	2.00E-04	9.00E-03
^{237}Np	5.50E-05	4.00E-03	2.00E-03
^{233}U	2.00E-04	1.20E+00	9.90E-01
^{229}Th	6.00E-06	4.00E-03	2.00E-03
^{226}Ra	2.50E-04	3.00E-02	2.00E-05
^{210}Pb	5.00E-07	2.00E-01	8.00E-01
^{239}Pu	5.00E-07	1.50E-04	8.00E-03
^{235}U	2.00E-04	1.20E+00	9.90E-01
^{231}Pa	1.00E-05	4.00E-03	2.00E-03
^{227}Ac	2.50E-05	4.00E-03	2.00E-03

TABLE 58. INTAKE RATES USED IN THE FARMER SCENARIO OF THE BOREHOLE TEST CASE

Intake	Distribution	Most likely value	Minimum	Maximum
Water (a^{-1})	Triangular	493	180	730
Water for sheep (d^{-1})	Uniform	-	1	10
Water for poultry (d^{-1})	Uniform	-	0.1	1.0
Sheep meat (kg y^{-1})	Triangular	31	15	62
Poultry (kg y^{-1})	Triangular	9.5	4.5	19
Eggs (kg y^{-1})	Triangular	15	7.5	30

3.4.3. Hunter- gatherer scenario

Development of conceptual model

The hunter-gatherer scenario considers reversion to a hunter-gather life style and eating termites as a source of protein. Consistent with the Farmer Scenario, it is assumed that termites made their nest right on top of the disposal borehole. The termite hole follows the trace of the borehole in an attempt to reach the water table. For the hunter-gatherer scenario it is assumed that the hole encounters a contaminated zone of soil, which is excavated by the termites to the surface. Activity is consequently accumulating in the termites. The hunter-gatherer is externally exposed to irradiation while harvesting the termites, as well as from eating the termites.

Scientific studies are available on the rate of excavation possible by the termite *Hodotermes Mossambicus* commonly found in the Vaalputs area. However, these studies pertain to near-surface action, where the insects are most active. Any potential disruption of the disposal facility by insects would be the result of a deep tunnel created to obtain water for the colony. Such tunnels have not yet been studied to any extent. As a result, some reasonable assumptions will be made in the current analysis for model development.

It is assumed that soil around the waste package is intersected by a single vertical tunnel. The tunnel is dug at some time after the waste begins to leach from the waste package, and the contaminated soil is brought to the surface by the insects. It is assumed that the tunnel is 1 cm in diameter. This value was chosen based on observations of deep termite holes evident at the Vaalputs site. The tunnel is assumed to follow the disposal borehole for 5 m of the disposal depth. This leads to a volume of $4x10^{-4}$ m^3 of contaminated soil excavated by the insects. Assuming a soil density of 1600 $kg.m^{-3}$ produces an estimate of 0.6 kg of excavated contaminated soil brought to the surface.

To calculate the activity excavated, additional assumptions are necessary. It is assumed that the activity is uniformly distributed across a 1 m diameter column as it migrates to the water table. The relationship of these volumes is shown in Fig. 82.

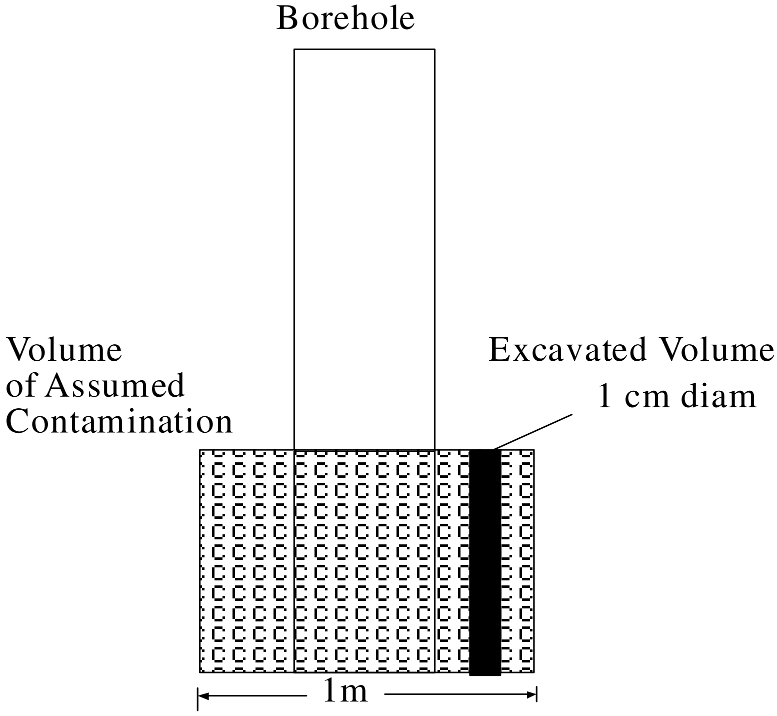


FIG. 82. Relationship between Borehole, Assumed Volume of Contamination, and Assumed Excavated Soil for the Borehole Test Case Hunter-Gatherer Scenario.

Borehole Test Case participants were unaware of any studies of bioaccumulation of radionuclides in termites or similar insects. Similarly, they were unaware of any scientific studies on consumption rates of insects among African tribes. For the current analysis, it is assumed that an individual consumes a single kilogram of contaminated insects during a year. The basis for this estimate is that it seems unlikely that an individual would use only a single nest for consumption, and that it is unlikely that more than one nest would be contaminated. However, this basis is highly speculative. It is also assumed that the specific activity of radionuclides in insects is 10 times the specific activity in the contaminated soil. This value is also highly speculative, and is intended as a bounding analysis.

Development of methematical model

At any time, the relationship between the specific activity available to the insects, SA_I ($Bq.kg^{-1}$), in the volume of contamination and the release rate for a radionuclide, Q_i ($Bq\ y^{-1}$), is given by:

$$SA_i = Q_i / \rho v \pi r^2, \quad (66)$$

where

v is the Darcy velocity associated with deep percolation (m y^{-1});
ρ is the bulk density of the geological medium (kg m^{-3});
r is the assumed radius of contamination (m).

The dose due to external exposure of excavated soil is given by:

$$D_{ext} = \sum_i Dil\, SA_i\, DF_{ext,i}\, F_{occ} \quad (67)$$

where

D_{ext} is the dose due to external exposure (Sv y^{-1});
DF_{ext} is the external exposure dose (Sv y^{-1} per Bq kg^{-1});
Dil is a dilution factor;
F_{occ} is the fraction of a year spent exposed to the contamination. The assumed dilution factor;
Dil, is related to dilution with clean soil during the excavation.

Ingestion doses from this pathway are calculated from:

$$D_{ing} = \sum_i SA_i Dil F_{cont} B_i I_t DF_{ing,i} \quad (68)$$

where

B is the bioaccumulation factor for radionuclides in termites;
F_{cont} is the fraction of insects consumed that are contaminated;
I_t is the ingestion rate of termites (kg y^{-1});
DF_{ing} if the dose coefficient for ingestion (Sv Bq^{-1}).

Implementation in software

The appropriate physical behaviour for the near field of the borehole was implemented in the computer code COMPASS [44] that was used to estimate the release rate of each radionuclide. COMPASS was originally written as a near field model for the proposed Yucca Mountain high-level waste repository in the United States. However, it was written with enough flexibility to be able to handle a wide variety of near field situations. COMPASS allows consideration of several modes of contact with water, both advective and diffusive [44]. It appropriately accounts for elemental solubility and sorption processes for decay chains. COMPASS is distributed by the Electric Power Research Institute (EPRI), Palo Alto.

Assessment data

Two set of parameters were used to calculate the release rate from the waste package, namely a bounding and a moderate set of parameters, both of which are listed in Table 59. The moderate parameters are intended to represent values that would be in the middle of a range of reasonable selections. They are *not* the most optimistic set of parameter values.

For this analysis, an actual Vaalputs infiltration value of 0.6 mm y^{-1} is used in the calculation of specific activity. This approach provides a conservative upper bound to the specific activity. Use of the 6 mm y^{-1} value used in groundwater analyses would lead to a decrease in specific activity by a factor of 10.

Assuming that the contaminated soil is mixed with soil from a vertical termite hole extending to the surface provides a dilution factor of 5 metres contaminated soil per 45 metres total or 0.11. The fraction of a year spent in contact with such a small volume of soil must be considered to be small. For this situation, it is assumed that the individual spends one percent of their time in contact with the contaminated soil.

International guidance for external dose coefficients are currently unavailable; consequently, the external dose coefficients are from Eckerman and Ryman [45], and represent soil contamination of infinite depth and the contributions of short lived progeny. These values per annum are 8.6×10^{-9} Sv kg Bq^{-1} for ^{226}Ra, 6.6×10^{-10} Sv kg Bq^{-1} for ^{210}Pb, and 1.4×10^{-11} Sv kg Bq^{-1} for ^{210}Po.

It is assumed that a small fraction of the insects in a nest would be contaminated, since only a few would dig to the depths necessary. No data are available on this parameter, and as a result it is chosen to be 0.01, which is judged to be a conservative value.

TABLE 59. BOUNDING AND MODERATE SET OF PARAMETERS USED IN THE BOREHOLE TEST HUNTER-GATHERER SCENARIO

Parameter	**Value**	
	Bounding Parameters	**Moderate Parameters**
Ra solubility	10^{-6} mol.l^{-1}	10^{-8} mol. $^{-1}$l
Pb solubility	10^{-5} mol. $^{-1}$l	10^{-8}mol.l^{-1}
Po solubility	10^{-5} mol.l^{-1}	10^{-8} mol.l^{-1}
Ra cement K_d	0.05 m^3.kg^{-1}	0.1 m^3.kg^{-1}
Pb cement K_d	0.05 m^3.kg^{-1}	0.5 m^3.kg^{-1}
Po cement K_d	0.05 m^3.kg^{-1f}	0.5 m^3.kg^{-1}
Container failure time	1000 yrs	2000 yrs

3.4. ASSESSMENT OF RESULTS

3.5.1. Farmer scenario

Monte Carlo simulations were performed using Latin Hypercube sampling, specifying 100 realisations. Latin Hypercube sampling causes probability distributions to be divided into a number of equally likely strata, which are then sampled. This has the effect of better ensuring that the space of the parameter is uniformly spanned. GoldSim also allows expected value simulation, in which a single realisation is carried out using the median values for any stochastic elements.

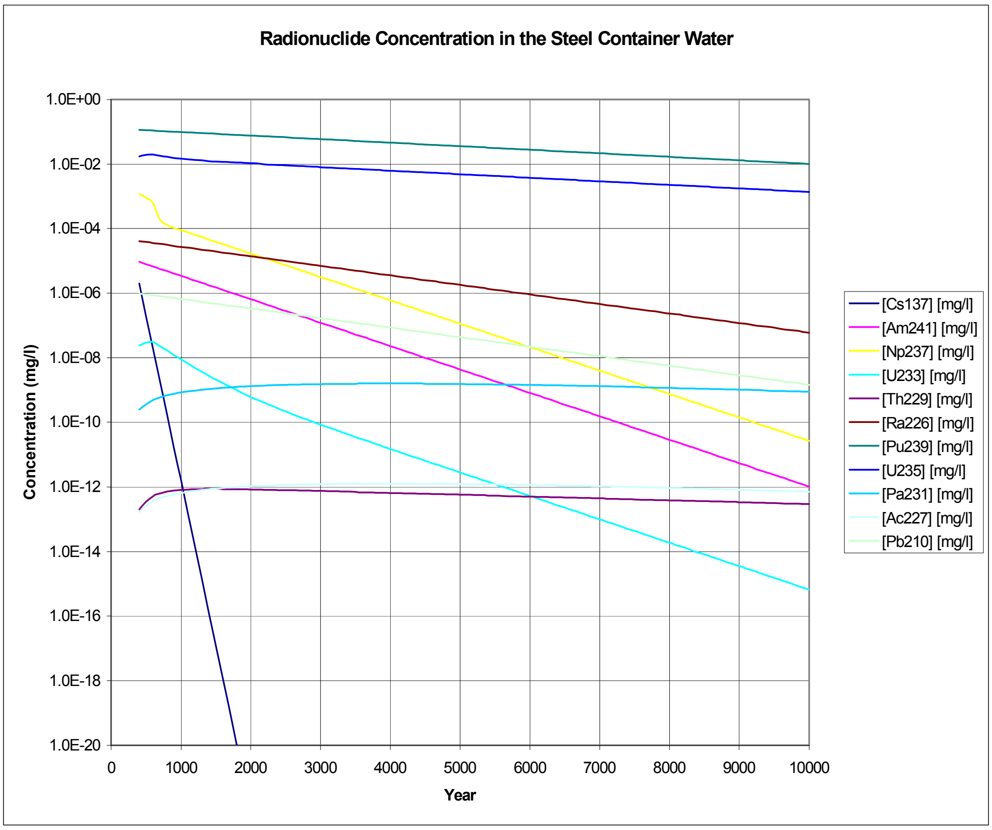


FIG. 83. Radionuclide Concentrations in the Stainless Steel Container Water for the Borehole Test Case Farmer Scenario.

Figure 83 shows the time history of the concentrations of the eleven radionuclides in the steel container (the result of an expected value run). The time histories of the concentrations of the radionuclides in the unsaturated and saturated zones are shown in Figs 84 and 85. Only six radionuclides - ^{237}Np, ^{233}U, ^{229}Th, ^{235}U, ^{231}Pa, and ^{227}Ac - show breakthrough within the 10 000 year simulation period. Borehole water concentrations in Bq.l^{-1} are shown in Fig. 108. The concentrations show an increasing trend; with concentrations still slightly rising at the end of the 10 000 year simulation period. The time history of the total effective dose equivalent (TEDE) for each radionuclide is shown in Fig. 87. The maximum dose occurs in 10 000 years after the facility closure. Most of the dose is from ^{237}Np and ^{233}U. The time history of the scenario dose is shown in Fig. 88, where 100 realisations are summarized. The mean, median, 95 percentile, and 5th percentile of the dose distribution are shown in the Fig. 88. The dose distribution at 10000 years (in Sv y^{-1}) has a mean of 9.4E-07, a median of 8.8E-07, a 95th percentile of 2.0E-06, and a 5 percentile of 5.0E-08. The results indicate that all dose realisations are well below the compliance criterion of 0.1 mSv y^{-1}.

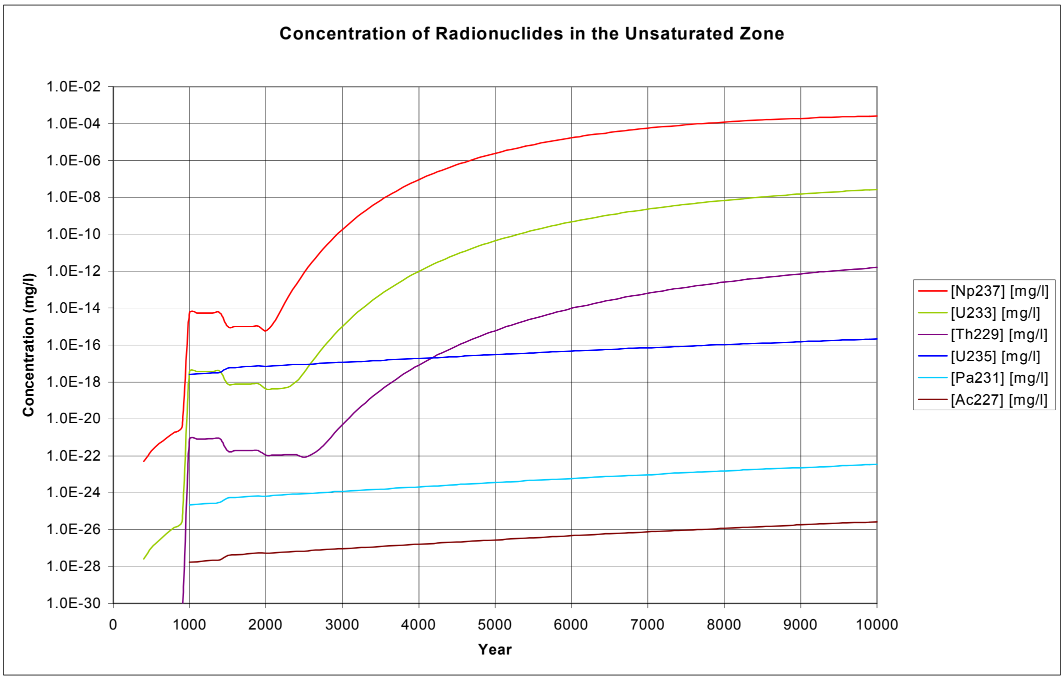


FIG 84. Concentrations of Radionuclides in the Unsaturated Zone for the Borehole Test Case Farmer Scenario.

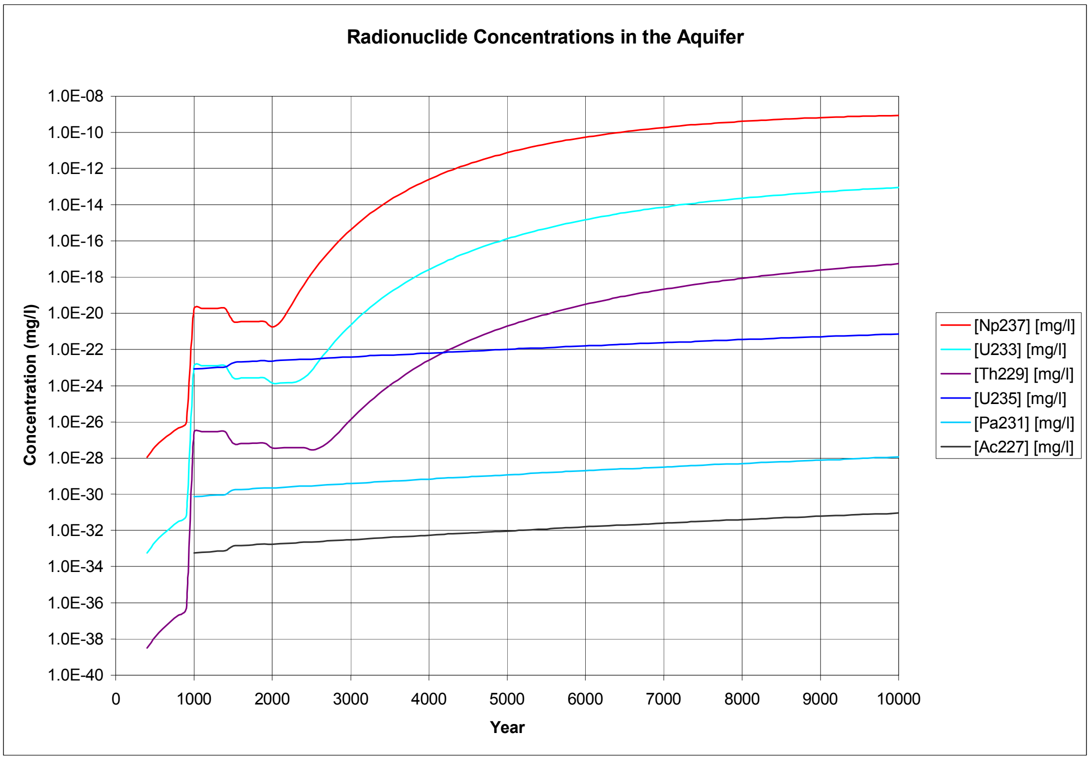


FIG 85. Radionuclide Concentrations in the Aquifer for the Borehole Test Case Farmer Scenario.

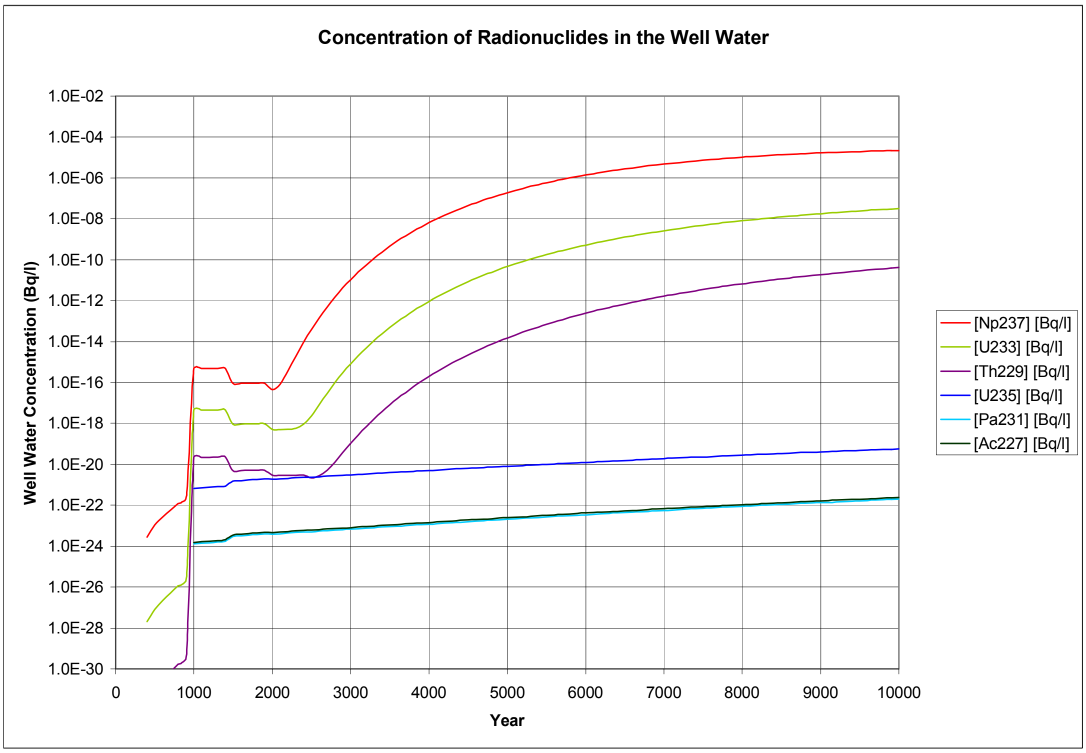


FIG 86. Radionuclide Activity Concentrations in Well Water for the Borehole Test Case Farmer Scenario.

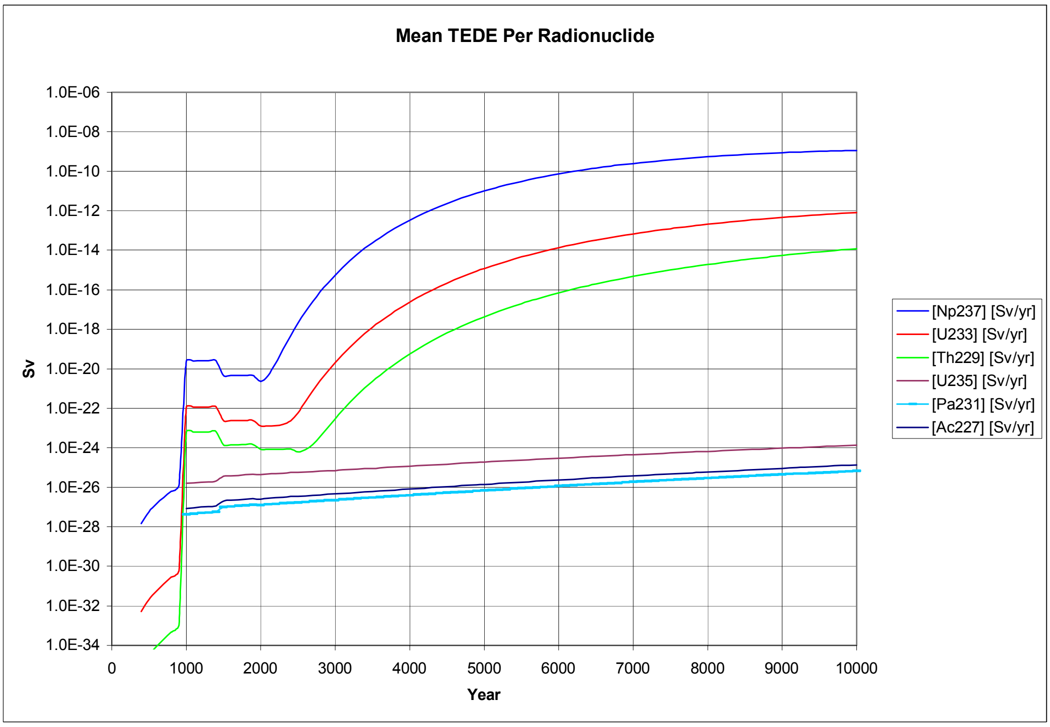


FIG. 87. Mean TEDE Sv per Radionuclide for the Borehole Test Case Farmer Scenario.

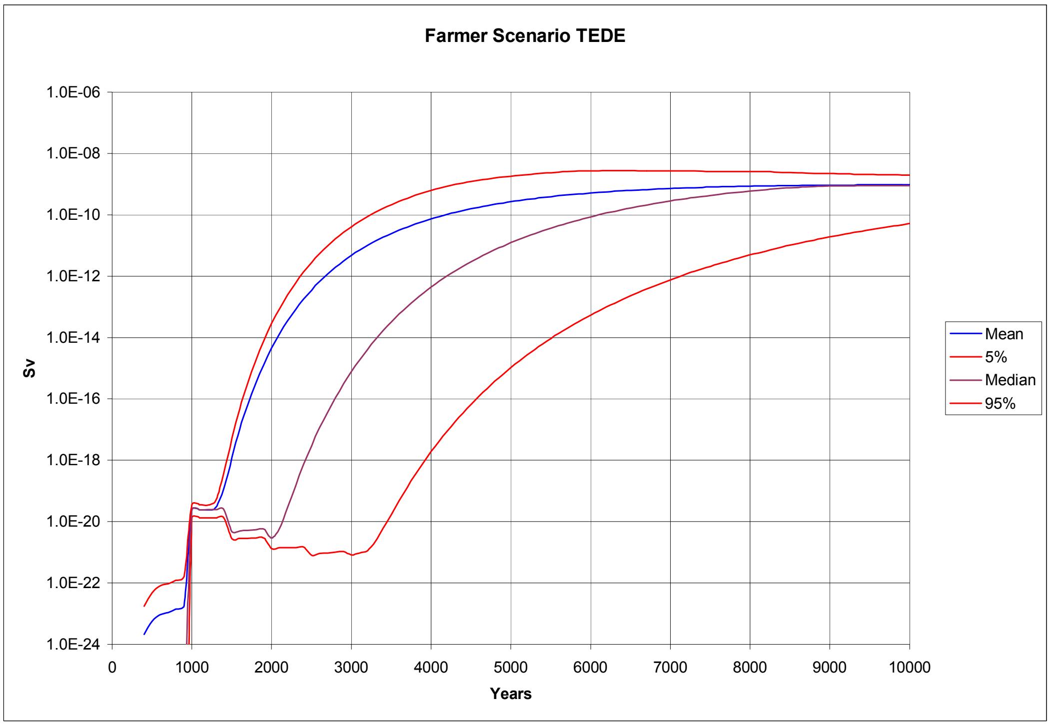


FIG 88. TEDE for the Borehole Test Case Farmer Scenario.

3.5.2. Hunter-gatherer scenario

Release rates from the bounding set of parameters are presented in Fig. 89. For this scenario, releases are assumed to begin at 1000 years after closure, when both containers are breached by crevice corrosion.

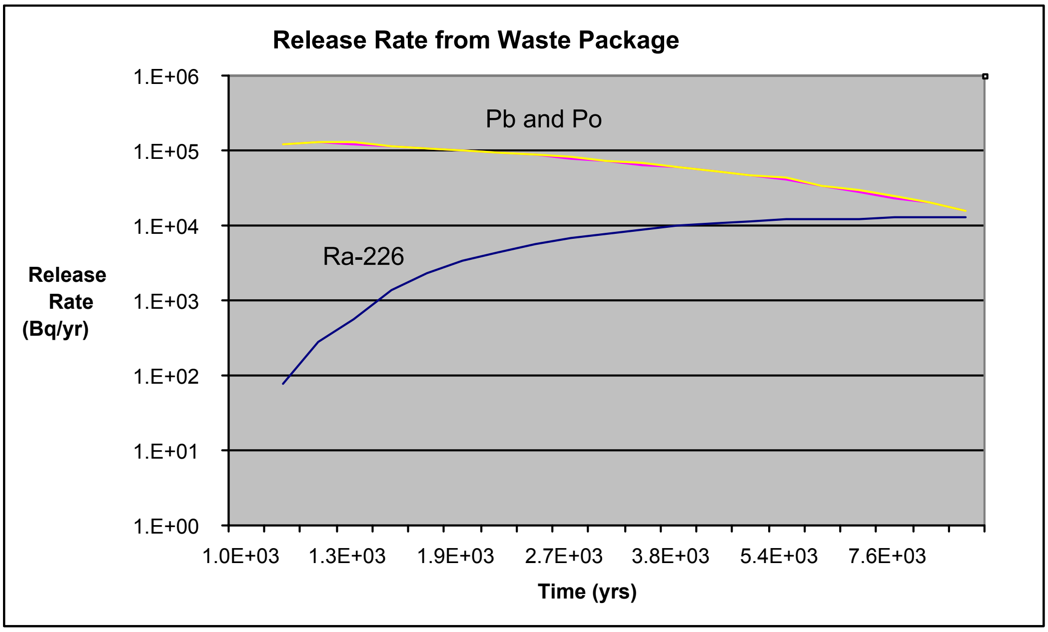


FIG. 89. Release Rates from the Waste Packages for Bounding Conditions for the Borehole Test Case Hunter-Gatherer Scenario.

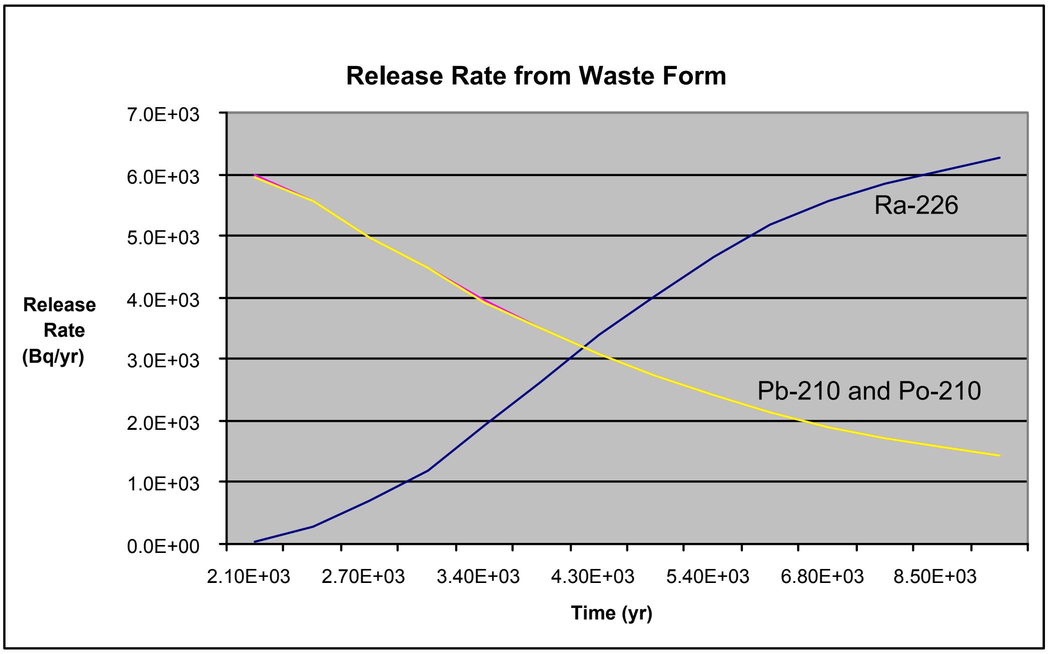


FIG. 90. Release Rates from the Waste Package for the Moderate Set of Parameters for the Borehole Test Case Hunter-Gatherer Scenario.

Release rates from the waste package for the moderate set of parameters are shown in Fig. 90. For this set of parameters, releases are assumed to begin at 2 000 years after closure. ^{226}Ra releases start quite low, and increase gradually. ^{210}Pb and ^{210}Po, by contrast, begin at their maximum release rate, and decrease somewhat in time.

The dose from ingestion of insects using these release rates is presented in Fig. 90 for the bounding set of parameter values. Doses for this set of parameter values are rather large for the insect consumption pathway, reaching a peak of about 3.5 mSv y^{-1} which is a factor of 35 above the dose constraint. However, the model for this pathway is speculative and it is uncertain how conservative it is. Also as discussed previously, the results are inversely dependent on the infiltration rate for this model. The results in Fig. 90 are based on the Vaalputs infiltration rate of 0.6 mm y^{-1}. Use of a value of 6 mm y^{-1}, consistent with the groundwater pathway, would decrease the dose by a factor of ten, and produce a result just above the dose constraint.

External exposure doses are presented in Fig. 91 for the bounding set of parameters. The doses are within the established constraint at all times.

Doses are presented in Figs 92 and 93 for the moderate set of parameter values. Even for these lower release rates, the peak dose from ingestion of insects exceeds both the dose constraint of 0.1 mSv y^{-1} and the dose limit of 1 mSv y^{-1}. Here, too, the use of higher infiltration rates in the model would decrease these values.

The external dose is low at all times. The external dose occurs predominantly as a result of exposure to ^{226}Ra, and the ingestion dose results from exposure to ^{210}Po and ^{210}Pb. As a result, the two dose curves resemble the release rate curves shown in Fig. 92.

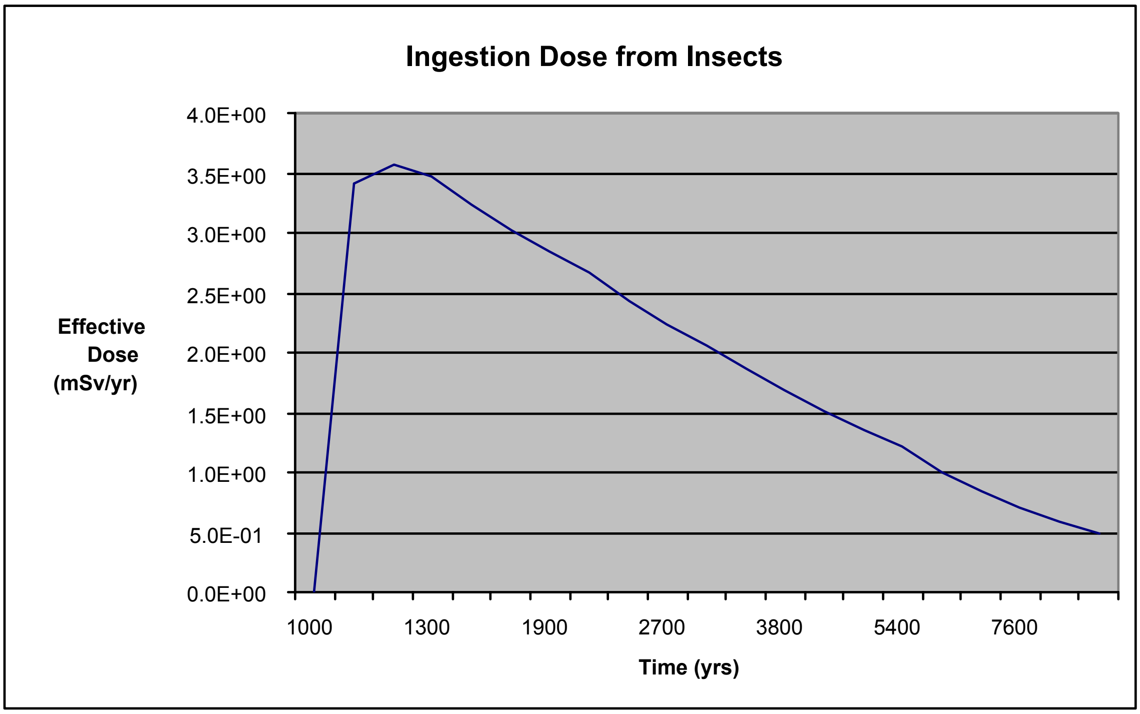


FIG 91. Dose from Ingestion of Insects for the Bounding Release Rate for the Borehole Test Case Hunter-Gatherer Scenario.

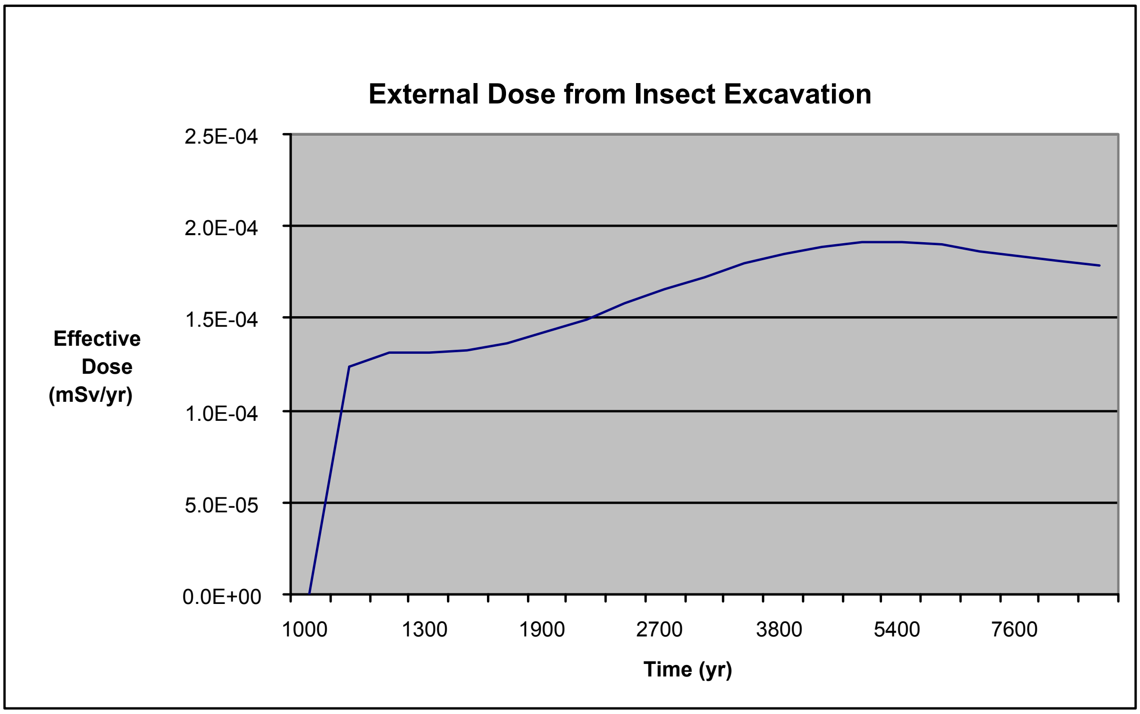


FIG. 92. External Dose Associated with Excavation of Soil for the Bounding Release Rate for the Borehole Test Case Hunter-Gatherer Scenario.

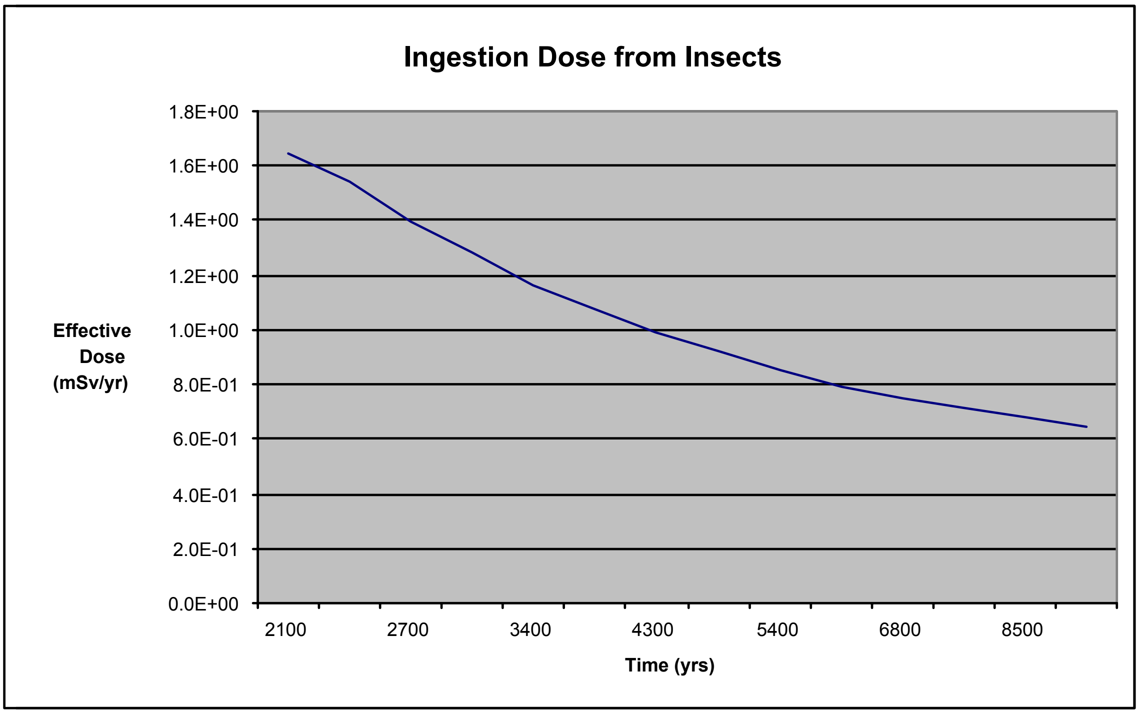


FIG. 93. Dose from Ingestion of Insects for Moderate Parameter Set for the Borehole Test Case Hunter-Gatherer Scenario.

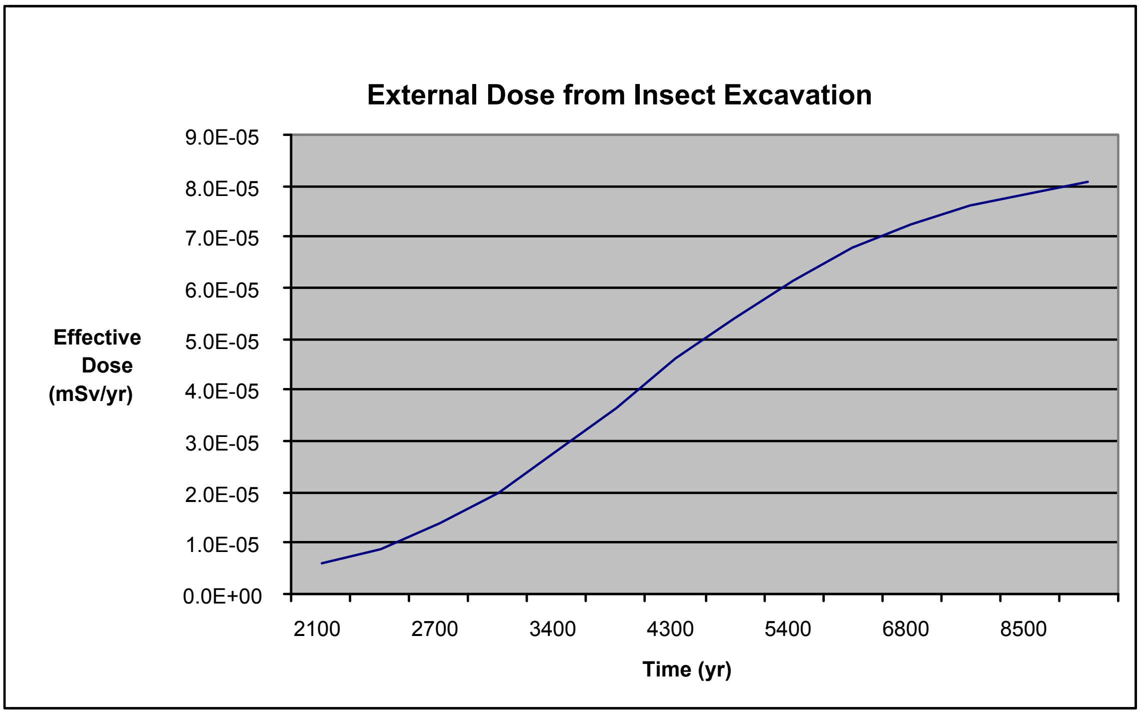


FIG. 94. External Dose Associated with Excavation of Soil for the Moderate Parameter Set for the Borehole Test Case Hunter-Gatherer Scenario.

3.5. LESSONS LEARND AND CONCLUSIONS

In the experience of working on the Borehole Test Case and applying the various steps of the ISAM project methodology, a number of valuable lessons have been learned. Lessons that are specific to the Borehole Test Case are presented in this section. More general conclusions that apply to the ISAM project methodology or are in common with the other ISAM Test Cases are collated in Section 4 of this report.

— The Borehole Test Case followed the ISAM project methodology, and although not applied to its full extent, proved useful in performing the safety assessments in a structured manner.

— A first iteration of the methodology was completed and serves as a basis for future iterations. This preliminary assessment can be enhanced, as more resources become available. Both the results and the decision-making process should be judged from the perspective of the assessment being preliminary.

— It is considered that the Borehole Safety Test has partially fulfilled each of the main objectives of the test case. However, time constraints prevented consideration of a wider set of scenarios and a further iteration of the assessment process.

— Two land use conditions specified in the assessment context limited the need to apply a formal systematic scenario generation approach. The first condition considers continuation of the current land use, characterized by small farms and agricultural activity to the extent supported by the local climate. The second condition is a reversion to traditional human behaviour, characterized by hunter-gatherer land uses. The ISAM FEPs list was used in a limited way to incorporate these land use conditions in the scenario generation processes. The FEPs list was viewed, and external FEPs were identified that might lead to potential exposures. In this way, an insect excavation scenario was identified that was not considered prior to the scenario generation procedure.

— More formal methods for developing scenarios or conceptual models from the FEPs were not used in the Borehole Test Case, owing to time limitations. However, the FEPs list proved to be very useful as an audit trail and to facilitate model development. Interaction matrixes complemented this process, but were used only to a limited extent.

— Only one set of results for each scenario was produced for the Borehole Test Case and only one iteration of the ISAM project methodology followed. It was consequently not possible to have a comparison of results between participants to increase confidence. Further iterations would be advisable once more information on critical parameters is available and to include a wider spectrum of scenarios.

— The results indicated that, when assessing a near-surface disposal facility, it is often important to consider release mechanisms in addition to liquid release. In the Borehole Test Case the ingestion of termites proved to be of significance. .

— This initial iteration allowed limited time for alternative ways to represent results, the treatment of uncertainties, quality assurance and detailed evaluation of the results to establish reasonable assurance of compliance with regulatory criteria.

4. GENERAL CONCLUSIONS

This section is a synopsis of the conclusions and lessons learned from the development of the three ISAM Test Cases.

4.1. CAUTIONARY COMMENTS

The ISAM Test Cases were implemented as demonstrations of applying the ISAM project methodology to different types of disposal facilities. However, there are limitations to the information that can be derived from the test cases. First, the level of effort expended on the ISAM Test Cases does not reflect the level of effort required for a complete assessment for an actual site. In particular, work on the test cases was only taken through a first iteration of the methodology, or through a limited second iteration. The iterative nature of the safety assessment methodology was therefore not fully studied in ISAM.

In addition, the test cases were conducted for hypothetical disposal facilities without regulatory or other independent review. This inevitable feature of the project has large implications for the amount of realism in the project results in certain areas. Among these areas is the application of confidence building techniques, which are used to develop the confidence of outside reviewers of the assessment. Since the ISAM Test Cases were not subjected to rigorous outside peer review or regulatory review, many time-consuming confidence-building approaches were not applied to any significant extent. For example, quality assurance procedures developed in the ISAM project were not applied to the ISAM Test Cases. In the development of a complete safety case, it is necessary to allocate sufficient time and resources to the project to conduct these functions. In a resource-limited project like ISAM, this was not possible.

Furthermore, the ISAM project was restricted to post-closure radiological safety aspects of facility safety. A number of potential issues were omitted from consideration in the project. Consequently, the test cases did not consider pre-closure safety, the effects of non-radiological components of the waste nor the effects on non-human biota. Each of these is an area that may need to be addressed as part of the development of an overall safety case.

Despite these limitations, considerable progress and knowledge were generated during the project. In the following sub-sections, the key issues are summarized on which consensus was developed from the test cases.

4.2. METHODOLOGY COMMENTS

Work was conducted to implement many of the steps in the ISAM project methodology, shown in Fig. 1 (Volume I), for each of the three test cases. Conclusions and lessons learned associated with these individual steps are discussed in this sub-section. It should be noticed that two of these steps, scenario development and modelling, were principal focus of the project, as discussed in Volume I of this report. Consequently, more detailed and specific comments are appropriate for these steps in the methodology than are possible for others, since more detailed and specific approaches were applied in the test cases.

4.2.1. Assessment context

Setting down the assessment context clearly and explicitly establishes, at an early stage in the process, some of the key aspects of the safety assessment. It can be used to help justify decisions taken later in the assessment. Indeed, it is helpful to refer back to the assessment context as the safety assessment is developed.

The assessment context is very important and provides the framework within which to perform the safety assessment calculations, and also to evaluate the results. If fundamental disagreements about aspects of the assessment context exist (e.g. applicable time frames, dose constraints, etc.) among interested parties, these must be resolved prior to conducting further safety assessment, or the subsequent work will be fruitless. A number of such issues were addressed in the ISAM Test Cases, and many of the assessment context issues proved to be contentious.

In setting down the assessment context, it is important to choose safety criteria that are:

- Reliable, based on well established principles and applicable over a wide range of situations;
- Relevant to the safety and the features of the repository and environment;
- Simple and facilitate communication;
- Direct and closely linked to some of the system's features;
- Understandable for the users; and
- Practical for the tools and practice available.

4.2.2. System description

The system description provides a valuable summary of the existing data that are available for the assessment. The data can be used to inform decisions taken later in the assessment process. The description should be undertaken with the assessment context firmly in mind.

When describing the system, it is important to distinguish between verifiable data and assumptions adopted for the purpose of the assessment. In particular, it is useful to consider uncertainties associated with characterising the system as it is at present and with its future evolution.

The system description will be developed and it need not be comprehensive to start the safety assessment process. At first, all available information specific to the disposal facility should be collected and taken into account. Further revisions of the system description can be necessitated by improvements in understanding and data availability after conducting later steps in the safety assessment. Use of the safety assessment methodology in this manner focuses efforts on *necessary* information, obviating the need to collect *all* information.

It is necessary to keep reviewing the safety assessment as it is implemented to ensure it remains relevant and consistent with the assessment context. Tracking changes in the system description as it evolves through the assessment is an important confidence-building approach.

Data quality is another key point in developing confidence in the safety assessment. The safety assessment shows that one of the most important pieces of information is the inventory, especially for an historical facility.

4.2.3. Development and justification of scenarios

All three test cases used the FEPs list in somewhat different ways, illustrating the flexibility of the list in being adapted to differing approaches. The ISAM FEPs list proved to be a very useful tool in the scenario development and justification procedure. The list can be used many times for auditing or checking during the development of an assessment; its use is not limited to the scenario development and justification step of the methodology.

The use of formal scenario generation methods does not ensure that the scenarios developed for a system are complete or correct. Instead, the formality of the approaches permits the logic to be traced by an independent reviewer. The ability of the analyst to justify the selection and description of a scenario is dependent on the clarity of application of the formal methods, and on their ability to respond appropriately to the inquiries of reviewers.

As demonstrated in the test cases, expert judgement is an important factor in the scenario development process. It is even more significant in the cases of limited information and data on the waste disposal system to be assessed. Therefore it is important to ensure that the scenario generation process is well documented, and provides well-justified arguments for the selection and elimination of FEPs.

4.2.4. Formulation and implementation of models

There are a number of tools available for identifying and presenting FEPs interactions in conceptual models, such as Interaction Matrices and Process Influence Diagrams. Each tool has its advantages and disadvantages and the selected approach may depend on the preferences of the assessment team and on the assessment context.

It is important to emphasize the need to develop models that are as simple as possible and encompass all the information relevant to the waste disposal system. The models should adequately represent the evolution of the disposal system in the future in compliance with the safety assessment context with due consideration of all assumptions made and uncertainties involved in the assessment process.

It is important to ensure that members of the assessment team have a good understanding of the conceptual and mathematical models, the associated data, and the software tools being used. It is important that they check that the models and data are appropriately implemented in their tools, and that the implementation is appropriately documented.

4.2.5. Interpretation of results and building of confidence

Relatively little work was carried out within the test cases on the interpretation of results in a context appropriate to a real licence application. In all of the test cases, there was insufficient time to treat model and parameter uncertainty, quality assurance, data needs, and similar topics to the extent needed for a real disposal system.

Overarching all aspects of the safety assessment methodology is the need to develop confidence in the assessment process. As discussed above, it was not possible to implement certain aspects of confidence building tools in the framework of the ISAM Test Case. However, it is noted that following the safety assessment process is, by itself, a mechanism for developing confidence in the assessment.

4.2.6. Review and modification

From the three cases, the RADON Test Case conducted a limited second iteration based on revisions to the scenarios assessed, as there was insufficient time available in the test cases to investigate the iterative nature of safety assessment. However, it is recognized that safety assessments need to be performed in an iterative manner in the development of safety case.

4.3. GENERAL COMMENTS ON THE TEST CASES

— The ISAM project methodology can be applied for all stages of the radioactive waste disposal facility life cycle. It can contribute to site selection, design of a disposal concept, licensing, updating of the post-closure safety case during the operational period, preparation of a closure safety case, and re-assessment of past-practices facilities.
— The safety assessment methodology was found to be a practical approach that helped ensure that the safety assessment was logical, well structured, well documented, transparent, and auditable.
— The ISAM project methodology provides a useful framework for safety assessment when the assessment is limited by resource constraints. Early iterations are undertaken with the available data and assessment capabilities, and the iterations proceed only until the assessment is judged to be adequate for its purpose. New data are collected only to the extent that they need be to provide the basis for the decision.
— The ISAM project methodology should be applied in an iterative manner. To the limited extent that the iterative nature of the process was explored in ISAM, it proved to be very valuable. It is acknowledged that additional iterations of the safety assessment would be needed to justify a regulatory decision in a real situation.
— Each of the test cases has contributed towards the fulfilment of the ISAM objectives. They have provided a critical evaluation of the approaches and tools currently used in the post-closure safety assessment of proposed and existing near-surface radioactive waste disposal facilities, enhanced the approaches and tools used, provided participants with practical experience in the implementation of the approaches and tools, and built confidence in the approaches and tools used.

It can be helpful to compare the results of two or more independent assessments. Any single assessment can be appropriately justified for the technical approaches used in the analysis. However in each of the test cases it was observed that only when multiple approaches are compared that misunderstandings, gaps and flaws in the analysis, and many outright errors can be recognized. In particular, in each test case it appeared to be desirable to have independent teams of investigators. By comparing the approaches from each team an improved understanding was generated for all experts involved.

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APPENDIX A: VAULT TEST CASE APPROACH TO SCENARIO DEVELOPMENT

Some of the key steps for the definition of scenarios to consider in the safety assessment are as follows:

- Structuring the information relating to the waste, the engineering system and the site, as well as the assessment context (see A-1);
- Definition of components and the design conditions, based on the objectives and criteria for the system safety assessment (see A-2); and
- Analysis and description of the system behaviour and evolution, according to the design characteristics, including the design scenario description and the identification and description of alternative scenarios (see A-3).

A-1. STRUCTURING THE INFORMATION RELATING TO THE WASTE, THE ENGINEERING SYSTEM AND THE SITE, AS WELL AS THE ASSESSMENT CONTEXT

The site characteristics including the location, demographic studies, meteorology and climate, natural resources and land use, seismic and geological studies, hydrology, hydrogeology and geochemical studies, description of the engineering concept, as well as waste streams characterization and the total radionuclide inventory will be analysed and considered together with the assessment context for the generation of scenarios to assess.

The objectives for the safety assessment are defined. This is an important part of the context that will determine the aspects over which the system functional analysis will be performed.

A1.1. Safety requirements

The safety requirements are derived from the objectives, guides and criteria specified by the regulatory authority. In general, they include: (i) minimize any burden for future generations, (ii) protection of the environment and (iii) protection of human health, taking into account economic and social factors.

The regulatory objectives may impose a series of constraints, such as the limitation in the temporal extension of the institutional control period.

The relevant issues or factors have to be identified and considered in an appropriate way during the scenario analysis.

Some of the radionuclides present in the wastes destined for near surface facilities have a half-life that will result in decay in a few hundreds of years. However, these wastes may also contain limited amounts of long-lived radionuclides that do not decay in those time scales.

The specific functional objectives have to be established in the design of the disposal concept to comply with the requirements referred to above. So, it can be assumed:

- Waste isolation. Two aspects can be investigated:

(i) Minimization of the contact of wastes with water.

The radionuclides can move in the advective water flow or due to the diffusive process. The former will be significantly more important; so, the minimization of water inflow is a clear objective. The design of the disposal area above the water table, as well as the cover material should minimize water entrance.

(ii) Avoid inadvertent intrusion.

The characteristics of the multiple-barriers systems provide some delay and reduction in the probability of inadvertent intrusion by humans, and intrusion by animals and plants. Physical, institutional and visual barriers will contribute to this.

- Confinement, by the reduction of radionuclides releases.

The migration of radionuclides takes place due to advection or diffusion, so the facility design needs to incorporate some retardation of radionuclide release into the environment. The radionuclide retardation mechanism will take effect in the three barriers: the unit of disposal, the engineering system and the site.

- Stability and durability, by considering:

(i) Structural integrity in the long term.

The engineered disposal structure must remain with its properties effective for at least some hundreds of years. Hence, the design needs to take into account factors that may cause some deterioration, and incorporate resistant materials and structures.

(ii) Avoid the need for maintenance in the long-term

The difficulty of supervising long time periods, requires a stable system, in a way to guarantee its effectiveness without any human active intervention.

A-2. DEFINITION OF COMPONENTS AND DESIGNED CONDITIONS, BASED ON THE OBJECTIVES AND CRITERIA FOR THE SYSTEM SAFETY

The assessment context establishes the institutional control period and the control activities during that time, as well as their timeframe. The period of time for which the functional requirements of the system are required would be extrapolated and have to be evaluated in the performance assessment for the long term.

A2.1. "Boundary" conditions for the design scenario

The FEPs List establishes three main categories; the assessment context, the external factors and factors of the system domain.

External factors (EFEPs) are considered to be causes and origins of some possible alteration, external to the system domain, and may be natural or human induced as well as their immediate effects. An example may be decisions about the facility design, operation and closure, whenever they are out of the temporal domain of the assessment.

A2.2. Definition of components

Each of the components of the barrier system or confinement system will be analysed:

- The first barrier: the physico-chemical form of the waste, the material in which the waste is disposed of can also participate in the confinement.
- The second barrier: the engineering systems and annexes devices, including the covering materials sited at the end of the operational phase.
- The third barrier: the site and its location.

A2.3. Functional analysis

A series of design requirements are imposed on the system, based on the safety requirements that guarantee the adequate function to comply with those requirements. The properties of each barrier will be reviewed, in the following aspects:

- Minimization of contact of the waste with water (isolation)

The site will be selected and the facility designed in order to minimize contact with water. In the same way, the design usually incorporates some components that reduce the water infiltration, such as:

- Concrete top layer; this layer maybe treated to increase water resistance;
- Multi-layer cover, including a drainage layer that will allow water movement lateral of the structure, this cover will protect the concrete from thermal-cycles. The surface can have channels for water runoff and is protected from erosion by the lateral slope and the vegetation cover;
- Backfill drainage material, this prevents water accumulation; and
- Maintaining the structural integrity in the long term (durability).

The structural integrity of the system would be guaranteed with the establishment of requirements such as the resistant to pressure and possible seismic movements, sitting on compacted and stable soil, assessing the fissures width in the design to be in an accepted order, studying the durability of concrete, protecting the concrete structure designed to resist erosion by water and wind, as well as thermal cycles.

- Resistance to inadvertent intrusion (isolation).

The cover is usually designed to reduce the possibility of intrusion.

- Reduce radionuclide releases (confinement).

The backfill and the base may be designed in order to limit the contact time of the waste with water and at the same time incorporate materials that increase the sorption of contaminants. Any other component that presents these same properties will be analysed.

- Minimising the need of long term maintenance (stability and durability).

The long term maintenance will be minimized with the facility design and the use of material stable and durable enough for the conditions of the site.

A-3. ANALYSIS AND DESCRIPTION OF THE PERFORMANCE AND EVOLUTION OF THE SYSTEM, IN ACCORDANCE WITH THE DESIGN CHARACTERISTICS

In the post-closure period, the system may be influenced by various processes that include (i) variations of characteristics and processes of the engineered system and the natural environment; (ii) natural events that may alter the system in some way; (iii) human activities that may alter or may be affected by the disposed waste.

Besides the processes, characteristics and events that may be included in the preceding topics, *deviation from the designed characteristics* can also be of interest, as the ones due to deviations in the properties of the barriers or the manner of drum allocation, etc.

A3.1. Description of the design scenario

The "Design Scenario" summarizes the description of the previously analysed aspects. It refers, in consequence, to each of the components of the barriers and the confinement system under adequate functional conditions, and for which they have been designed.

The possible variation or deviation due to loss or degradation of the durability characteristics, as well as the temporal scales for which this happens will also be mentioned in the description.

A3.2. Identification and description of alternative scenarios

The analysis of the possible radiological impact for the Design Scenario will allow the identification of some aspects that may be the object of further analysis. So, the possible alterations caused by human activities, or natural events and processes may be investigated. Particular issues requiring further investigation may be highlighted during the development of the Design Scenario (e.g. what if the cover fails to perform as planned, etc.).

APPENDIX B: INTERACTION MATRIX APPROACH AND ITS APPLICATION TO THE DEVELOPMENT OF CONCEPTUAL MODELS FOR THE VAULT TEST CASE

B-1. THE INTERACTION MATRIX (IM)

The Interaction Matrix was initially applied to the joint SKI/SKB scenario development project. At the time when the approach of "Rock Engineering System" (RES) was presented, it became evident that this methodology could be applied to scenario development and analysis for waste storage in hard rock.

The methodology used can be named as top-down, in order to ensure that all aspects of the problem are being covered. The method used the Interaction Matrix as a visual and graphical device or tool for the representation of the "components" and "interactions" among them.

The main factors are identified and listed along the leading diagonal elements (LDEs) of a square matrix. The interactions between the factors occur in the off-diagonal elements (ODEs). Clockwise for the influence direction was adopted for convention [B1].

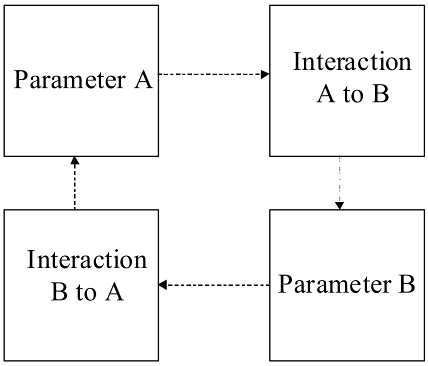

FIG. B.1. Principle of Interaction Matrix.

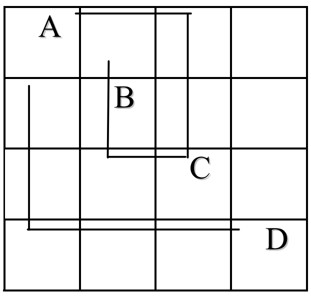

FIG. B.2. Pathway Representation.

In Fig. B.1 this is illustrated: there are two parameters, and hence two interactions. When more than two parameters are involved, the interaction is a pathway through the matrix.

The pathway (D, A, C, B) is indicated schematically in Fig. B.2. This provides a visual clarification for the understanding of the interactions.

B-2. INTERACTION MATRIX CONSTRUCTION

The matrix construction begins with:

(i) Definition of the Leading Diagonal Elements (LDEs)
(ii) Definition of Off-Diagonal Elements (ODEs).

LDEs would normally be considered to represent 'Features'. Other FEPs, representing properties of the main components or processes are not considered for inclusion in the interaction matrix and instead, they are considered at a later stage, in the modelling step.

It is important to declare explicitly the specific purpose to build the matrix. Consecutive iterations of the matrix, can be built to finally achieve the decided purpose [B2]. In this way, a first iteration could help determining where and how bulk materials move in the system. A second one would incorporate contaminants transport and doses to humans due to radionuclide releases, according to the details given in the assessment context.

B-3. AUDIT OF THE MATRIX AGAINST THE FEP LIST

This step aims to ensure that [B3]:

(i) All previously identified FEPs can be associated with the interaction matrix;
(ii) All interactions correspond to at least one FEP.

For the mapping of the FEPs List, BIOMOVS II suggested the use of tables, recording the code of the FEP, the FEP name, the interaction (from LDE, to LDE), the type (interaction, pathway), comments and number of pathway. A scheme of the pro-forma is shown in Table B.1.

TABLE B.1. TABLE PRO-FORMA FOR MAPPING OF FEP LIST [B3]

Code	**FEP-name**	**From_LDE**	**To_LDE**	**Type**	**Comments**	**N_PATH**

B-4. IDENTIFICATION OF IMPORTANT OFF-DIAGONAL ELEMENTS

The main objective is to identify important pathways for radionuclide transport [B3]. Decisions would be documented. The Reference Biosphere WG of BIOMOVS II established the ranking, using the following scheme (Table B.2).

TABLE B.2. CATEGORIZATION OF IMPORTANCE OF THE CODES

Category	Importance	Knowledge	In Assessment Model
A	Always	Good	Yes
B	Probably	Bad	Possibly
C	Conditionally	Variable	Conditionally
D	Probably not	Bad	Possibly
E	Never	Good	No

In other cases, based on the level of knowledge and the information given, expert judgement has to be used to screen those processes that will be primarily considered for the first quantitative analysis. Afterwards, review of this screening process may be done in order to compare assessment endpoints against those FEPs and identify which transport routes may need further consideration for a second iteration.

It is also envisaged that Interaction Matrices representing different components of the disposal system (e.g. near field, far field and biosphere) may be linked together, focusing attention on the conceptualization of model interfaces.

B-5. BUILDING THE INTERACTION MATRIX FOR THE DESIGN SCENARIO: LIQUID RELEASE

Initial work was undertaken by Inmaculada Simón. First the Leading Diagonal Elements (LDEs) were selected (see B-5.1.). They were based on the safety relevant features identified in Table 43 of this report, plus additional information from the system description (Section 1 of this report) and Design Scenario description (Section 1.3.3 of the main report).

Then the IM was developed in two iterations. Firstly, interactions or Off Diagonal Elements (ODEs) of the 'uncontaminated' system were identified focusing on processes, which affect the global mass balance of material (see B-5.1.). In the second iteration the behaviour and transport of radionuclides in the system were considered (see B-5.2). This allows the consideration of the impact of each process on the system and then consideration of its impact on radionuclide behaviour.

The resulting IMs were then reviewed by the VSC Group (Appendix B-5.3) and an audit of the IM against the ISAM FEP list undertaken (Appendix B-5.4).

B.5.1 First iteration

Identification of the leading diagonal elements (LDEs)

(1.1) Waste form

(2.2) Containers (200 l steel drums) and grout

(3.3) Concrete cubes

(4.4) Vault base, walls, grout (membrane & roof slabs)

(5.5) Multiple layers cover (concrete, sand, clay, geotextile, natural soil, vegetation cover).

(6.6) Unsaturated zone (depth 50-70m, average 55m) – sand (processed), calcite, sandy clay and white kaolinite, weathered granite

(7.7) Saturated zone (average depth 55m) – aquifer (weathered granite, fractured granite)

(8.8) Location (general characteristics). This element can be more detailed to distinguish the most relevant components. So it will include:

(8.8) Soils and sediments;

(9.9) Surface water bodies;

(10.10) Atmosphere;

(11.11) Flora;

(12.12) Fauna;

(13.13) Human.

Table B.3 shows the LDEs as well as the characteristics and implicit attributes to each of them, according to the ISAM FEPs List.

TABLE B.3. INITIAL VERSION OF THE LEADING DIAGONAL ELEMENT COMPONENTS AND ASSOCIATED CHARACTERISTICS AND PROCESSES FOR THE DESIGN SCENARIO: LIQUID RELEASE

LDE	**Characteristics**	**Internal processes**
Waste form	Mechanical processes and conditions Hydraulic/hydrogeological processes and conditions Chemical/geochemical processes and conditions Biological/biochemical processes and conditions (Corrosion, degradation) Inventory, radionuclides and other materials	Water flow (advection, diffusion)
Steel drum container (200 l) and grout	Mechanical processes and conditions Hydraulic/hydrogeological processes and conditions Chemical/geochemical processes and conditions Biological/biochemical processes and conditions (Corrosion, degradation)	Water flow (advection, diffusion)
Concrete cubes	Mechanical processes and conditions Hydraulic/hydrogeological processes and conditions Chemical/geochemical processes and conditions Biological/biochemical processes and conditions (Corrosion, degradation)	Water flow (advection, diffusion)
Vault structure (base, walls & roof)	Mechanical processes and conditions Hydraulic/hydrogeological processes and conditions (preferential pathways) Chemical/geochemical processes and conditions Biological/biochemical processes and conditions Containers disposition	Water flow (advection, diffusion)
Multi layer cover (concrete, sand, clay, geotextile, natural soil, vegetation layer)	Mechanical processes and conditions Hydraulic/hydrogeological processes and conditions Chemical/geochemical processes and conditions Biological/biochemical processes and conditions (degradation of the barrier)	Water flow (advection, diffusion)
Unsaturated zone (depth 50-70m, average 55m) – sand (processed), calcite, sandy clay and white	Mechanical processes and conditions Hydraulic/hydrogeological	Water flow (advection, diffusion)

LDE	Characteristics	Internal processes
kaolinite, weathered granite	processes and conditions (presence of fractures or discontinuities, seasonal variability) Chemical/geochemical processes and conditions Biological/biochemical processes and conditions	
Saturated zone (average depth 55m) – aquifer (weathered granite, fractured granite)	Mechanical processes and conditions Hydraulic/hydrogeological processes and conditions (presence of fractures or discontinuities, seasonal variability) Chemical/geochemical processes and conditions Biological/biochemical processes and conditions	Water flow (advection, diffusion)
Soils and sediments	Physico-chemical characteristics (topography, morphology)	Erosion and deposition Water flow (advection, diffusion)
Surface water bodies	Physico-chemical characteristics (lakes, rivers, stream, springs) – Hydrological regime and water balance	Erosion and deposition Water flow (advection, diffusion)
Atmosphere	Characteristics (meteorology – seasonality)	Dispersion
Flora	Considered crops (green vegetables, roots, etc)	
Fauna	Animal products (food) Diet and fluid ingestion	
Human	Wild and natural land and water use Rural and agricultural land and water use Individual and community characteristics Diet and fluid ingestion Human Habits	

Identification of off-diagonal elements (ODEs)

For the definition of the off-diagonal elements, processes that affect the global mass balance will be considered.

(1.1) Water flow (advection, diffusion);

(2.1) Water flow (advection, diffusion);

(2.3) Water flow (advection, diffusion);

(3.2) Water flow (advection, diffusion);

(3.4) Water flow (advection, diffusion);

(4.6) Water flow (advection, diffusion);

(5.3) Water flow (advection, diffusion);

(6.7) Water flow (advection, diffusion);

(7.6) Capillarity;

(7.8) Capillarity;
Discharge;

(7.9) Discharge;

(7.11) Irrigation of crops;

(7.12) Ingestion;

(7.13) Extraction via well;

(8.7) Infiltration;
Percolation;

(8.9) Runoff;
Solid material transport (erosion);

(8.10) Evapotranspiration;

(8.11) Root uptake;
Rainsplash;

(8.12) Ingestion;

(9.8) Sedimentation;

Erosion;

Diffusion;

Advection;

(9.10) Evaporation;
Suspension of particles;

(9.11) Absorption (aquatic flora);
Irrigation of crops;

(9.12) Ingestion;
(9.13) Ingestion;
Immersion;

(10.5) Erosion;
Deposition;
Precipitation;

(10.8) Erosion;
Deposition;
Precipitation;

(10.9) Deposition;
Precipitation;

(10.11) Precipitation;
Deposition;

(10.12) Inhalation;

(10.13) Inhalation;
Immersion;

(11.10) Evapotranspiration;

(11.12) Ingestion;

(11.13) Ingestion;

(12.8) Bioturbation;

(12.13) Ingestion;

(13.7) Extraction/recharge of water;
Water treatment;

(13.8) Draining sediments;
Irrigation;
Ploughing;

(13.9) Extraction/water recharge;
Reservoirs;

(13.11) Storage;

(13.12) Storage;

Waste	1.2 Y	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10	1.11	1.12	1.13	1.14
2.1 Y	Steel drum	2.3 Y	2.4	2.5	2.6	2.7	2.8	2.9	2.10	2.11	2.12	2.13	2.14
3.1	3.2 Y	Cube	3.4 Y	3.5	3.6	3.7	3.8	3.9	3.10	3.11	3.12	3.13	3.14
4.1	4.2	4.3	Vault	4.5	4.6 Y	4.7	4.8	4.9	4.10	4.11	4.12	4.13	4.14
5.1	5.2	5.3 Y	5.4	Cover	5.6	5.7	5.8	5.9	5.10	5.11	5.12	5.13	5.14
6.1	6.2	6.3	6.4	6.5	Unsat. Zone	6.7 Y	6.8	6.9	6.10	6.11	6.12	6.13	6.14
7.1	7.2	7.3	7.4	7.5	7.6	Aquifer	7.8 Y	7.9 Y	7.10	7.11 Y	7.12 Y	7.13 Y	7.14 Y
8.1	8.2	8.3	8.4	8.5	8.6	8.7 Y	Soil- sedim	8.9 Y	8.10 Y	8.11 Y	8.12 Y	8.13 Y	8.14 Y
9.1	9.2	9.3	9.4	9.5	9.6	9.7	9.8 Y	Water bodies	9.10 Y	9.11 Y	9.12 Y	9.13 Y	9.14 Y
10.1	10.2	10.3	10.4	10.5 Y	10.6 Y	10.7	10.8 Y	10.9 Y	Atmosphere	10.11 Y	10.12	10.13 Y	10.14 Y
11.1	11.2	11.3	11.4	11.5	11.6	11.7	11.8	11.9	11.10 Y	Flora	11.12 Y	11.13 Y	11.14 Y
12.1	12.2	12.3	12.4	12.5	12.6	12.7	12.8 Y	12.9	12.10	12.11	Fauna	12.13 Y	12.14 Y
13.1	13.2	13.3	13.4	13.5	13.6	13.7 Y	13.8 Y	13.9 Y	13.10	13.11 Y	13.12 Y	Human	13.14 Y
14.1	14.2	14.3	14.4	14.5	14.6	14.7	14.8	14.9	14.10	14.11	14.12	14.13	Exp. path

FIG. B.4. Second Iteration for the Interaction Matrix for the Design Scenario: Lquid Release.

B5.3. Review of IMs

Mass transport IM

The review started by revising Table B.3, focusing on the internal processes and characteristics of the LDEs. The LDEs and associated internal processes were reviewed, remaining at a relatively high level in light of the time constraints on the VSC Group and the VSC assessment context indicating the relatively early stage of disposal facility development. For other assessments, there might well be the need to breakdown the FEPs into more detail and then to prioritise them. Key findings from the review are summarized below.

- On the basis of site specific information, the "water bodies" LDE from the matrix was deleted. There is no permanent surface water bodies at the site, although there might be some temporary water bodies that develop following storm events. For the purposes of the current assessment, it was cautiously assumed that contaminated groundwater reaches the biosphere via a well.
- The roof of the vault was not considered as part of the vault LDE, it was included in the cover LDE. Only the base and the sides were included. The definition of the vault LDE was modified to include the roof of the vault. Similarly, the definition of the cover LDE was modified to exclude the roof of the vault.
- The sand base is not a separate LDE but is included as part of the unsaturated zone. However, it is important not to forget about its drainage function although it is only an operational phase feature.
- Both the cover and unsaturated zone consists of multi-layers with different properties.
- It should be recognized that there will be losses of radionuclides and other material from the system and therefore there might be a need to include a "sink" LDE. However, it was decided there was no need to explicitly include such an LDE at this stage. Nevertheless, it should be noted that the atmosphere and soil/sediment LDEs should have loss terms to outside the system.

In light of the review, Table B.3 was revised to produce Table B.4.

The Off-Diagonal Elements (ODEs) were then reviewed. Processes that affect the global mass balance were considered initially and additional processes affecting the migration and fate of radionuclides were then considered. The focus of attention remained the liquid release pathway for which the main transport media is the infiltrated water penetrating through the disposal system to unsaturated layer and aquifer.

The revised ODE's with modification/additions to the ODEs identified in Appendix B-5.1 are listed immediately following Table B.4.

TABLE B.4. REVISED VERSION OF THE LEADING DIAGONAL ELEMENT COMPONENTS AND ASSOCIATED CHARACTERISTICS AND PROCESSES FOR THE DESIGN SCENARIO: LIQUID RELEASE

LDE	Characteristics/Processes	Examples
Waste form (waste and grout)	Mechanical processes and conditions Hydraulic/hydrogeological processes and conditions Chemical/geochemical processes and conditions Biological/biochemical processes and conditions Thermal processes & conditions Gaseous sources and effects Inventory	- expansion/collapse - water content - corrosion - microbial degradation - heat generation - radon generation - radionuclides and other materials
Steel drum container	Mechanical processes and conditions Hydraulic/hydrogeological processes and conditions Chemical/geochemical processes and conditions Biological/biochemical processes and conditions Gaseous sources and effects	- expansion - barrier to water flow - corrosion - microbe induced corrosion - corrosion gases e.g. hydrogen
Concrete cubes & grout backfill	Mechanical processes and conditions Hydraulic/hydrogeological processes and conditions Chemical/geochemical processes and conditions Biological/biochemical processes and conditions Gaseous sources and effects	- structural stability - effect on water flow - alkaline reactions - effect on microbial activity - effect on gas flow
Vault structure (base, walls & roof)	Mechanical processes and conditions Hydraulic/hydrogeological processes and conditions Chemical/geochemical processes and conditions Biological/biochemical processes and conditions Gaseous sources and effects	- structural stability - effect on water flow - alkaline reactions - effect on microbial activity - effect on gas flow
Multi layer cover (waterproof layer, compacted clay, concrete intrusion barrier?, soil cover, erosion resistant rock/gravel layer)	Mechanical processes and conditions Hydraulic/hydrogeological processes and conditions Chemical/geochemical processes and conditions Biological/biochemical processes and conditions Gaseous sources and effects	- structural stability - infiltration rate - infiltrating water chemistry - microbial activity - gas pathways thru cap
Unsaturated zone	Mechanical processes and	- structural stability

LDE	Characteristics/Processes	Examples
(depth 50-70m, average 55m) engineered sand bed, natural sediments, weathered granite	conditions Hydraulic/hydrogeological processes and conditions Chemical/geochemical processes and conditions Biological/biochemical processes and conditions Gaseous sources and effects	- preferential pathways - groundwater chemistry - microbial activity - gas pathways to the biosphere
Saturated zone (aquifer) (average depth 55m) weathered granite, fractured granite	Mechanical processes and conditions Hydraulic/hydrogeological processes and conditions Chemical/geochemical processes and conditions Biological/biochemical processes and conditions Gaseous sources and effects	- structural stability - advection & diffusion - groundwater chemistry - microbial activity - transport of dissolved gases
Soils and sediments	Topography & morphology Physico-chemical properties Hydrology Erosion/deposition	- surface relief - mineralogy - water content - effect of these processes
Atmosphere	Meteorology Physico-chemical properties	- rainfall - exchange rates
Flora	Characteristics and processes	- edible plants
Fauna	Characteristics and processes Diet and fluid ingestion	- food and animal products - transfer rates
Human (habits and behaviour)	Rural and agricultural land & water use Leisure and other uses of environment Community characteristics Individual habits Diet and fluid ingestion Human characteristics	- agricultural production rates - amenities available - population density - non-diet related behaviour - food sources - physiology, metabolism

(1.2) Unsaturated water flow (advection, diffusion) – infiltration/percolation;

(2.1) Unsaturated water flow (advection, diffusion) – infiltration/percolation;

(2.3) Unsaturated water flow (advection, diffusion) – infiltration/percolation;

(3.2) Unsaturated water flow (advection, diffusion) – infiltration/percolation;

(3.4) Unsaturated water flow (advection, diffusion) – infiltration/percolation;

(4.3) Unsaturated water flow (advection, diffusion) – infiltration/percolation;
Unsaturated water flow (advection, diffusion) – infiltration/percolation;

(5.3) Delete interaction because the interaction is now considered to be via the vault;

(5.4) Unsaturated water flow (advection, diffusion) – infiltration/percolation;

(6.7) Unsaturated water flow (advection, diffusion) – infiltration/percolation. May be have some fracture flow;

(7.6) Capillarity but to what level does capillarity have an effect;

(7.8) Capillarity;

Groundwater discharge/seepage. Flow will probably be dominated by fracture flow.

(7.11) Irrigation of crops – but water might be too saline for irrigation. However there might be some uptake of water by plants at the salt pan;

(7.12) Ingestion via salt or via well;

(7.13) Extraction via well;

(8.6) Percolation;

(8.7) Infiltration;

Percolation;

These processes might occur via fractures;

(8.10) Evapotranspiration;

(8.11) Root uptake;

Rain splash;

(8.12) Ingestion;

Ingestion;

(row 9) Delete row because not considering surface water bodies;

(column 9) Delete row because not considering surface water bodies;

(10.5) Erosion;

Deposition;

Precipitation;

(10.6) Needs to be deleted since the interaction is via the soil;

(10.8) Erosion;

Deposition;

Precipitation;

(10.11) Precipitation;

Deposition;

(10.12) Inhalation (need to put a Y in the IM), also add Immersion – external irradiation to atmosphere;

(10.13) Inhalation;

Immersion – external irradiation to atmosphere;

Ingestion (if someone was to collect and drink the rainwater);

(11.10) Evapotranspiration;

(11.12) Ingestion;

(11.13) Ingestion;

(12.5) Bioturbation;

(12.6) Bioturbation;

(12.7) Might wish to include bioturbation but would termites burrow that far down?

(12.8) Bioturbation;

(12.13) Ingestion;

(13.7) Extraction/recharge of water;

Water treatment;

(13.8) Draining sediments;

Irrigation;

Ploughing;

(13.11) Storage;

(13.12) Storage;

Mass transport IM

The FEPs identified in Appendix B-5.2 were reviewed and a few modifications/additions suggested. It was felt that there was no need to add the exposure pathway LDE (Fig. B1.4 in Appendix B). Instead, all the exposure mechanisms in column 14 (listed below) could be moved to column 13 (i.e. leading to humans).

(7.14) Ingestion;

Other water uses;

(8.14) External irradiation;

(9.11) External irradiation (immersion);

Ingestion;

(10.14) Inhalation;

External irradiation (immersion);

(11.14) Ingestion;

(12.14) Ingestion;

In addition, the following processes, not included as LDEs in the matrix, were identified for consideration.

(1.1), (2.2), (3.3), (4.4), (5.5), (6.6), (7.7), (8.8) Radionuclide decay and retardation and enhanced transport

(11.11) Radionuclide migration in and from the crops (translocation and weathering);

(12.12) Internal transfer in animals;

B5.4. Audit of IM

WASTE	1.2 Y	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10	1.11	1.12	1.13
2.1 Y	STEEL DRUM	2.3 Y	2.4	2.5	2.6	2.7	2.8	2.9	2.10	2.11	2.12	2.12
3.1	3.2 Y	CUBES	3.4 Y	3.5	3.6	3.7	3.8	3.9	3.10	3.11	3.12	3.13
4.1	4.2	4.3 Y	VAULT	4.5	4.6 Y	4.7	4.8	4.9	4.10	4.11	4.12	4.13
5.1	5.2	5.3	5.4 Y	COVER	5.6	5.7	5.8	5.9	5.10	5.11	5.12	5.13
6.1	6.2	6.3	6.4	6.5	UNSAT. ZONE	6.7 Y	6.8	6.9	6.10	6.11	6.12	6.13
7.1	7.2	7.3	7.4	7.5	7.6 Y	AQUIFER	7.8 Y	7.9 Y	7.10	7.11 Y	7.12 Y	7.13 Y
8.1	8.2	8.3	8.4	8.5	8.6 Y	8.7 Y	SOIL + SEDIM.	8.9	8.10 Y	8.11 Y	8.12 Y	8.13 Y
9.1	9.2	9.3	9.4	9.5	9.6	9.7	9.8	SURFACE WATER	9.10	9.11 Y	9.12	9.13
10.1	10.2	10.3	10.4	10.5 Y	10.6	10.7	10.8 Y	10.9 Y	ATMOSP.	10.11 Y	10.12 Y	10.13 Y
11.1	11.2	11.3	11.4	11.5	11.6	11.7	11.8	11.9	11.10 Y	FLORA	11.12 Y	11.13 Y
12.1	12.2	12.3	12.4	12.5	12.6 Y	12.7 Y	12.8 Y	12.9	12.10	12.11	FAUNA	12.13 Y
13.1	13.2	13.3	13.4	13.5	13.6	13.7 Y	13.8 Y	13.9	13.10	13.11 Y	13.12 Y	HUMAN

FIG. B.5. First Revised Version of the Interaction Matrix for the Design Scenario: Liquid Release.

The interaction matrix revised in light of the reviewed documented in section B-5.3 (Fig. B.5) was audited with the help of the ISAM FEP list by Peter Lietava.

The goal of this audit was to establish links between matrix elements and the screened ISAM FEPs (Tables B.5 and B.6). The screened ISAM FEP list (see Section 1.3.2 of main report) contains not only the FEPs, which should be considered by the scenario generation procedure (category 'yes'), but also those, whose influence on the disposal facility evolution cannot be assumed as sure (category 'maybe').

TABLE B.5. LINKS BETWEEN LDEs AND ODEs OF THE INTERACTION MATRIX AND SCREENED ISAM FEPs

Interaction No.	External FEPs No.	Environmental FEPs No.	Contaminant FEPs No.
1.1		2.1.1;2.1.2	3.1.1;3.1.3-6; 3.3.6
1.2	1.1.9;1.1.12;1.2.3; 1.3.6	2.1.7-11	3.2.1-7; 3.2.9
2.1	1.1.2;1.1.9	2.1.7-12	
2.2		2.1.3	
2.3	1.1.9; 1.1.12; 1.2.3	2.1.7-11	3.2.1-7; 3.2.9
3.2	1.1.2; 1.1.9	2.1.7-12	
3.3		2.1.3;2.1.4	
3.4	1.1.2;1.1.3; 1.1.9; 1.1.12; 1.2.3; 1.3.6	2.1.7-11	3.2.1-7; 3.2.9
4.3	1.1.3;1.1.7;1.1.8; 1.1.9	2.1.7-12	
4.4		2.1.5;2.1.6	
4.6	1.1.2;1.1.7;1.1.8; 1.1.9; 1.1.12; 1.2.3; 1.3.6	2.1.7-11;2.2.6;2.2.11	3.2.1-7; 3.2.9
5.4	1.1.4;1.3.1;1.3.2;1.3.6	2.1.7-11;2.3.12	
5.5		2.1.5;2.1.6	
6.6		2.2.2;2.2.5;2.2.7-9;2.2.12;2.3.1;2.3.11	
6.7	1.1.1;1.1.2; 1.1.9;1.2.10;1.3.7		3.2.1-7; 3.2.9
7.6	1.2.10; 1.3.7		
7.7		2.2.3-5;2.2.7-9;2.2.12-13;2.3.1;2.3.3	3.3.1-2
7.8		2.2.5	3.2.1-7; 3.2.9
7.9	1.3.7	2.2.5	3.2.7
7.11	1.3.7		3.2.7
7.12	1.3.7		3.2.7
7.13	1.3.7	2.4.3;2.4.8; 2.4.8-9	3.2.13
8.6		2.3.11	
8.7		2.3.11	
8.8		2.3.2	3.3.2
8.10			3.2.8; 3.2.9
8.11	1.2.7		3.2.6
8.12	1.2.7		3.2.6
8.13		2.4.8; 2.4.8-9	3.2.13; 3.3.8
9.9		2.3.4	3.3.1-2
9.11			3.2.7;3.2.13
10.5	1.2.7	2.3.12	
10.8	1.2.7	2.3.12	
10.9		2.3.12	
10.10		2.3.7;2.3.10; 2.3.12	3.3.2
10.11	1.3.8		3.2.10
10.12	1.3.8		3.2.10
10.13		2.4.1	3.2.10
11.10	1.3.8		
11.11		2.3.8;2.3.13	3.3.1-2
11.12	1.3.8		3.2.11; 3.2.13
11.13	1.3.8	2.4.3	3.2.11; 3.2.13
12.6	1.3.8		
12.7	1.3.8		
12.8	1.3.8		
12.12		2.3.9;2.3.13	3.3.1-2
12.13	1.3.8	2.4.3	3.2.11; 3.2.13
13.7	1.3.9;1.4.7; 1.4.8;1.4.11		3.2.12
13.8	1.3.9;1.4.6; 1.4.8		3.2.12
13.11	1.3.9; 1.4.8		3.2.12
13.12	1.3.9; 1.4.8		3.2.12
13.13		2.4.1;2.4.2;2.4.5-7	3.3.4-5

TABLE B.6. COMMENTS ON SELECTED SCREENED ISAM FEPS AND THEIR LINKS TO THE LDEs AND ODEs

FEP No.	Comment
1.1.1	The stratigraphy of the site helps to define the physical properties of the hydrogeological environment. GW levels in the boreholes at the site can be used by the calibration of the hydrogeological flow model.
1.1.2	Excavations and construction of the vaults can influence the water flow field inside and in the vicinity of the repository. Therefore this FEP is related to the most water flow ODEs.
1.1.3	The properties of the backfill material between cubes can affect the water flow field in the repository, the degradation of the concrete cubes and the contaminant transport in the near field.
1.1.4	Multilayer cover design and performance influences the rate of infiltrating water penetrating into the vault structure of the repository.
1.1.5	Existing record and markers can limit the activities leading to the human intrusion into the repository - NO INTRUSION ODE (it is proposed to add interaction between „HUMAN“ and „WASTE FORM“ - 13.1)
1.1.6	Allocation of different types of waste can influence the effect of human intrusion - NO INTRUSION ODE (see FEP No. 1.1.5)
1.1.7	Repository design – used materials and their properties have impact on the infiltrated water flow rates and pathways and on the contaminant flow rates.
1.1.8	Quality control by the construction of the repository can influence the properties of the construction materials of the vaults.
1.1.9	The length of the operational period defines the time moment, when the conditions inside the repository change (impact on the gas and water flow pathways).
1.1.10	Administrative control can contribute to the reduction of the probability of the intrusion - NO INTRUSION ODE (see FEP No. 1.1.5)
1.1.12	Accidents can influence the structural stability and performance of waste forms and overpacks and to some extend the properties of engineered barriers – fractures in concrete vaults, ...
1.2.3	Seismic activities can have the same effects as accidents, but the extent of seismicity driven changes is much larger and covers not only the repository structure itself. FEP No. 1.2.10 is related to the regional hydrological response to geological changes and therefore FEP No. 1.2.3 is linked only to the ODEs describing the near field.
1.2.7	Global erosion and sedimentation influences the vegetation and animal population in the whole region.
1.2.10	See comment to the FEP No. 1.2.3
1.3.1	Global and local climatic changes can influence the rate of infiltrating water into the repository, the performance of engineered barriers, ...
1.3.2	See FEP No. 1.3.1
1.3.6	The warm climate effects influence the same items as the climatic changes 1.3.1 and 1.3.2
1.3.7	Hydrological and hydrogeological response to the climatic changes is related to the regional scale and is assumed for ODEs linked to some of the aquifer LDE.
1.3.8	As in case of FEP No. 1.3.7 is the ecological response is related to the regional scale and is assumed for ODEs linked to some of the „Flora“ and „Fauna“ LDEs.
1.3.9	Human response to climate changes influences some of the interactions related to the last LDE - „HUMAN“
1.4.1	Human influence on climate as e.g. global warming is not included in the interaction matrix - NO HUMAN INFLUENCE ON CLIMATE ODE (it is proposed to add interaction between „HUMAN“ and „ATMOSPHERE“ – 13.10)
1.4.2	Motivation and knowledge issues are related to the human intrusion into the repository - NO INTRUSION ODE (see FEP No. 1.1.5)
1.4.4	As in previous case this FEP is related to the human intrusion into the repository - NO INTRUSION ODE (see FEP No. 1.1.5)
1.4.5	As in FEPs No. 1.4.2 and 1.4.4 this FEP is related to the human intrusion into the repository - NO INTRUSION ODE (see FEP No. 1.1.5)

1.4.6	Human activities at the surface as excavations, site development, archaeology, etc. are included in ODE 13.8, but there is no influence on the surface water – MISSING ODE (it is proposed to add interaction between „HUMAN“ and „SURFACE WATER“ - 13.9)
1.4.7	The issue of groundwater management is included in interaction No. 13.7, but as in previous FEP there is no relationship between surface waters and water management - MISSING ODE (it is proposed to add interaction between „HUMAN“ and „SURFACE WATER“ - 13.9).
1.4.8	Social and institutional developments can change the human behaviour towards environment and can influence the societal memory related to the repository issues. Therefore this FEP is related to the same ODEs as FEP No. 1.1.5 and 1.3.9.
1.4.11	Explosion and crashes induced by human activities can significantly affect the performance of engineered structures of the repository and the transport properties of hydrogeological environment - MISSING ODE (it is proposed to add interaction between „HUMAN“ and „VAULT“ - 13.4, between „HUMAN“ and „UNSATURATED ZONE“ - 13.6 and between „HUMAN“ and „COVER“ - 13.5).
2.1.7-12	Physical and chemical processes and conditions in the near field are related to the interactions among engineered structures of vault repository including a part of geological environment affected by the construction activities.
2.2.6 - 11	Physical and chemical processes and conditions in the far field are related to the interactions among the components of geological and hydrogeological environment - MISSING ODE (it is proposed to add interaction between „VAULT“ and „AQUIFER“ - 4.7 as an interaction caused due to the mechanical effects of the vault structure to the structure and properties of the aquifer at the sites, where aquifer is close enough to the bottom of the repository).
2.3.12	Local erosion can speed up the degradation of the multilayer cover and can lead to the direct exposure of the engineered structures of the repository to the atmosphere.
2.3.14	Intrusion of animals and plant into the repository is not included in any interactions. It is assumed that this intrusion can affect the performance of the repository due to the generation of water preference pathways in engineered structures of the repository and therefore there is proposed only the interaction between „FLORA“/“FAUNA“ and „COVER“ and „FLORA“/“FAUNA“ and „VAULT“ - MISSING ODEs 11.4, 11.5, 12.4 and 12.5.
2.4.3	Diet and fluid intake depends on the food and water resources at the site.
2.4.4	Non-dietary habits as exploitation of surface water resources on the leisure activities creates additional interaction between relevant environmental LDEs and LDE „HUMAN“ - MISSING ODEs 9.13.
2.4.8-9	Natural and agricultural land and water use makes links between groundwater supply in aquifer, surface water and soil/sediment LDE with human behaviour at the site. Two groups of these interactions are already included in the matrix, but one group related to the surface water use is missing - MISSING ODEs 9.13.
3.2.1	Contaminant dissolution, precipitation and crystallisation is initiated by the penetration of infiltrating water to the waste form and can occur in all segments of transport pathways to the man and environment.
3.2.2 - 6	Other chemical, physical and biological processes can occur in all parts of transport pathway in near field and far field. Some biological and plant-mediated processes (3.2.6) are bounded to the biosphere.
3.2.9	For the gas-mediated transport of contaminants the direct release of gaseous contaminants form repository to the atmosphere is not included in the interaction matrix - MISSING ODEs 4.5 and 5.10. For the second gas pathway - through the unsaturated and saturated hydrogeological environment, a release of contaminants to the atmosphere follows the pathway 6.7, 7.8, 8.10.
3.2.12	Intrusion to the repository can be considered as the main human-action-mediated transport of contaminants (see FEP No. 1.1.5). Another human-action-mediated transport of contaminants is related to the agricultural and construction activities at the site.

This audit of the IM led to the proposal to include 14 more interactions as shown in Fig. B.6 (marked with "P"). The links between the proposed new and the screened ISAM FEPs are summarized in the Table B.7. These were reviewed at a further Vault Test Case meeting and it was decided to exclude:

- The surface water diagonal element and all ODEs related to it (9.13 and 13.9), because according to the site description there are no significant surface streams, rivers, lakes, etc;
- Interactions no. 4.7 and 5.10 related to the gas release rather the liquid release; and
- Interactions no. 13.1, 13.4-6, 13.10, which are included in the alternative scenario.

WASTE	1.2 Y	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10	1.11	1.12	1.13
2.1 Y	STEEL DRUM	2.3 Y	2.4	2.5	2.6	2.7	2.8	2.9	2.10	2.11	2.12	2.12
3.1	3.2 Y	CUBES & BACKFILL	3.4 Y	3.5	3.6	3.7	3.8	3.9	3.10	3.11	3.12	3.13
4.1	4.2	4.3 Y	VAULT	4.5 P	4.6 Y	4.7 P	4.8	4.9	4.10	4.11	4.12	4.13
5.1	5.2	5.3	5.4 Y	COVER	5.6	5.7	5.8	5.9	5.10 P	5.11	5.12	5.13
6.1	6.2	6.3	6.4	6.5	UNSAT. ZONE	6.7 Y	6.8	6.9	6.10	6.11	6.12	6.13
7.1	7.2	7.3	7.4	7.5	7.6 Y	AQUIFER	7.8 Y	7.9 Y	7.10	7.11 Y	7.12 Y	7.13 Y
8.1	8.2	8.3	8.4	8.5	8.6 Y	8.7 Y	SOIL + SEDIM.	8.9	8.10 Y	8.11 Y	8.12 Y	8.13 Y
9.1	9.2	9.3	9.4	9.5	9.6	9.7	9.8	SURFACE WATER	9.10	9.11 Y	9.12	9.13 P
10.1	10.2	10.3	10.4	10.5 Y	10.6	10.7	10.8 Y	10.9 Y	ATMOSP.	10.11 Y	10.12 Y	10.13 Y
11.1	11.2	11.3	11.4 P	11.5 P	11.6	11.7	11.8	11.9	11.10 Y	FLORA	11.12 Y	11.13 Y
12.1	12.2	12.3	12.4 P	12.5 P	12.6 Y	12.7 Y	12.8 Y	12.9	12.10	12.11	FAUNA	12.13 Y
13.1 P	13.2	13.3	13.4 P	13.5 P	13.6 P	13.7 Y	13.8 Y	13.9 P	13.10 P	13.11 Y	13.12 Y	HUMAN

FIG. B.6. Proposed Additional Revisions to the First Revised Version of the Interaction Matrix for the Design Scenario: Liquid Release.

The final version of Design Scenario interaction matrix for liquid release is presented in the main text (Fig. 8).

TABLE B.7. LINKS BETWEEN PROPOSED NEW ODEs OF THE INTERACTION MATRIX AND SCREENED ISAM FEPs

Interaction No.	External FEPs No.	Environmental FEPs No.	Contaminant FEPs No.
4.5			3.2.9
4.7		2.2.6 - 11	
5.10			3.2.9
9.13		2.4.4; 2.4.8-9	
11.4		2.3.14	
11.5		2.3.14	
12.4		2.3.14	
12.5		2.3.14	
13.1	1.1.5-6; 1.1.10; 1.4.2; 1.4.4-5		3.2.12
13.4	1.4.11		
13.5	1.4.11		
13.6	1.4.11		
13.9	1.4.6-7		
13.10	1.4.1		

REFERENCES TO APPENDIX B

[B1] STEPHANSSON, O., HUDSON, J.A., SKI/SKB FEPs Identification and Charaterisation via the "Rock Engineering Systems" Approach. SKB Final Report SKB 93-36, (1993)

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[B3] BIOMOVS II Development of a Reference Biospheres Methodology for Radioactive Waste Disposal. Final Report of the Reference Biospheres Working Group of the BIOMOVS II Study. Technical Report No. 6. Published by the BIOMOVS II Steering Committee. ISBN 91-972134-5-4. Stockholm (1996).

APPENDIX C: MATHEMATICAL MODELS AND ASSOCIATED SOFTWARE IMPLIMENTATION FOR THE VAULT TEST CASE DESIGN SCENARIO: LIQUID RELEASE

Two participants (Chang-Lak Kim and Richard Little) developed mathematical models for the design scenario liquid release. Their mathematical models and associated software implementation are described in sections C.1, C.2. and C.3, respectively.

C-1. KIM'S MODEL

Kim used the DUST-MS code [C1] to represent the release of radionuclides from the repository and their migration through the unsaturated zone. GWSCREEN [C2] was then used to model the migration of radionuclides through the saturated zone to a well using an analytical solution of the advection dispersion equation.

C1.1. Repository and unsaturated zone

The time history assumed for the failure of the artificial barriers (drums, cubes and cover), the increase in infiltration rate, and the chemical degradation of the repository (in terms of sorption coefficients) is shown in Fig. C1. The assumption that the concrete cubes do not fail until 300 years after closure means that radionuclides are not released due to leaching until 300 years.

A diffusive release source term model is assumed with no solubility limitation. Release mechanism for daughters is assumed to be the same as the parent. This conceptual model for release assumes that the wastes are uniformly and homogeneously distributed throughout a solidified waste form and that diffusion is the only important release process from the waste to the surrounding repository material. Under these conditions, analytical solutions for the release rate from the waste forms can be obtained for a variety of geometries. Analytical models solve the diffusion equation with radioactive decay:

$$\frac{\partial C_i(x,t)}{\partial t} = D_i \Delta^2 C_i(x,t) - \lambda_i C_i(x,t) \quad \text{(C1)}$$

where

C is the concentration within the waste form (kg m^{-3});
D is the waste form diffusion coefficient (m^2 y^{-1});
Λ is the radioactive decay constant (y^{-1});
X is the spatial location vector;
T is the time since container failure (y);
I is the radionuclide.

The initial condition is:

$$C_i(x,0) = C_{i,0} \quad \text{(C2)}$$

The analytical model for cylindrical waste form simulates a cylinder with radius, R, and height, H. At the edge of the waste form, the contaminant concentration is zero. This boundary condition causes the maximum concentration gradient to be maintained and leads to the highest release as compared to other possible boundary conditions. The boundary conditions are:

$$\frac{\partial C(0,z,t)}{\partial r} = 0$$

$$C(R,z,t) = C(r,0,t) = C(r,H,t) = 0 \qquad \text{(C3)}$$

The solution for the cumulative fractional release (CFR) for a semi-infinite waste form model for release is:

$$CFR = \frac{2\,SA}{V}\sqrt{\frac{D\ t}{\pi}} \qquad \text{(C4)}$$

where

SA is the surface area of the waste form (m^2);
V is the volume of the waste form (m^3).

Radionuclide transport through the repository and the unsaturated zone is modelled using the finite-difference model in DUST-MS. Seven types of material are assigned and 472 nodal points are used. Two constant node spacing (10 cm for zone no. 1 to 6 (concrete lid, waste, concrete base, red sand/calcrete, brown sand/gritty clay, and white kaolinite clay), and 20 cm for zone 7(weathered granite)) are assigned. The top boundary condition is specified as a zero flux condition to prevent mass from leaving the system, and a zero concentration bottom boundary condition is specified for the base of the unsaturated zone.

The processes of advection, dispersion, diffusion, decay and sorption are considered in one dimension and are represented thus:

$$\frac{\partial}{\partial t}\left(R_i \theta C_i\right) = \frac{\partial}{\partial x}\left(\theta D_i \frac{\partial C_i}{\partial x}\right) - \frac{\partial}{\partial x}\left(V_d C_i\right) - \lambda_i \theta R_i C_i + S \qquad \text{(C 5)}$$

$$D_i = D_{eff\ i} + \frac{\alpha\ |V_d|}{\theta} \qquad and \qquad R_i = 1 + \frac{\rho\ k_{d\,i}}{\theta} \qquad \text{(C6)}$$

where

C_i is the concentration of the radionuclide i in the aqueous phase (Bq m^{-3});
D_i is the diffusion-dispersion coefficient for radionuclide i ($m^2\ y^{-1}$);
V_d is the darcy velocity (m y^{-1});
θ is the moisture content (–);
λ_i is the radioactive decay constant for radionuclide i (y);
R_i is the retardation coefficient for radionuclide i (–);
S_i is the external volumetric source which includes the release from the waste form (Bq $m^{-3}\ y^{-1}$);
$D_{eff,i}$ is the effective diffusion coefficient for radionuclide i ($m^2\ y^{-1}$);
α is the transverse dispersion coefficient (m);
$k_{d,i}$ is the distribution coefficient for for radionuclide i ($m^3\ kg^{-1}$);
ρ is the dry bulk density of the medium through which the radionuclide is transported (kg m^{-3}).

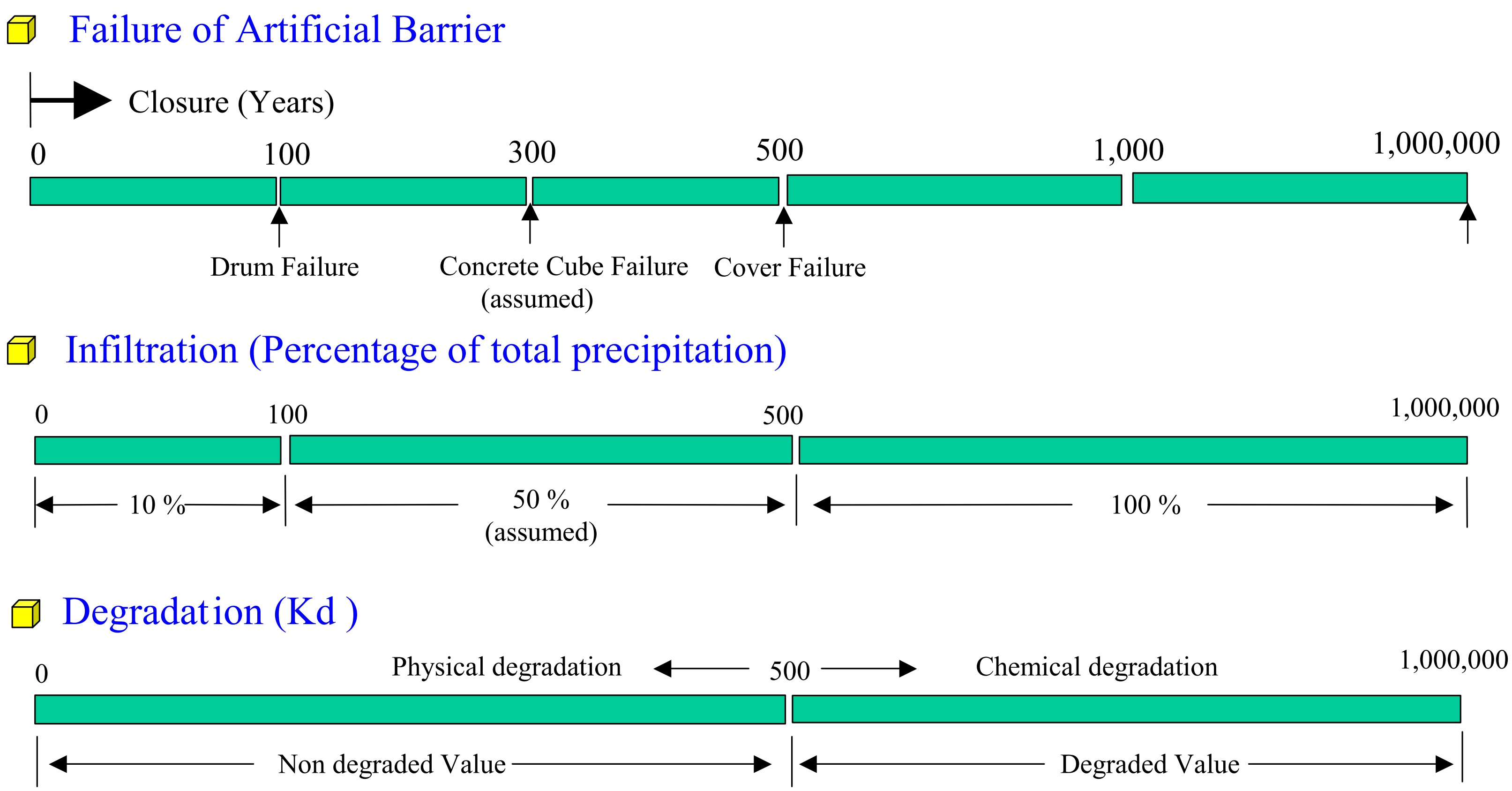

FIG. C.1. Time History for Repository Assumed by Kim for the Design Scenario: Liquid Release.

C1.2. Saturated zone

GWSCREEN was used to model the migration of radionuclides through the saturated zone to a well using an analytical solution of the advection-dispersion equation. It is capable of simulating up to three dimensional transport of radionuclides. In one dimension, the transport equation is:

$$R_i \frac{\partial C_i}{\partial t} = \frac{d_X}{\vartheta_w} \frac{\partial^2 C_i}{\partial x^2} - \frac{q}{\vartheta_w} \frac{\partial C_i}{\partial x} - R_i \lambda_i C_i \tag{C7}$$

x denotes the axis of groundwater flow;
ϑ_w is the effective porosity of the far field (–);
q is the darcy velocity of the groundwater (m y^{-1});
C_j is the concentration of radionuclide i in the groundwater (Bq m^{-3});
d_X is the longitudinal dispersion coefficient (m^2 y^{-1}),
λ_i is the decay constant for radionuclides i (y^{-1});
R_i is the retardation factor in the saturated zone for radionuclide i (–).

R is calculated using:

$$R = 1 + \frac{\rho\, Kd}{\vartheta_w} \tag{C8}$$

ρ is the dry bulk density of the saturated zone (kg m^{-3});
Kd is the distribution coefficient of the saturated zone (m^3 kg^{-1}).

For multiple member chains, each daughter radionuclide is treated as a single member chain.

C1.3. Estimation of dose

Only dose via ingestion of drinking water by humans was considered.

The annual individual effective dose to a human from the consumption of drinking water (D_{Wat}, in Sv y^{-1}) is given by:

$$D_{Wat} = C_W\, Ing_{Wat}\, DC_{Ing} \tag{C9}$$

where

C_w is the radionuclide concentration in the well from which the water is taken (Bq m^{-3});
Ing_{Wat} is the individual ingestion rate of freshwater (m^3 y^{-1});
DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}).

C-2. LITTLE'S MODEL

Little used the AMBER compartment model software application [C3] to represent the entire disposal system (repository, unsaturated zone, saturated zone, and biosphere) and calculated doses. The model developed is shown in Fig. C2.

FIG. C.2. Amber Model for the Design Scenario: Liquid Release.

A brief introduction is given to AMBER in section C2.1. The mathematical models used to represent the migration and fate of the radionuclides leached from repository are described in section C.2.2.

C2.1. Overview of AMBER

AMBER uses a compartment model approach to represent the migration and fate of contaminants in the environment. A disposal system may be represented by breaking it down into compartments, each of which may represent a medium which is distinct from other associated media. It is assumed that, as soon as a radionuclide enters a compartment, instantaneous mixing occurs so that there is a uniform concentration over the whole compartment. Each compartment must be chosen to represent a region of the environment for which this assumption is reasonable.

Radionuclides in one compartment may be transferred to another by various processes. The transfer is described by transfer coefficients that represent the fraction of the activity in a particular compartment transferred from that compartment to another one in unit time. Radionuclides can also be lost from the system altogether (by radioactive decay).

The mathematical representation of the intercompartmental transfer processes takes the form of a matrix of transfer coefficients that allow the compartmental amounts to be represented as a set of first order linear differential equations. For the i^{th} compartment, the rate at which the compartment inventory changes with time is given by:

$$\frac{dN_i}{dt} = \left(\sum_{j \neq i} \lambda_{ji} N_j + \lambda_N M_i + S_i(t) \right) - \left(\sum_{j \neq i} \lambda_{ij} N_i + \lambda_N N_i \right) \qquad \text{(C10)}$$

where

i, *j*	indicate compartments;
N, *M*	are the amounts (Bq) of radionuclides N and M in a compartment (M is the precursor of N in a decay chain);
S(t)	is a time dependent external source of radionuclide *N*, Bq y^{-1};
λ., λ_N	is the decay constant for radionuclide *N* (in y^{-1}); and
λ_{ji} , λ_{ij}	are transfer coefficients (y^{-1}) representing the gain and loss of radionuclide *N* from compartments *i* and *j* .

The solution of the matrix of equations given above provides the time-dependent inventory of each compartment. Assumptions for compartment sizes then result in estimates of concentrations in the corresponding media.

C-3. MODEL DEVELOPMENT

Leaching of radionuclides from the repository

The model developed to represent the repository is shown in Fig. C3. A single compartment is used to represent the entire repository. Although a more detailed AMBER model can be used to represent the repository in more detail, it is considered that, for the purposes of the current study, the use of a single compartment is appropriate. A similar approach was used to represent the disposal facilities in IAEA [C4] and was found to be satisfactory [C5].

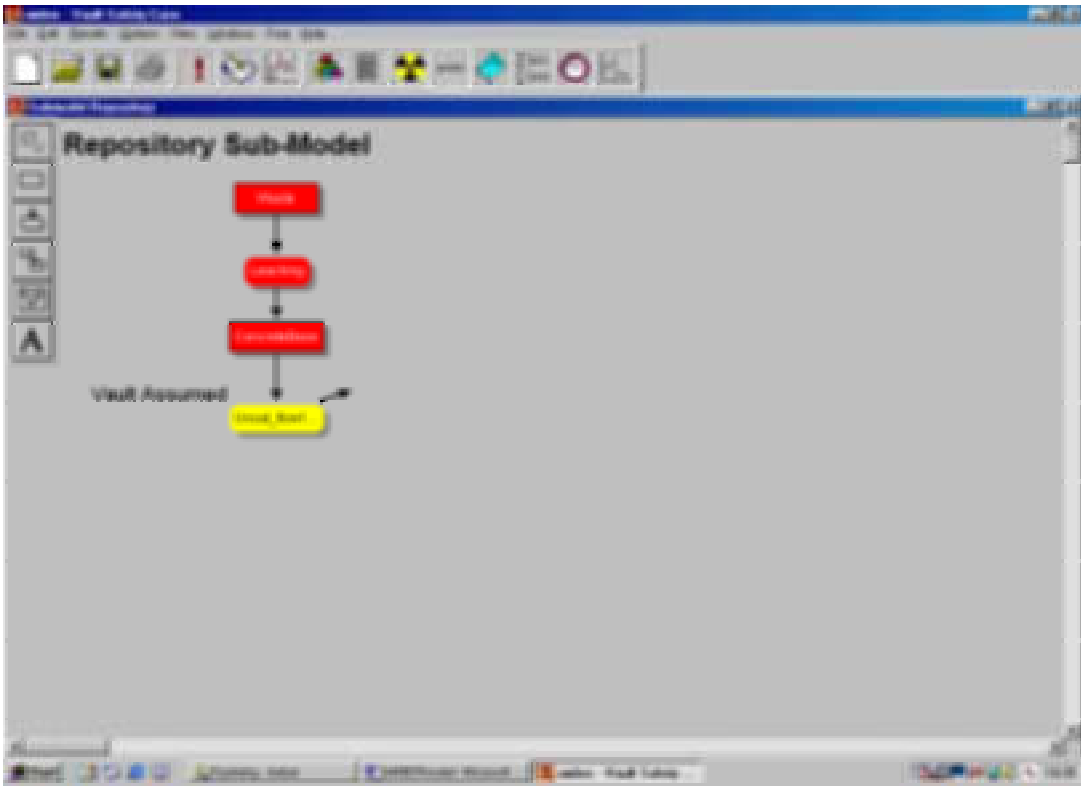

FIG. C.3. Amber Repository Sub-model for the Design Scenario: Liquid Release.

The leaching rate from the waste in the repository depends on the flow rate through the waste and the physical and chemical properties of the waste. It is assumed that the transfer is vertically downwards. It is assumed that leaching occurs once the drums containing the waste fail (i.e after 100 years - see Appendix D).

For a given radionuclide in the facility, the net vertical advective transfer (leaching) rate (y^{-1}), λ_{leach}, is:

$$\lambda_{leach} = \frac{q_{Adv}}{R\,D} = \frac{q_{In}}{\vartheta_w D R} \tag{C11}$$

where

q_{Adv}	is the advective velocity of water (m y^{-1});
q_{In}	is the Darcy velocity of water through the medium (m y^{-1}) (equivalent to the infiltration rate);
ϑ_w	is the water filled porosity (-) of the medium;
D	is depth of the medium through which the radionuclide is transported (m); and
R	is the retardation coefficient (-) given by:

$$R = 1 + \frac{\rho\,(1-\vartheta)\,Kd}{\vartheta_w} \tag{C12}$$

where

ρ	is the grain density of the medium (kg m^{-3});
θ	is the total porosity (-) of the medium; and
Kd	is the sorption coefficient of the medium (m^3 kg^{-1}).

q_{In} and K_d are time dependent (see Appendix D). For the purposes of the AMBER model, it is assumed that there is a linear failure in the performance of the cap between 100 years (intact: infiltration rate of 1.8E-3 m y^{-1}) and 500 years after closure (totally degraded infiltration rate of 1.8E-2 m y^{-1}) (see Appendix D). It is also assumed that chemical degradation of the repository is linear, starting at closure (undegraded) and lasting until 1000 years after closure (totally degraded). Chemical degradation is represented by varying the *Kd* values consistent with Appendix D.

C3.1. Transport in the unsaturated zone

The model developed to represent the unsaturated zone is shown in Fig. C4. Consistent with the data provided in Appendix D, the unsaturated zone has been discretised into four lithologies with differing physical and chemical properties: red sand/calcrete; brown sand/gritty clay; white kaolinite clay; and weathered granite. Scott [C5] has demonstrated that the compartmental approach can result in significant numerical dispersion if an inappropriate number of compartments are used to represent flow in the geosphere. Therefore, the unsaturated zone lithologies have been discretised in the AMBER model to reduce the impact of numerical dispersion.

Transport in the unsaturated zone is assumed to be vertically downward and advectively dominated. It is represented in AMBER using Equations C10 and C11 with the appropriate physical and chemical characteristics taken from Appendix D.

C3.2. Transport in the saturated zone

For transport through the saturated zone, the general advection-dispersion relation, in one dimension with unidirectional flow, is:

$$R\frac{\partial C}{\partial t} = \frac{d_X}{\vartheta_w}\frac{\partial^2 C}{\partial x^2} - \frac{q}{\vartheta_w}\frac{\partial C}{\partial x} - R\ \lambda_T\ C + \sum_p R_p \lambda_p C_p \qquad \text{(C13)}$$

where

x denotes the axis of groundwater flow;
ϑ_w is the effective porosity of the saturated zone (-);
q is the Darcy velocity of the groundwater (m y^{-1});
C is the concentration of the radionuclide in the groundwater (Bq m^{-3});
d_X is the longitudinal dispersion coefficient (m^2 y^{-1}), approximately equal to $a_X q$ where a_X (m) is the longitudinal dispersivity; and
λ_T is the rate of decay of the radionuclide (y^{-1}).

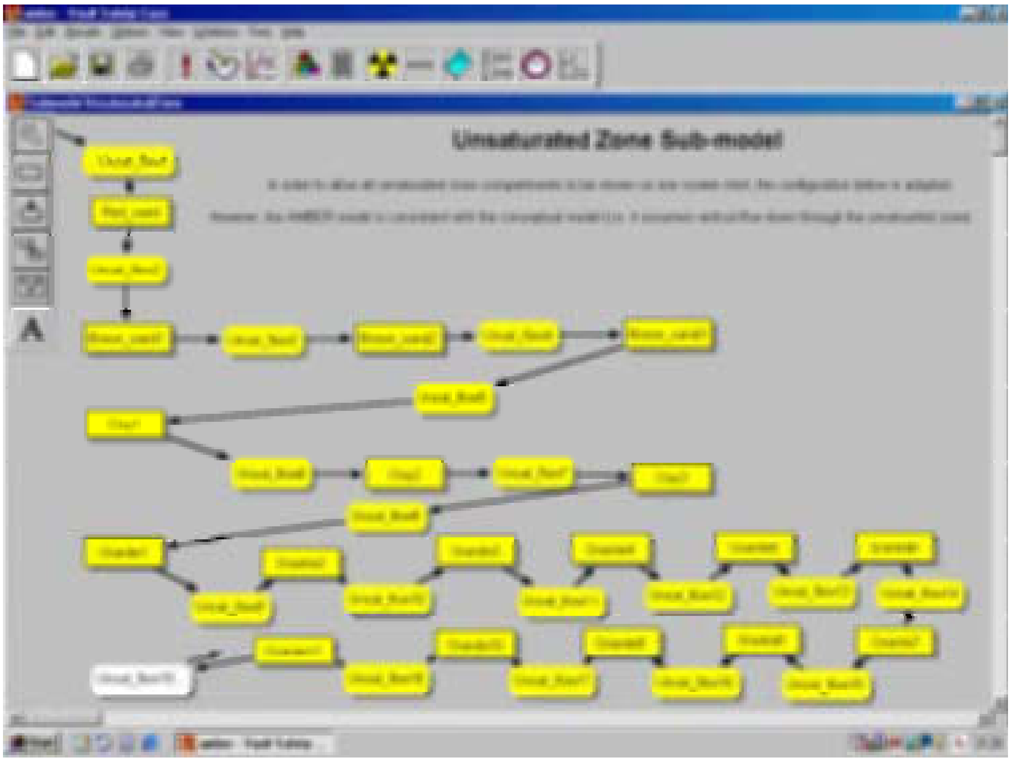

FIG. C.4. Amber Unsaturated Zone Sub-model for the Design Scenario: Liquid Release.

Elemental retardation in the geosphere (R) is taken into account using the well established approach of equilibrium sorption coefficients (Equation C11). These empirical parameters represent a number of physical and chemical processes with the ratio of the equilibrium concentration of an element sorbed to a surface to the concentration in the groundwater.

λ_p are the decay constants for the radionuclide's parent radionuclides (y^{-1});
R_p (unitless) is the retardation factor in the saturated zone for each of the radionuclide's parent radionuclides; and
C_p is the concentration of the radionuclide's parent radionuclides in the groundwater (Bq m^{-3}).

In Equation C13, the Darcy velocity (q, in m y^{-1}) of the groundwater is calculated from the hydraulic conductivity of the medium (K, in m y^{-1}) and the hydraulic gradient through which water flows:

$$q = -K \frac{\partial H}{\partial x} \tag{C14}$$

where

$\partial H/\partial x$ is the hydraulic gradient (–).

The approach used to solve the above equations in AMBER for the Design Scenario liquid release case is to discretise the far field into a number of compartments (as described by Scott [C5]). The optimum number of compartments required can be determined by comparing the advective and dispersive components of flow thus:

$$Pe = \frac{L_T}{a_X} \tag{C15}$$

where

Pe is the Peclet number
L_T is the total length of the path in the saturated zone (m).

The number of compartments required should exceed the Peclet number, otherwise the accuracy of the model will significantly decrease due to numerical dispersion [C5]. Using the data in Appendix D, 10 compartments are required to represent the saturated zone (Fig. C5).

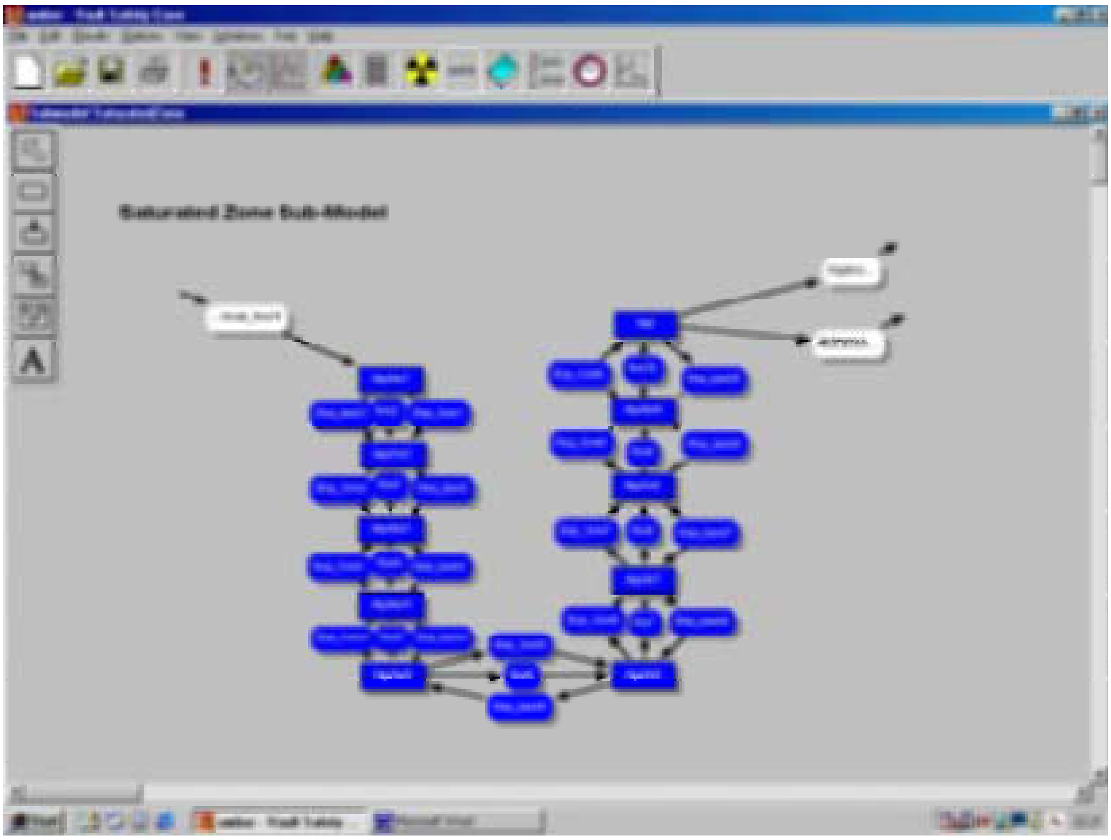

FIG. C.5. Amber Saturated Zone Sub-model for the Design Scenario: Liquid Release.

As discussed above, the advection-dispersion/diffusion equations may be solved by segmenting the geosphere into discrete compartments and estimating fluxes between them. For a one dimensional representation of flow in the geosphere, there are three transfers associated with each compartment:

Advective flux from i to j $\lambda_{A,ij} = \dfrac{q}{\vartheta_w \; L_i \; R}$ (C16)

Forward dispersion (i to j) $\lambda_{D,ij} = \dfrac{a_x}{\Delta_x} \lambda_{A,ij}$ (C17)

Backward dispersion (j to i) $\lambda_{D,ji} = \dfrac{a_x}{\Delta_x} \lambda_{A,ji}$ (C18)

where

$\lambda_{A,ij}$ is the rate of transfer of a contaminant by advection from compartment i to j (y^{-1});
$\lambda_{D,ij}$ is the rate of transfer of a contaminant by dispersion from compartment i to j (y^{-1});
L_i is the length of compartment i (m); and
Δ_X is the distance over which the gradient in radionuclide concentration is calculated (m).

Other parameters are as described above, with subscripts i or j showing to which compartment they relate.

C3.5. Transport in the biosphere

The model developed to represent dynamic transfers in the biosphere is shown in Fig. C6.

It is assumed that groundwater is abstracted via a well that is sunk at the site boundary following loss of institutional control (300 years after closure). The abstracted water is used for irrigation of pasture for sheep, drinking water for humans and animals, and bathing water for humans.

For the purposes of long term assessments of radioactive waste disposal, concentrations of radionuclides in certain biosphere media (for example the atmosphere, crops and animals) can often be assumed to be in equilibrium with their donor media. Therefore, they do not need to be modelled dynamically, instead their radionuclide concentrations can be assumed to be in equilibrium with the dynamically modelled concentrations in the biosphere media from which they obtain their radionuclides (donor media). For example, the concentration in a crop grown in the soil can be assumed to be in equilibrium with the concentration in the soil and any irrigation water applied. This approach is valid because the processes affecting the concentrations in such media are rapid compared with those affecting concentrations in the donor media, particularly because of the long term nature of the release.

This is the approach that it adopted for the AMBER biosphere model for the Design Scenario liquid release model. The well compartment is modelled as part of the saturated zone. The only two dynamic biosphere compartments are the soil and a “sink” compartment which represents the biosphere beyond the area of interest for the assessment. The remaining biosphere media (animals, pasture and air) are assumed to be in equilibrium with their donor compartments.

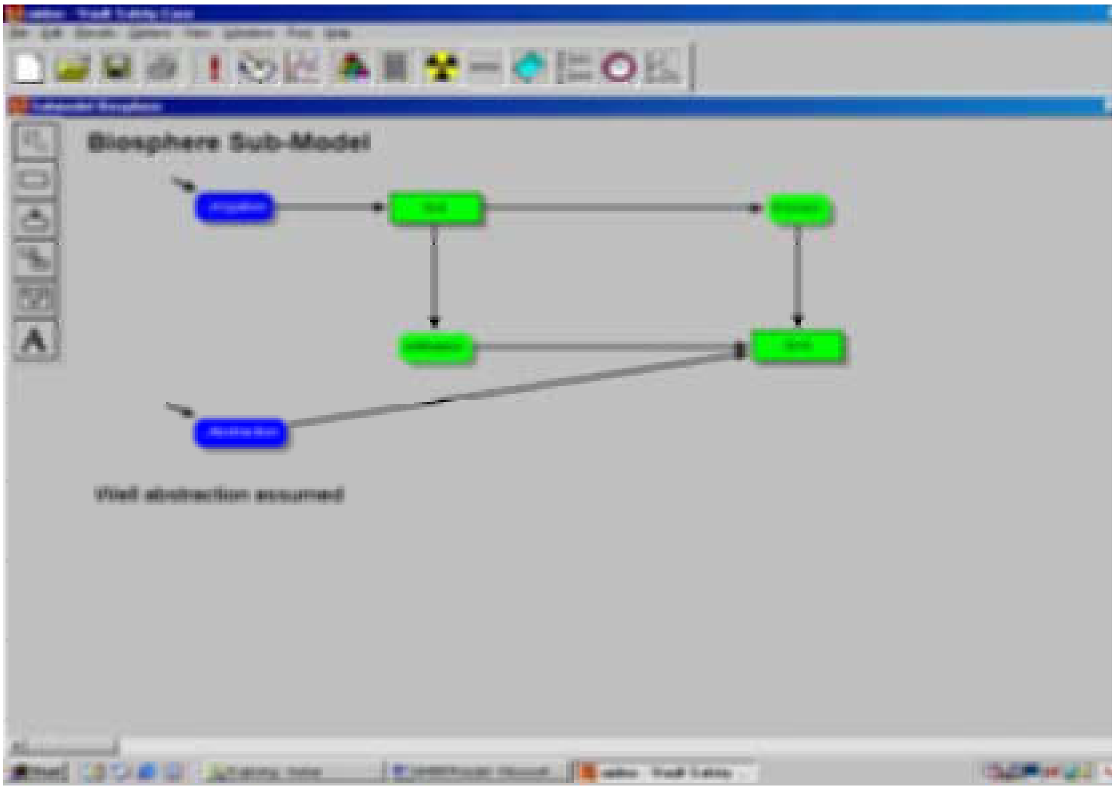

FIG. C.6. Amber Biosphere Sub-model for the Design Scenario: Liquid Release.

The transfer rate of radionuclides to the soil due to irrigation of pasture (y^{-1}), λ_{irrig}, is given by:

$$\lambda_{irrig} = \frac{A_{irr}\ d_{irrig}}{\vartheta_w V_w R_w} \tag{C19}$$

where

A_{irr} is the area irrigated (m^2);

d_{irrig} is the depth of effective irrigation water applied ($m\ y^1$) (i.e. total depth of irrigation water less loss due to interception and evaporation);

ϑ_w is the water filled porosity (–) of the saturated zone from which the water is abstracted;

V_w is the volume of the compartment representing the well (m^3);and

R_w is the retardation coefficient (–) of the saturated zone (well).

The transfer rate of radionuclides due to abstraction of water for other purposes (y^{-1}), $\lambda_{non\text{-}irrig}$, is given by:

$$\lambda_{non-irrig} = \frac{V_{non-irrig}}{\vartheta_w V_w R_w} \tag{C20}$$

where

$V_{non\text{-}irrig}$ is the volume of water abstracted for non-irrigation purposes plus loss due to interception and evaporation ($m^3\ y^{-1}$).

The transfer of radionuclides by erosion (y^{-1}), λ_{eros}, is given by:

$$\lambda_{eros} = \frac{E_{Soil}}{d_{Soil}} \tag{C21}$$

where:

E_{Soil} is the erosion rate from soil (m y^{-1}) and d_{Soil} is the depth of soil (m).

The transfer due to leaching can be calculated using Equation C11, with *D* being set equal to the depth of the appropriate thickness of soil (m).

C-4. CALCULATION OF DOSES

C4.1 Ingestion of water

The annual individual effective dose to a human from the consumption of drinking water (E_{Wat}, in Sv y^{-1}) is given by:

$$E_{Wat} = C_W \; Ing_{Wat} \; DC_{Ing} \tag{C22}$$

where

C_w is the radionuclide concentration in the well from which the water is taken (Bq m^{-3});
Ing_{Wat} is the individual ingestion rate of freshwater (m^3 y^{-1}); and
DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}).
C_W is given by:

$$C_W = \frac{Amount_w}{\vartheta_w V_w R_w} \tag{C23}$$

where

$Amount_w$ is the amount of the radionuclide in the well from which the water is abstracted (Bq);
ϑ_w is the water filled porosity (-) of the saturated zone (well) from which the water is abstracted;
V_w is the volume of the compartment representing the well (m^3); and
R_w is the retardation coefficient (-) of the saturated zone (well).

C4.2 Ingestion of animal products

The annual individual effective dose to a human from the consumption of animal produce (E_{Anm}, in Sv y^{-1}) is given by:

$$E_{Anm} = \chi_{Anm} Ing_{Anm} DC_{Ing} \tag{C24}$$

where

χ_{Anm} is the radionuclide concentration in the animal product (Bq kg^{-1} fresh weight of product);
Ing_{Anm} is the individual consumption rate of the animal product (kg fresh weight of product y^{-1}); and
DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}).

For sheep, the χ_{Anm} term is calculated using:

$$\chi_{Anm} = CF_{Anm}\left(\chi_{Past} Ing_{Past} + C_W \ Ing_{AW} + \chi_{Wet} \ Ing_{ASoil}\right) \tag{C25}$$

where

CF_{Anm} is the concentration factor for the animal product (d kg^{-1} fresh weight of product);
χ_{Past} is the radionuclide concentration in the pasture (Bq kg^{-1} fresh weight of pasture);
Ing_{Past} is the consumption rate of pasture by the animal (kg fresh weight of pasture d^{-1});
C_w is the radionuclide concentration in the well from which water for animals is taken (Bq m^{-3});
Ing_{AW} is the consumption rate of water by the animal (m^3 d^{-1});
χ_{Wet} is the radionuclide concentration in the wet soil (Bq kg^{-1}); and
Ing_{Asoil} is the consumption rate of soil by the animal (kg wet weight of soil d^{-1}).

χ_{Past} is given by:

$$\chi_{Past} = (CF_{Past} + s_{Past})\chi_{Dry} + \frac{\mu_{Past} d_{irrig} C_W}{Y_{Past}\lambda_{Weather} + N_{Anm} Ing_{Past}\ 365} \tag{C26}$$

where

CF_{past} is the concentration factor for pasture (Bq kg^{-1} fresh weight of pasture per Bq kg^{-1} dry weight of soil);
s_{Past} is the soil contamination on pasture (kg dry weight soil kg^{-1} fresh weight of pasture);
χ_{Dry} is the radionuclide concentration in the dry surface soil (Bq kg^{-1} dry weight soil);
μ_{past} is the interception fraction for irrigation water on pasture (–);
d_{irrig} is the depth of total irrigation water applied (m y^{-1});
Y_{past} is the yield of pasture (kg fresh weight m^{-2});
$\lambda_{Weather}$ is the removal rate of irrigation water from the crop by weathering processes (weathering rate) (y^{-1}), N_{Anm} is the stocking density of the animals (m^{-2}); and
Ing_{Past} is the consumption rate of pasture by the animals (kg fresh weight of pasture d^{-1}).

The factor of 365 is applied to convert from d^{-1} to y^{-1}.

χ_{Dry} (the radionuclide concentration in the dry surface soil (Bq kg^{-1} dry weight soil)) is given by:

$$\chi_{Dry} = \frac{C_{Soil}}{(1-\vartheta_{Soil})\rho_{Soil}} \tag{C27}$$

where

C_{soil} is the radionuclide concentration in the soil (Bq m^{-3});
ϑ_{Soil} is the total porosity of the soil (–);
ρ_{Soil} is the grain density of the soil (kg m^{-3}); and

C_{Soil} is given by:

$$C_{Soil} = \frac{Amount_{Soil}}{V_{Soil}} \tag{C28}$$

where:

$Amount_{Soil}$ is the amount of the radionuclide in the soil (Bq);
V_{Soil} is the volume of the compartment representing the soil (m^3); and
χ_{Wet} (the radionuclide concentration in the wet soil (Bq kg^{-1})) is given by:

$$\chi_{Wet} = \frac{C_{Soil}}{(1-\vartheta_{Soil})\rho_{Soil} + \vartheta_{wSoil}\rho_{Wat}} \quad \text{(C29)}$$

where

ϑ	is the total porosity (–);
ϑ_w	is the water filled porosity (–); and
ρ	is the density (kg m^{-3}). The subscript *Soil* indicates the value for soil, *Wat* indicates the value relates to water.

For cows and chickens, the χ_{Anm} term is calculated using:

$$\chi_{Anm} = CF_{Anm}\left(C_W\ Ing_{AW}\right) \quad \text{(C30)}$$

C4.3. Inadvertent ingestion of soil

Soil can be inadvertently ingested by humans. The annual individual dose to a human from the ingestion of soil (E_{Sed}, in Sv y^{-1}) is given by:

$$E_{Sed} = \chi_{Wet}\ Ing_{Sed}\ DC_{Ing} \quad \text{(C31)}$$

where

χ_{Wet}	is the radionuclide concentration in the soil (Bq kg^{-1} wet weight) (given by Equation C1.2.19);
Ing_{Sed}	is the individual inadvertent ingestion rate of soil (kg wet weight soil y^{-1}); and
DC_{Ing}	is the dose coefficient for ingestion (Sv Bq^{-1}).

Inhalation of dust

The annual individual dose to a human from the inhalation of suspended soil (E_{Dust}, in Sv y^{-1}) is given by:

$$E_{Dust} = C_{Air}\ O_{Out}\ Inh_{Sed}\ DC_{Inh} \quad \text{(C32)}$$

where:

C_{Air}	is the radionuclide concentration in the air above the soil (Bq m^{-3})
O_{Out}	is the individual occupancy on the contaminated soil (h y^{-1})
Inh_{Sed}	is the breathing rate of the human on the contaminated soil (m^3 h^{-1})
DC_{Inh}	is the dose coefficient for inhalation (Sv Bq^{-1}).

C_{Air} is given by:

$$C_{Air} = \chi_{Dry}\ \frac{(R_{Soil}-1)}{R_{Soil}}\ c_{Dust} \quad \text{(C33)}$$

where:

R_{Soil}	is the retardation coefficient for surface soil compartment (–)
c_{Dust}	is the dust level in the air above the surface soil compartment (kg m^{-3}).

C4.4. External irradiation from soil

The annual individual dose to a human from external irradiation from soil (E_{ExSoil}, in Sv y^{-1}) is given by:

$$E_{ExSoil} = C_{Soil}\ O_{Out}\ DC_{Exts} \quad \text{(C34)}$$

where

C_{Soil} is the concentration in the soil (Bq m^{-3});
O_{Out} is the individual occupancy outdoors on the contaminated soil (h y^{-1}); and
C_{Exts} is the dose coefficient for external irradiation from soil (Sv h^{-1}/Bq m^{-3}).

C4.5. External irradiation from bathing water

The annual individual dose to a human from external irradiation from bathing water (E_{ExWat}, in Sv y^{-1}) is given by:

$$E_{ExWat} = C_W\ O_{Wat} DC_{Extw} \quad \text{(C35)}$$

where

C_w is the radionuclide concentration in the water abstracted from the well (Bq m^{-3});
O_{wat} is the individual occupancy in the bathing water (h y^{-1}); and
DC_{Extw} is the dose coefficient for external irradiation from immersion in water (Sv h^{-1} / Bq m^{-3}).

C-5. DESIGN SCENARIO: GAS RELEASE

One participant (Richard Little) developed a mathematical model for the design scenario gas release and implemented it in the AMBER compartment model software application [C3]. The model is described below.

C5.1. Source term

For ^{3}H and ^{14}C, the release rate in gas, R_{gas} [Bq m^{-2} y^{-1}], is given by:

$$R_{gas} = \frac{A_r \cdot f_{gas}}{\tau_{gas}\ A_w} \quad \text{(C36)}$$

where

A_r is the residual activity in the repository (assuming loss by decay only) [Bq];
f_{gas} is the fraction of the activity associated with the gas [–];
τ_{gas} is the average timescale of generation of each gas [y]; and
A_w is the surface area of the repository [m^2].

For ^{222}Rn, the release rate in gas, R_{gas} [Bq m^{-2} y^{-1}], can be derived using NEA [C6]:

$$R_{gas} = \lambda\ A_{Ra226} \tau\ H_1\ e^{\frac{-h_2}{H_2}}\ /\ V_w \quad \text{(C37)}$$

where

λ is the decay constant of ^{222}Rn [y^{-1}];
A_{Ra226} is the ^{226}Ra concentration in the waste [Bq];
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 [–];

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]; and
V_w is the volume of the repository [m^3].

C5.2. Air concentrations

The associated concentration of a radionuclide in the air above the repository, $C_{air,gas}$ [$Bq.m^{-3}$], can be approximated by:

$$C_{air,gas} = R_{gas}\ A_w / V_{air} \tag{C38}$$

where

R_{gas} is the release rate of the radionuclide in gas [$Bq\ m^{-2}\ y^{-1}$];
A_w is the surface area of the repository [m^2]; and
V_{air} is the air volume into which the activity released per year is diluted [$m^3 \cdot y^{-1}$].

$$V_{air} = W \cdot u \cdot h \cdot 3.16\ 10^7 \tag{C39}$$

where

W is the width of the source perpendicular to the wind direction [m];
u is the mean wind speed [$m \cdot s^{-1}$];
h is the height for vertical mixing [m]; and
$3.16\ 10^7$ are the number of seconds in a year [$s \cdot y^{-1}$].

The associated concentration of radon in a house built on top of the repository, $C_{house,Rn}$ [$Bq.m^{-3}$], can be approximated by:

$$C_{house,Rn} = R_{Rn}\ A_{house} / (V_{house}\ Vent) \tag{C40}$$

where

R_{Rn} is the release rate of the radon [$Bq\ m^{-2}\ y^{-1}$];
A_{house} is the surface area of the house [m^2];
V_{house} is the volume of the house [m^3]; and
Vent is the ventilation rate for the house [y^{-1}].

C5.3. Inhalation dose

For ^3H and ^{14}C, the dose due to inhalation of the gas, $Dose_{inh}$ [$Sv \cdot y^{-1}$], is given by:

$$Dose_{inh} = C_{air,gas}\ t_{out}\ b_r\ DF_{inh} \tag{C41}$$

where

$C_{air,gas}$ is the concentration of the gas in the air [$Bq\ m^{-3}$];
t_{out} is the time spent outside in the gas plume by the human [$h\ y^{-1}$];
$b_{r,}$ is the breathing rate of the human [$m^3\ h^{-1}$]; and
DF_{inh} is the dose factor for inhalation [$Sv\ Bq^{-1}$].

For ^{222}Rn, the dose due to inhalation of the gas in the air above the repository, $Dose_{inh,\ air}$ [$Sv \cdot y^{-1}$], is given by:

$$Dose_{inh,air} = C_{air,Rn}\ t_{out}\ DF_{inh} \tag{C42}$$

where

$C_{air,Rn}$ is the concentration of the radon in the air [Bq m^{-3}];
t_{out} is the time spent outside in the gas plume by the human [h y^{-1}]; and
DF_{inh} is the dose factor for inhalation [Sv h^{-1} / Bq m^{-3}].

For ^{222}Rn, the dose due to inhalation of the gas in a house built on top of the repository, $Dose_{inh,\ house}$ [Sv·y^{-1}], is given by:

$$Dose_{inh,house} = C_{house,Rn}\ t_{in}\ DF_{inh} \tag{C43}$$

where

$C_{house,Rn}$ is the concentration of the radon in the house [Bq m^{-3}];
t_{in} is the time spent inside the house by the human [h y^{-1}]; and
DF_{inh} is the dose factor for inhalation [Sv h^{-1} / Bq m^{-3}].

C-6. DESIGN SCENARIO: SOLID RELEASE

One participant (Richard Little) developed a mathematical model for the design scenario solid release and implemented it in the AMBER compartment model software application [C3]. The model is described below.

The radionuclide concentration (C_{Soil}, Bq m^{-3}) in the source term is assumed to be the same as that in the waste:

$$C_{Soil} = A/V \tag{C44}$$

where

C_{Soil} is the radionuclide concentration in the soil (Bq m^{-3}); and
A is the radionuclide inventory in the repository (Bq), and V is the total repository volume (m^3).

The source term is reduced as a function of time due only to radioactive decay.

C6.1. Ingestion of animal products

The annual individual effective dose to a human from the consumption of animal produce (E_{Anm}, in Sv y^{-1}) is given by:

$$E_{Anm} = \chi_{Anm} Ing_{Anm} DC_{Ing} \tag{C45}$$

where

χ_{Anm} is the radionuclide concentration in the animal product (Bq kg^{-1} fresh weight of product);
Ing_{Anm} is the individual consumption rate of the animal product (kg fresh weight of product y^{-1}); and
DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}).

For chicken products (meat and eggs), the χ_{Anm} term is calculated using:

$$\chi_{Anm} = CF_{Anm}\left(\chi_{Grain} Ing_{Grain} + \chi_{Wet} \; Ing_{ASoil}\right) \tag{C46}$$

where

CF_{Anm} is the concentration factor for the animal product (d kg^{-1} fresh weight of product);
χ_{Grain} is the radionuclide concentration in the grain (Bq kg^{-1} fresh weight of grain);
Ing_{Grain} is the consumption rate of grain by the animal (kg fresh weight of grain d^{-1});
χ_{Wet} is the radionuclide concentration in the wet soil (Bq kg^{-1}); and
Ing_{Asoil} is the consumption rate of soil by the animal (kg wet weight of soil d^{-1}).

χ_{Grain} is given by:

$$\chi_{Grain} = (CF_{Grain} + s_{Grain})\chi_{Dry} \tag{C47}$$

where

CF_{Grain} is the concentration factor for grain (Bq kg^{-1} fresh weight of grain per Bq kg^{-1} dry weight of soil);
s_{Grain} is the soil contamination on grain (kg dry weight soil kg^{-1} fresh weight of grain);
χ_{Dry} is the radionuclide concentration in the dry surface soil (Bq kg^{-1} dry weight soil). and
χ_{Dry} (the radionuclide concentration in the dry surface soil (Bq kg^{-1} dry weight soil)) is given by:

$$\chi_{Dry} = \frac{C_{Soil}}{(1-\vartheta_{Soil})\rho_{Soil}} \tag{C48}$$

where:

C_{soil} is the radionuclide concentration in the soil (Bq m^{-3});
ϑ_{Soil} is the total porosity of the soil (-) and ρ_{Soil} is the grain density of the soil (kg m^{-3}).

C_{Soil} is given by:

$$C_{Soil} = \frac{Amount_{Soil}}{V_{Soil}} \tag{C49}$$

where

$Amount_{Soil}$ is the amount of the radionuclide in the soil (Bq);
V_{Soil} is the volume of the compartment representing the soil (m^3); and
χ_{Wet} (the radionuclide concentration in the wet soil (Bq kg^{-1})) is given by:

$$\chi_{Wet} = \frac{C_{Soil}}{(1-\vartheta_{Soil})\rho_{Soil} + \vartheta_{wSoil}\rho_{Wat}} \tag{C50}$$

where

ϑ is the total porosity (-);
ϑ_w is the water filled porosity (-), and ρ the density (kg m^{-3}). The subscript *Soil* indicates the value for soil, *Wat* indicates the value relates to water; and

For sheep, the χ_{Anm} term is calculated using:

$$\chi_{Anm} = CF_{Anm}\left(\chi_{Past} Ing_{Past} + \chi_{Wet} \; Ing_{ASoil}\right) \tag{C51}$$

where

CF_{Anm} is the concentration factor for the animal product (d kg^{-1} fresh weight of product);
χ_{Past} is the radionuclide concentration in the pasture (Bq kg^{-1} fresh weight of pasture);
Ing_{Past} is the consumption rate of pasture by the animal (kg fresh weight of pasture d^{-1});
χ_{Wet} is the radionuclide concentration in the wet soil (Bq kg^{-1}); and
Ing_{Asoil} is the consumption rate of soil by the animal (kg wet weight of soil d^{-1}).

χ_{Past} is given by:

$$\chi_{Past} = (CF_{Past} + s_{Past})\chi_{Dry} \tag{C52}$$

where:

CF_{past} is the concentration factor for pasture (Bq kg^{-1} fresh weight of pasture per Bq kg^{-1} dry weight of soil);
s_{Past} is the soil contamination on pasture (kg dry weight soil kg^{-1} fresh weight of pasture);
χ_{Dry} is the radionuclide concentration in the dry surface soil (Bq kg^{-1} dry weight soil).

C6.2. Ingestion of crops

The annual individual effective dose to a human from the consumption of a crop, (E_{Crop}, Sv y^{-1}), is given by:

$$E_{Crop} = \chi_{Crop} Ing_{Crop} DC_{Ing} \tag{C53}$$

where

χ_{Crop} is the radionuclide concentration in the crop (Bq kg^{-1} fresh weight of crop);
Ing_{Crop} is the individual ingestion rate of the crop (kg fresh weight y^{-1}); and
DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}).

The χ_{crop} term is calculated using:

$$\chi_{Crop} = (CF_{Crop} + s_{Crop})\chi_{Dry} \tag{C54}$$

where

CF_{crop} is the concentration factor for the crop (Bq kg^{-1} fresh weight of crop/Bq kg^{-1} (dry weight of soil));
s_{Crop} is the soil contamination on the crop (kg dry weight soil kg^{-1} fresh weight of crop); and
χ_{Dry} is the radionuclide concentration in the dry surface soil (Bq kg^{-1} dry weight soil) given by Equation C54.

C6.3. Inadvertent ingestion of soil

Soil can be inadvertently ingested by humans. The annual individual dose to a human from the ingestion of soil (E_{Sed}, in Sv y^{-1}) is given by:

$$E_{Sed} = \chi_{Wet}\ O_{Out}\ Ing_{Sed}\ DC_{Ing} \tag{C55}$$

where

χ_{Wet} is the radionuclide concentration in the soil (Bq kg^{-1} wet weight) (given by Equation C55);

O_{Out} is the individual occupancy on the contaminated soil (h y^{-1});
Ing_{Sed} is the individual inadvertent ingestion rate of soil (kg wet weight soil h^{-1}); and
DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}).

Inhalation of dust

The annual individual dose to a human from the inhalation of suspended soil (E_{Dust}, in Sv y^{-1}) is given by:

$$E_{Dust} = C_{Air}\ O_{Out}\ Inh_{Sed}\ DC_{Inh} \qquad \text{(C56)}$$

where

C_{Air} is the radionuclide concentration in the air above the soil (Bq m^{-3});
O_{Out} is the individual occupancy on the contaminated soil (h y^{-1});
Inh_{Sed} is the breathing rate of the human on the contaminated soil (m^3 h^{-1}); and
DC_{Inh} is the dose coefficient for inhalation (Sv Bq^{-1}).

C_{Air} is given by:

$$C_{Air} = \chi_{Dry}\ \frac{(R\ -1)}{R} c_{Dust} \qquad \text{(C57)}$$

where

R is the retardation coefficient for surface soil compartment (-); and
c_{Dust} is the dust level in the air above the surface soil compartment (kg m^{-3}).

R is given by:

$$R = 1 + \frac{\rho_{Soil}\ (1 - \vartheta_{Soil})\ Kd_{Soil}}{\vartheta_{wSoil}} \qquad \text{(C58)}$$

where

ρ_{Soil} is the grain density of the soil (kg m^{-3});
θ_{Soil} is the total porosity (–) of the soil;
Kd_{Soil} is the sorption coefficient of the soil (m^3 kg^{-1}); and
ϑ_{wSoil} is the water filled porosity of the soil (–).

C.6.4. External irradiation from soil

The annual individual dose to a human from external irradiation from soil (E_{ExSoil}, in Sv y^{-1}) is given by:

$$E_{ExSoil} = C_{Soil}\ O_{Out}\ DC_{Exts} \qquad \text{(C59)}$$

where

C_{Soil} is the concentration in the soil (Bq m^{-3});
O_{Out} is the individual occupancy outdoors on the contaminated soil (h y^{-1}); and
DC_{Exts} is the dose coefficient for external irradiation from soil (Sv h^{-1}/Bq m^{-3}).

C.7 HUMAN INTRUSION SCENARIO

Two participants (Peter Lietava and Richard Little) developed mathematical models for the human intrusion scenario. Their mathematical models and associated software implementation are described in sections C.4.1 and C4.2, respectively.

C7.1. Lietava's Model

The description of mathematical models is based on the properties of RESRAD 5.91 code. RESRAD is a family of computer codes developed at Argonne National Laboratory for the U.S. Department of Energy to calculate site-specific RESidual RADioactive material guidelines as well as radiation dose and excess lifetime cancer risk to a chronically exposed on-site resident [C7]. Two main sources of contamination are considered: radioactive waste in vault; and excavated radioactive material spread out at the surface surrounding the building.

C.7.1.1. Source term 1 (radioactive waste in vault)

The concentration in source term 1 was calculated using:

$$C_{waste} = A/V \tag{C60}$$

where

C_{waste} is the radionuclide concentration in the waste [Bq m^{-3}];
A is the radionuclide inventory in the repository [Bq]; and
V is the total repository volume [m^3].

The inventory of radioactive waste, which is not excavated during the construction of dwelling at the top of vault cover, contributes only to the external irradiation pathway. Depending on the shielding and time spent indoors and outdoors, the external irradiation exposure pathways from the residual inventory in the vault contains these two parts.

$$D_{ext}\,(cover) = D_{ext}\,(no\ cover).\ exp[-k.\ \rho_{cover}.(TH_{cover}(0)-ER_{cover}.t)];$$

$$0 \le t \le t_{cover}$$

$$D_{ext}\,(cover) = \rho_{cont}.OSF.AF.SF.\{1-exp[-k.\ \rho_{cont}.(TH_{cont}(0)-ER_{cont}.(t-t_{cover}))]\}$$
$$.S(0).SOF(t).\ DCF_{exter}; \qquad t > t_{cover} \tag{C61}$$

where

D_{ext} (no cover) = ρ_{cont}.OSF.AF.SF.{1-exp[-k. ρ_{cont}.$TH_{cont}(0)$]}.S(0).SOF(t). $DCF_{exter;}$
SF shape factor [–];
ASR air/soil concentration ratio [kg/m^3];
AF area factor [–];
OSF occupancy and shielding factor [–];
S(0) initial concentration of radionuclide in vault [Bq/m^3];
SOF(t) correction factor for source term (decay, ingrowth, leaching)[–];
DCF_{exter} external irradiation from soil [Sv.m^3 /(Bq.h)];
$TH_{cont}(t)$ time dependent thickness of contaminated zone [m];
$TH_{cover}(t)$ time dependent thickness of cover [m];
ρ_{cont} density of contaminated soil material [kg/m^3];
ρ_{cover} density of cover material [kg/m^3];
k empirical constant for the calculation of the depth factor [m^2/kg];

ER_{cont} erosion rate of the contaminated zone [m/y];
ER_{cover} erosion rate of the cover material [m/y];
t_{cover} time for the cover removal by erosion [y]; and
t time [y].

C7.1.2 Source term 2 (excavated radioactive material)

The initial concentration for source term 2 was derived from the total amount of radioactive waste excavated by the construction of the house which is given by:

$$C(0) = A_{vault} \,.\, S_{house} \,.\, [(TH_{foundation} - TH_{cover})/V_{vault}] \,/\, (S_{excavation} \,.\, TH_{soil}) \qquad \text{(C62)}$$

where

A_{vault} radionuclide inventory in the vault [Bq];
S_{house} area of the house [m^2];
$TH_{foundation}$ foundation depth [m];
TH_{cover} over depth [m];
V_{vault} total vault volume [m^3];
$S_{exavation}$ area contaminated by excavated material [m^2]; and

TH_{soil} epth of contaminated soil layer [m].

The same mathematical model as for source term 1 (Equation C61) describes the external radiation pathway.

The inhalation exposure pathway is described using the following equation:

$$D_{dust}(cover) = D_{dust}\,(no\ cover).TH_{cont}(t)/TH_{mix}\ ; \qquad TH_{mix}>TH_{cover}(t)+TH_{cont}(t)$$

$$D_{dust}(cover) = D_{dust}(no\ cover).(1\text{-}TH_{cover}(t)/TH_{mix}); \quad TH_{mix}>TH_{cover}(t),$$

$$_{over}(t)+TH_{cont}(t) \qquad \text{(C63)}$$

where

D_{dust} (no cover) = ASR.AF.OF.DF_{air}.S(0).SOF(t).
DF_{air} annual intake of air [m^3/y]
TH_{mix} depth of soil mixing layer [m]
DCF_{inh} meaning of the remaining symbols is the same as for Equation C61

The crop ingestion exposure pathway is described using the following equation:

root uptake — foliar dust deposition

$$D_{plants}=\{AF.FCD.DF_{plant}.B+FCD.DF_{plant}.AF.ASR.3,16.10^4.(v_{dep}.f_r.TRANS_{plant}.$$

$$.[1\text{-}exp(-\lambda_{weath}.\ t_{exp})]/(Y.\ \lambda_{weath})\}.S(0).SOF(t).DCF \qquad \text{(C64)}$$

The animal product ingestion exposure pathway is described using the following equation:

root uptake ← → foliar dust deposition

$$D_{meat/eggs} = \{AF.FCD.DF_{fodder}.B+FCD.\ DF_{fodder}.AF.ASR.3,16.10^{4}.(v_{dep}.f_{r}.0,1).$$

soil ingestion

$$.[1-exp(-\lambda_{weath}.t_{exp})]/(Y.\lambda_{weath})+AF.FCD.DFA_{soil}.B\}$$
$$TRANS_{meat}.DF_{meat}.\ .S(0).SOF(t).DCF \qquad (C65)$$

where

DF_{plant} leafy/root vegetable consumption rate [kg/y];
DF_{meat} meat/eggs consumption rate (chicken only) [kg/y];
DF_{fodder} fodder consumption rate [kg/y];
DFA_{soil} soil consumption rate (chicken) [kg/y]; and
FCD cover and depth factor.

For root uptake:

FCD = 0; $TH_{root}=0$ or $TH_{cover}(t) \geq TH_{root;}$

1- $TH_{over}(t)=0$, $TH_{cont}(t) \geq TH_{root;}$

$TH_{cont}(t)$ /TH_{root} ; $TH_{cover}(t)+ TH_{cont}(t) < TH_{root;}$

1- $TH_{cover}(t)/TH_{root}$; $TH_{cover}(t) < TH_{root}$; and

$TH_{cover}(t) + TH_{cont}(t) \geq TH_{root.}$

For foliar deposition and livestock soil intake

FCD = 1; $TH_{cover}=0$ or $TH_{cont}(t) \geq TH_{mix;}$

$TH_{cont}(t)$ /Th_{mix}; $TH_{cover}(t)+ TH_{cont}(t) < TH_{mix;}$

0; $TH_{cover}(t) \geq TH_{mix;}$

$TH_{cover}(t)/TH_{root}$; $TH_{cover}(t) < TH_{mix}$;

$TH_{cover}(t) + TH_{cont}(t) \geq TH_{mix;}$

OCF occupacy factor [–];

B food(fodder)/soil concentration ratio [–];

v_{dep} dust deposition velocity [m/y];

f_{r} fraction of deposited radionuclides retained on the vegetation [–];

λ_{weath} weathering removal constant [1/y];

t_{exp} time of exposure during the growing season [–];

Y yield [kg/m^2];

$TRANS_{plant}$ foliage to food transfer coefficient for root/leafy vegetable [–]; and

$TRANS_{meat}$ radionuclide trasnsfer factor for meat/eggs [y/kg];

The soil ingestion exposure pathway is described using the following equation:

$$D_{soil} = DF_{soil}.FCD.OCF.\ S(0).SOF(t).\ DCF_{ing} \quad (C66)$$

where

DF_{soil} soil consumption rate [kg/y] and meaning of the remaining symbols is the same as for Equations C64 and C65

C7.2. Little's Model

Little developed the following mathematical model for the human intrusion scenario and implemented it in the AMBER compartment model software application [QuantiSci and Quintessa, 2000].

Only one source term is considered – the excavated waste. It is assumed that the dose from external irradiation from the unexcavated waste will be small in comparison with that from the excavated waste. The concentration in the excavated waste is given by:

$$C_{Soil} = A.\ S_{house}\ .\ [(TH_{foundation} - TH_{cover})\ /V]\ /\ (S\ .\ TH_{soil}) \quad (C67)$$

where

C_{Soil} is the radionuclide concentration in the soil (Bq m^{-3});
A is the radionuclide inventory in the repository (Bq);
S_{house} is the area of the house (m^2);
$TH_{foundation}$ is the foundation depth (m); and
TH_{cover} is the cover depth (m), V is the total repository volume (m^3), S is the area used to grow crops (m^2), and TH_{soil} is the depth of soil (m).

The source term is reduced as a function of time due only to radioactive decay.

C7.2.1. Ingestion of animal products

The annual individual effective dose to a human from the consumption of animal produce (E_{Anm}, in Sv y^{-1}) is given by:

$$E_{Anm} = \chi_{Anm} Ing_{Anm} DC_{Ing} \quad (C68)$$

where:

χ_{Anm} is the radionuclide concentration in the animal product (Bq kg^{-1} fresh weight of product);
Ing_{Anm} is the individual consumption rate of the animal product (kg fresh weight of product y^{-1})
DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}).

For chicken products (meat and eggs), the χ_{Anm} term is calculated using:

$$\chi_{Anm} = CF_{Anm}\left(\chi_{Grain} Ing_{Grain} + \chi_{Wet}\ Ing_{ASoil}\right) \tag{C69}$$

where:

CF_{Anm} is the concentration factor for the animal product (d kg^{-1} fresh weight of product);
χ_{Grain} is the radionuclide concentration in the grain (Bq kg^{-1} fresh weight of grain)
Ing_{Grain} is the consumption rate of grain by the animal (kg fresh weight of grain d^{-1});
χ_{Wet} is the radionuclide concentration in the wet soil (Bq kg^{-1}); and
Ing_{Asoil} is the consumption rate of soil by the animal (kg wet weight of soil d^{-1}).

χ_{Grain} is given by:

$$\chi_{Grain} = (CF_{Grain} + s_{Grain})\chi_{Dry} \tag{C70}$$

where

CF_{Grain} is the concentration factor for grain (Bq kg^{-1} fresh weight of grain per Bq kg^{-1} dry \`weight of soil);
s_{Grain} is the soil contamination on grain (kg dry weight soil kg^{-1} fresh weight of grain); and
χ_{Dry} is the radionuclide concentration in the dry surface soil (Bq kg^{-1} dry weight soil).

χ_{Dry} (the radionuclide concentration in the dry surface soil (Bq kg^{-1} dry weight soil)) is given by:

$$E_{Crop} = \chi_{Crop} Ing_{Crop} DC_{Ing} \tag{C71}$$

where

χ_{Crop} is the radionuclide concentration in the crop (Bq kg^{-1} fresh weight of crop);
Ing_{Crop} is the individual ingestion rate of the crop (kg fresh weight y^{-1}); and
DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}).

The χ_{crop} term is calculated using:

$$\chi_{Crop} = (CF_{Crop} + s_{Crop})\chi_{Dry} \tag{C72}$$

where

CF_{crop} is the concentration factor for the crop (Bq kg^{-1} fresh weight of crop/Bq kg^{-1} (dry weight of soil));
s_{Crop} is the soil contamination on the crop (kg dry weight soil kg^{-1} fresh weight of crop); and
χ_{Dry} is the radionuclide concentration in the dry surface soil (Bq kg^{-1} dry weight soil) given by Equation C71.

C7.2.2. Inadvertent ingestion of soil

Soil can be inadvertently ingested by humans. The annual individual dose to a human from the ingestion of soil (E_{Sed}, in Sv y^{-1}) is given by:

$$E_{Sed} = \chi_{Wet}\ O_{Out}\ Ing_{Sed}\ DC_{Ing} \tag{C73}$$

where

χ_{Wet} is the radionuclide concentration in the soil (Bq kg^{-1} wet weight) (given by Equation C72);
O_{Out} is the individual occupancy on the contaminated soil (h y^{-1});
Ing_{Sed} is the individual inadvertent ingestion rate of soil (kg wet weight soil h^{-1});
DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}).

Inhalation of dust

The annual individual dose to a human from the inhalation of suspended soil (E_{Dust}, in Sv y^{-1}) is given by:

$$E_{Dust} = C_{Air}\ O_{Out}\ Inh_{Sed}\ DC_{Inh} \tag{C74}$$

where:

C_{Air} is the radionuclide concentration in the air above the soil (Bq m^{-3});
O_{Out} is the individual occupancy on the contaminated soil (h y^{-1});
Inh_{Sed} is the breathing rate of the human on the contaminated soil (m^3 h^{-1}); and
DC_{Inh} is the dose coefficient for inhalation (Sv Bq^{-1}).

C_{Air} is given by:

$$C_{Air} = \chi_{Dry}\ \frac{(R\ -1)}{R} c_{Dust} \tag{C75}$$

where

R is the retardation coefficient for surface soil compartment (–); and
c_{Dus} is the dust level in the air above the surface soil compartment (kg m^{-3}).

R is given by:

$$R = 1 + \frac{\rho_{Soil}\ (1-\vartheta_{Soil})\ Kd_{Soil}}{\vartheta_{wSoil}} \tag{C76}$$

where

ρ_{Soil} is the grain density of the soil (kg m^{-3});
θ_{Soil} is the total porosity (–) of the soil;
Kd_{Soil} is the sorption coefficient of the soil (m^3 kg^{-1}); and
ϑ_{wSoil} is the water filled porosity of the soil (–).

C7.2.3. External irradiation from soil

The annual individual dose to a human from external irradiation from soil (E_{ExSoil}, in Sv y^{-1}) is given by:

$$E_{ExSoil} = C_{Soil}\ O_{Out}\ DC_{Exts} \tag{C77}$$

where

C_{Soil} is the concentration in the soil (Bq m^{-3});
O_{Out} is the individual occupancy outdoors on the contaminated soil (h y^{-1}); and
DC_{Exts} is the dose coefficient for external irradiation from soil (Sv h^{-1}/Bq m^{-3}).

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APPENDIX D: DATA FOR MATHEMATICAL MODELS FOR THE VAULT TEST CASE

DESIGN SCENARIO: LIQUID RELEASE

D-1. NEAR FIELD DATA

The disposal facility is a set of 20 concrete vaults located above ground level (see Fig. 3.5 from the main text). The waste disposal area contains two sets of 10 vaults. The approximate dimensions of the disposal area are 170 m by 210 m giving a surface area of 35,700 m^2. There is a buffer zone in all directions of 200 m between the disposal area and the site perimeter fence.

150,000 m^3 of grouted waste is disposed in standard 200 litre drums (diameter of ~0.5 m and height ~1 m) and placed into concrete cubes, and grout filled in between the drums. The cubes are then stacked in the vaults. It is assumed waste drums represent 50% of the total repository volume, i.e. the concrete cubes and grout between the drums also occupy 150,000 m^3 and the total vault capacity is about 300,000 m^3. The facility has a total of about 750,000 drums (37,500 per vault).

It is assumed that the chemical and physical characteristics of the near field change with time are as follows:

- Near field effective and total porosity = 0.3 (consistent with [D4]);
- Near field water filled porosity = 0.2 (consistent with Vaalputs specific data);
- Near field bulk density = 1600 kg m^{-3} (consistent with [D4]);
- Near field hydraulic conductivity (non-degraded) = 3.15E-2 m y^{-1} (consistent with [D4]);
- Near field hydraulic conductivity (degraded at 500 years) = 3.15E+2 m y^{-1} (consistent with [D4]);
- Effective diffusion coefficients for the concrete and waste (non-degraded) = 1.0E-8 cm^2 s^{-1} (MS-DUST recommended value); and
- Effective diffusion coefficients for the concrete and waste (degraded) = 5.0E-6 cm^2 s^{-1} (MS-DUST recommended value).

At closure, a multiple layer cover is placed over the vaults. It is assumed that for the first 100 years the cover only allows 10% of the water infiltration through into the vaults, but thereafter it degrades so that by 500 years the cover does not limit water infiltration through into the vault. The water infiltration rate through the fully degraded cover is assumed to be 0.018 m y^{-1} (consistent with site specific soil percolation rates).

TABLE D 1. RADIONUCLIDE INVENTORY AT CLOSURE

Radionuclide	**Inventory disposed (Bq)**
^{3}H	1E+15
^{14}C	1E+13
^{59}Ni	2E+10
^{63}Ni	1E+15
^{90}Sr	1E+14
^{99}Tc	3E+10
^{129}I	6E+9
^{137}Cs	8E+15
^{234}U	5E+10
^{238}U	5E+10
^{238}Pu	2E+10
^{239}Pu	3E+10
^{241}Pu	6E+11
^{241}Am	2E+10

TABLE D 2. RADIONUCLIDES AND DECAY CHAINS CONSIDERED

Parent	**Daughters (1)**
^{3}H	
^{14}C	
^{59}Ni	
^{63}Ni	
^{90}Sr	
^{99}Tc	
^{129}I	
^{137}Cs	
^{234}U	$^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{210}Po$
^{238}U	$^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{210}Po$
^{238}Pu	$^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{210}Po$
^{239}Pu	$^{235}U \rightarrow {}^{231}Pa \rightarrow {}^{227}Ac$
^{241}Pu	$^{241}Am \rightarrow {}^{237}Np \rightarrow {}^{233}Pa \rightarrow {}^{233}U \rightarrow {}^{229}Th$
^{241}Am	$^{237}Np \rightarrow {}^{233}Pa \rightarrow {}^{233}U \rightarrow {}^{229}Th$

Note:

(1) Decay chains have been simplified to include only daughters with a half life greater than 25 days. The radiation effects of other, shorter lived, daughters have been included with those of the immediate parent, assuming secular equilibrium within each medium.

TABLE D 3. RADIONUCLIDE HALF LIVES AND DECAY CONSTANTS

Radionuclide	**Half Life (y) (1)**	**Decay Constant (y^{-1}) (2)**
^{3}H	1.24E+01	5.59E-02
^{14}C	5.73E+03	1.21E-04
^{59}Ni	7.54E+04	9.19E-06
^{63}Ni	9.60E+01	7.22E-03
^{90}Sr	2.91E+01	2.38E-02
^{99}Tc	2.13E+05	3.25E-06
^{129}I	1.57E+07	4.41E-08
^{137}Cs	3.00E+01	2.31E-02
^{210}Pb	2.23E+01	3.11E-02
^{210}Po	3.79E-01	1.83E+00
^{226}Ra	1.60E+03	4.33E-04
^{227}Ac	2.18E+01	3.18E-02
^{229}Th	7.34E+03	9.44E-05
^{230}Th	7.70E+04	9.00E-06
^{231}Pa	3.28E+04	2.11E-05
^{233}Pa	7.39E-02	9.38E+00
^{233}U	1.59E+05	4.36E-06
^{234}U	2.45E+05	2.83E-06
^{235}U	7.04E+08	9.85E-10
^{238}U	4.47E+09	1.55E-10
^{237}Np	2.14E+06	3.24E-07
^{238}Pu	8.77E+01	7.90E-03
^{239}Pu	2.41E+04	2.88E-05
^{241}Pu	1.44E+01	4.81E-02
^{241}Am	4.32E+02	1.60E-03

Notes:

(1) Half life data taken from [D1]

(2) Decay constant = $\frac{\ln 2}{half\ life}$

TABLE D4. NEAR FIELD DISTRIBUTION COEFFICIENTS ($m^3 kg^{-1}$)

Element	**Non-degraded Vault (1)**	**Degraded Vault (1)**
H	0E+0	0E+0
C	2E+0	2E-1
Ni	1E-1	1E-2
Sr	1E-3	1E-3
Tc	1E-3	0E+0
I	1E-2	1E-3
Cs	2E-2	2E-2
Pb	5E-1	5E-2
Po	0E+0	0E+0
Ra	5E-2	5E-2
Ac	1E+0	2E-1
Th	5E+0	1E+0
Pa	5E+0	1E-1
U	2E+0	1E-1
Np	5E+0	1E-1
Pu	5E+0	1E+0
Am	1E+0	2E-1

Note:

(1) Assumed to be applicable to the entire vault. Data taken from [D2].

D-2. FAR FIELD DATA

The unsaturated zone is made up of a sequence of lithologies, starting with the red sand/calcrete at the surface. Their characteristics are summarized in Tables D 5 and D 6.

TABLE D 5. CHARACTERISTICS OF UNSATURATED ZONE LITHOLOGIES AT VAALPUTS

Lithology	**Depth (m)**	**Hydraulic conductivity ($m\ y^{-1}$)**	**Bulk density ($kg\ m^{-3}$)**	**Total Porosity (-)**	**Water filled porosity (-)**	**Longitudinal dispersivity (m) (2)**
Red sand/ calcrete (1)	2.7	0.91	1989	0.33	0.2	0.27
Brown sand/ Gritty clay	8.5	2.37	2230	0.41	0.2	0.85
White kaolinite clay	8	1.86	2160	0.37	0.2	0.8
Weathered granite	35.8	2.37	1683	0.36	0.2	3.58

Notes:

(1) Includes the sand base to the disposal facility

(2) Calculated assuming that longitudinal dispersivity is 10% of the length of the flow path

TABLE D6. UNSATURATED ZONE DISTRIBUTION COEFFICIENTS ($m^3\ kg^{-1}$)

Element	**Red sand/ calcrete** (1)	**Brown sand/ gritty clay** (1)	**White kaolinite clay** (2)	**Weathered granite** (1)
H	0.0E+0	0.0E+0	0.0E+0	0.0E+0
C	5.0E-3	5.0E-3	1.0E-3	5.0E-3
Ni	4.0E-1	4.0E-1	6.0E-1	4.0E-1
Sr	8.8E-3 (3)	7.1E-3 (3)	8.3E-3 (3)	5.5E-3 (3)
Tc	1.0E-4	1.0E-4	1.0E-3	1.0E-4
I	1.0E-3	1.0E-3	1.0E-3	1.0E-3
Cs	5.4E-1 (3)	3.4E-1 (3)	2.2E-1 (3)	2.6E-1 (3)
Pb	3.0E-1	3.0E-1	5.0E-1	3.0E-1
Po	1.5E-1	1.5E-1	3.0E+0	1.5E-1
Ra	5.0E-1	5.0E-1	9.0E+0	5.0E-1
Ac	3.4E-1	3.4E-1	7.6E+0	3.4E-1
Th	3.0E+0	3.0E+0	6.0E+0	3.0E+0
Pa	3.4E-1	3.4E-1	7.6E+0	3.4E-1
U	2.5E-3 (3)	6.8E-3 (3)	1.4E-3 (3)	3.0E-3 (3)
Np	3.4E-1	3.4E-1	7.6E+0	3.4E-1
Pu	3.4E-1	3.4E-1	7.6E+0	3.4E-1
Am	3.4E-1	3.4E-1	7.6E+0	3.4E-1

Notes:

(1) Assumed to have the same characteristics as sand. Data taken from [D3] and [D4].

(2) Assumed to have the same characteristics as clay. Data taken from [D3] and [D4].

(3) Vaalputs specific data.

It is assumed that the series of fractures in the saturated zone that intercept the percolating water from the disposal facility can be represented by a single streamtube with the following characteristics:

— Effective and total porosity = 0.25 (representative value adopted to ensure physically realistic values);
— Bulk density = 2000 kg m^{-3} (representative value);
— Hydraulic conductivity = 1.8E+3 m y^{-1} (Vaalputs specific value);
— Hydraulic gradient = 1 in 10 (representative value for fracture gradient not regional gradient);
— Cross sectional area = 3 m^2 (representative value);
— Length = 300 m (representative value); and
— Longitudinal dispersivity = 30 m (assuming that longitudinal dispersivity is 10% of the length of the streamtube).

This streamtube yields 540 m^3 y^{-1} (1800*0.1*3). Based on site specific data, a yield of 8300 m^3 y^{-1} is assumed from the well. It is therefore assumed that the remaining 7760 m^3 y^{-1} is derived from other fractures that carry uncontaminated water.

TABLE D 7. SATURATED ZONE DISTRIBUTION COEFFICIENTS (m^3 kg^{-1})

Element	**Weathered granite** (1)
H	0.0E+0
C	5.0E-3
Ni	4.0E-1
Sr	5.5E-3 (2)
Tc	1.0E-4
I	1.0E-3
Cs	2.6E-1 (2)
Pb	3.0E-1
Po	1.5E-1
Ra	5.0E-1
Ac	3.4E-1
Th	3.0E+0
Pa	3.4E-1
U	3.0E-3 (2)
Np	3.4E-1
Pu	3.4E-1
Am	3.4E-1

Notes:

(1) Assumed to have the same characteristics as sand. Data taken from [D3], and [D4].

(2) Vaalputs specific data.

D-3. BIOSPHERE DATA

Where possible, data are site specific (i.e. from the Vaalputs site) or taken from another assessment of an arid site (Yucca Mountain in the USA). Otherwise the data are generic and taken from internationally recognized data collations.

Human behaviour:

- Breathing rate outdoor = 1.8 m^3 h^{-1} (value for high activity taken from EPRI report on Yucca Mountain PA [D7]);
- Time spent outdoors = 4380 h y^{-1} (assumes 50% of the time is spent outdoors, consistent with EPRI report on Yucca Mountain PA [D7]);
- Time spent bathing = 120 h y^{-1} (about 0.33 hours per day, consistent with EPRI report on Yucca Mountain PA [D7]);
- Consumption of drinking water = 0.8 m^3 y^{-1} (Vaalputs specific data);
- Consumption of beef = 180 kg y^{-1} (Vaalputs specific data);
- Consumption of cow milk = 255 kg y^{-1} (Vaalputs specific data); consumption of mutton = 140 kg y^{-1} (Vaalputs specific data);
- Consumption of eggs = 20 kg y^{-1} (Vaalputs specific data); and
- Inadvertent consumption of soil = 3 10^{-2} kg y^{-1} (representative value taken from EPRI report on Yucca Mountain PA [D7]).

Atmosphere:

- Inhalable dust outdoor = 2 10^{-6} kg m^{-3} (high dust loading factor, consistent with EPRI report on Yucca Mountain PA [D7]).

Well:

- Abstraction rate = 8300 m^3 y^{-1} (Vaalputs specific data).

Pasture:

- Total volume of water applied to pasture = 7.14E+3 m^3 y^{-1} (representative value, assuming an average irrigation rate of 0.07 m y^{-1} (10% of rate used in EPRI report on Yucca Mountain PA [D7] due to the limited well yield) over the area of soil used for sheep pasture);
- Interception factor = 0.3 (representative value, consistent with EPRI report on Yucca Mountain PA [D7]);
- Net volume of water applied to soil = 5.0E+3 m^3 y^{-1}(assumes 30% of total irrigation is intercepted by pasture and evapotranspired before reaching the soil);
- Yield of pasture = 1.0 kg.m^{-2} y^{-1} (wet weight) (representative value, consistent with EPRI report on Yucca Mountain PA [D7]); and
- Soil contamination of pasture = 8.0E-3 kg dw soil/kg fw pasture (representative value, consistent with EPRI report on Yucca Mountain PA [D7]).

Top soil:

- Area = 1.0E+5 m^2 (consistent with area required for growing pasture and arising sheep)
- Thickness = 0.3 m (representative value, consistent with EPRI report on Yucca Mountain PA [D7])
- Water percolation rate through soil = 0.018 m y^{-1}(Vaalputs specific data assuming that no extra infiltration occurs due to irrigation)

— Water filled porosity = 0.2 (Vaalputs specific data)
— Total porosity = 0.25 (Vaalputs specific data)
— Dry bulk density = 1989 $kg.m^{-3}$ (Vaalputs specific data)
— Erosion rate = 4.3E-4 $m\ y^{-1}$ (representative value, consistent with EPRI report on Yucca Mountain PA [D7])

Rainfall = 0.074 $m\ y^{-1}$(Vaalputs specific data)

Animal data taken from EPRI report on Yucca Mountain PA [D7] are given in Table D 8.

TABLE D 8. ANIMAL DATA

Animal	**Pasture ($kg\ fw\ d^{-1}$)**	**Soil (kg wet weight d^{-1})**	**Water ($m^3\ d^{-1}$)**	**Stocking Density (m^{-2})**
Cow	N/A	N/A	6E-2	N/A
Sheep	7E+0	8E-2	4E-3	4.8E-4
Chicken	N/A	N/A	5E-4	N/A

TABLE D 9. TOP SOIL DISTRIBUTION COEFFICIENTS ($m^3\ kg^{-1}$) (1)

Element	**Sandy Soil**
H	1.0E-4
C	1.0E-1
Ni	4.0E-1
Sr	1.3E-2
Tc	1.4E-4
I	1.0E-3
Cs	2.7E-1
Pb	2.7E-1
Po	1.5E-1
Ra	4.9E-1
Ac	4.5E-1
Th	3.0E+0
Pa	5.4E-1
U	3.3E-2
Np	4.1E-3
Pu	5.4E-1
Am	2.0E+0

Notes:

(1) Data compiled from [D5] and [D6].

TABLE D.10 TRANSFER COEFFICIENTS TO BEEF (days kg^{-1} fresh weight), MILK (days 1^{-1}), MUTTON (days kg^{-1} fresh weight), AND EGGS (days kg^{-1} fresh weight) (1)

Element	Beef	Cow Milk	Mutton	Eggs
H	2.9E-2	1.5E-2	4.1E-1	5.8E+0
C	1.2E-1	1.0E-2	1.7E+0	2.3E+1
Ni	5.0E-3	1.6E-2	1.2E-1	1.7E+0
Sr	8.0E-3	2.8E-3	4.0E-2	3.0E-1
Tc	1.0E-4	2.3E-5	8.6E-2	1.2E+0
I	4.0E-2	1.0E-2	6.0E-3	1.6E+0
Cs	5.0E-2	7.9E-3	3.0E-1	4.0E-1
Pb	4.0E-4	3.0E-4	8.8E-2	1.2E+0
Po	5.0E-3	3.4E-4	5.0E-2	1.2E+0 (2)
Ra	9.0E-4	1.3E-3	9.9E-2	2.5E-1
Ac	1.6E-4	4.0E-7	4.7E-4	1.6E-2
Th	2.7E-3	5.0E-6	1.3E-2	1.8E-1
Pa	5.0E-5	5.0E-6	3.4E-4	4.1E-3
U	3.0E-4	4.0E-4	7.4E-3	1.0E-1
Np	1.0E-3	5.0E-6	1.4E-4	1.7E-2
Pu	1.0E-5	1.1E-6	1.0E-3	8.0E-3
Am	4.0E-5	1.5E-6	2.0E-3	3.9E-3

Note:

(1) Data compiled from a range of compilations including [D8] and [D9].

(2) Data based on Pb as an analogue.

TABLE D 11. SOIL TO PLANT CONCENTRATION FACTORS (Bq kg^{-1} fresh weight/Bq kg^{-1} dry soil), WEATHERING RATES (y^{-1}) AND TRANSLOCATION FRACTION FOR PASTURE (1)

Element	**Concentration Factor**	**Weathering Rate**	**Translocation Fraction (2)**
H	5E+0	1.8E+1	2.3E-2
C	1E-1	1.8E+1	5.8E-1
Ni	2E-2	1.8E+1	3.7E-1
Sr	3E+0	1.8E+1	2.0E-1
Tc	1E+1	1.8E+1	2.8E-1
I	1E-1	1.8E+1	6.1E-1
Cs	3E-2	1.8E+1	1.9E-1
Pb	1E-2	1.8E+1	2.2E-1
Po	2E-4	1.8E+1	2.2E-1
Ra	4E-2	1.8E+1	1.8E-1
Ac	1E-3	1.8E+1	4.5E-1
Th	5E-4	1.8E+1	3.8E-2
Pa	4E-2	1.8E+1	4.5E-1
U	1E-3	1.8E+1	3.6E-1
Np	5E-3	1.8E+1	4.5E-1
Pu	1E-3	1.8E+1	3.6E-1
Am	5E-3	1.8E+1	2.8E-1

Note:

(1) Data compiled from a range of compilations including [D6], [D7] [D9], [D5] and [D10].

(2) In the absence of specific data, data values given are for green vegetables.

TABLE D 12. DOSE COEFFICIENTS FOR INGESTION, INHALATION AND EXTERNAL IRRADIATION

	Dose coefficients (adults) (1)			
Radionuclide	Ingestion (Sv Bq^{-1}) (2)	Inhalation (Sv Bq^{-1}) (2)	External irradiation from soil (Sv.h^{-1}.Bq^{-1}.m^{3}) (3)	External irradiation from water (Sv.h^{-1}.Bq^{-1}.m^{3}) (4)
^{3}H	1.8E-11	2.6E-10	0.0E+00	0.0E+00
^{14}C	5.8E-10	5.8E-09	2.6E-19	1.6E-18
^{59}Ni	6.3E-11	4.4E-10	0.0E+00	0.0E+00
^{63}Ni	1.5E-10	1.3E-09	0.0E+00	0.0E+00
^{90}Sr	3.1E-08	1.6E-07	4.7E-16	1.4E-15
^{99}Tc	6.4E-10	1.3E-08	2.4E-18	1.1E-17
^{129}I	1.1E-07	3.6E-08	2.5E-16	3.2E-15
^{137}Cs	1.3E-08	3.9E-08	6.6E-14	2.1E-13
^{210}Pb	6.9E-07	5.7E-06	1.2E-16	7.0E-16
^{210}Po	1.2E-06	4.3E-06	1.0E-18	3.3E-18
^{226}Ra	2.8E-07	9.5E-06	2.2E-13	6.9E-13
^{227}Ac	1.2E-06	5.7E-04	3.9E-14	1.5E-13
229Th	6.1E-07	2.6E-04	3.1E-14	1.2E-13
230Th	2.1E-07	1.0E-04	2.3E-17	1.4E-16
^{231}Pa	7.1E-07	1.4E-04	3.7E-15	1.4E-14
^{233}Pa	8.7E-10	3.9E-09	2.0E-14	7.4E-14
^{233}U	5.1E-08	9.6E-06	2.7E-17	1.3E-16
^{234}U	4.9E-08	9.4E-06	7.7E-18	6.3E-17
^{235}U	4.7E-08	8.5E-06	1.5E-14	6.2E-14
^{238}U	4.8E-08	8.0E-06	2.9E-15	1.1E-14
^{237}Np	1.1E-07	5.0E-05	1.5E-15	8.4E-15
^{238}Pu	2.3E-07	1.1E-04	2.9E-18	4.1E-17
^{239}Pu	2.5E-07	1.2E-04	5.7E-18	3.5E-17
^{241}Pu	4.8E-09	2.3E-06	3.6E-19	1.8E-18
^{241}Am	2.0E-07	9.6E-05	8.4E-16	6.8E-15

Notes:

(1) Values include effects of short lived daughters not explicitly listed, assuming secular equilibrium at time of intake or exposure.

(2) All data are taken from [D9].

(3) The external irradiation dose coefficient is for exposure to soil contaminated to an infinite depth. All data are taken from [D10].

(4) All data are taken from [D10].

DESIGN SCENARIO: GAS RELEASE

Data values required for the parameters in the gas release model developed by Little (section C2) are given below together with the source of the data.

The inventory of ^{3}H and ^{14}C is taken from Table D 1. ^{222}Rn is assumed to in-grow from the decay of ^{226}Ra which in turn in-grows from the ^{234}U, ^{238}U and ^{238}Pu chains. The inventory of ^{234}U, ^{238}U and ^{238}Pu is taken from Table D 1.

- Fraction of ^{3}H activity associated with the gas = 0.039 [-] [D11];
- Fraction of ^{14}C activity associated with the gas = 0.2 [-] [D11];
- Average timescale of generation of ^{3}H gas = 100 y (representative values consistent with [D14];
- Average timescale of generation of ^{14}C gas = 100 y (representative values consistent with [D14];
- Surface area of the repository = 35 700 m^2 (see section D1.1);
- Volume of repository = 321 300 m^3 (see section D1.1);
- Decay constant for ^{222}Rn = 66 y^{-1} (ICRP [D12]);
- Emanation factor, defined as the fraction of the radon atoms produced which escape from the solid phase of the soil into the pore spaces = 0.2 (consistent with [D13]);
- Effective diffusion relaxation length for the waste = 1 m (consistent with [D13]);
- The thickness of the cover = time dependent. Initial thickness of 2 m assumed with linear erosion rate from 100 years onwards resulting in removal of cover by 2985 years (consistent with the design scenario (Section 2.3.3 of the main text));
- The effective relaxation length of the cover = 1 m (assumed to be the same as the effective diffusion relaxation length for the waste, consistent with IAEA [D14]);
- The width of the source perpendicular to the wind direction = 170 m (assumed to equal the shorter width of the repository, section D1.1);
- The mean wind speed = 4 m s^{-1} (representative value, consistent with [D14])
- The height for vertical mixing = 2 m (approximate height of human);
- The surface area of the house = 150 m^2 (consistent with the human intrusion scenario (section D4));
- The volume of the house = 355 m^3 (consistent with the human intrusion scenario (sectionD4));
- Ventilation rate of the house = 8760 h^{-1} [D15];

- The time spent outdoors in the gas plume by human = 4380 h y^{-1} (consistent with the design scenario liquid release (section D1.3));

- The outdoor breathing rate of human = 1.8 m^3 h^{-1} (consistent with the design scenario liquid release (section D1.3));

- The time spent indoors by human = 7884 h y^{-1} (cautiously assumed to be 90% of time);

- The indoor breathing rate of human = 0.96 m^3 h^{-1} (representative value);

- The dose factor for inhalation of ^{3}H = 1.8E-13 Sv Bq^{-1} [D16];

- The dose factor for inhalation of ^{14}C = 6.2E-12 Sv Bq^{-1} [D16];

- The dose factor for inhalation of ^{222}Rn = 2.4E-9 Sv h^{-1} / Bq m^{-3} [D17].

DESIGN SCENARIO: SOLID RELEASE

Data values required for the parameters in the solid release model developed by Little (Appendix C3) are given below together with the source of the data. Where appropriate, these data are consistent with the data used for the liquid release model (Appendix D1.3). Indeed, the radionuclide inventory, decay chains, half lives/decay constants, and dose coefficients information (provided in Tables D 1, D 2, D 3, and D 12), are exactly the same and so are not reproduced here.

Human behaviour:

— Breathing rate outdoor = 1.8 m^3 h^{-1} (value for high activity taken from EPRI report on Yucca Mountain PA [D7]);
— Time spent outdoors on exposed waste = 2190 h y^{-1} (assumes 25% of the time is spent outdoors on exposed waste);
— Consumption of mutton = 140 kg y^{-1} (Vaalputs specific data);
— Consumption of chicken = 15 kg y^{-1} (consistent with Human Intrusion Scenario);
— Consumption of eggs = 20 kg y^{-1} (Vaalputs specific data);
— Consumption of leafy vegetables = 40 kg y^{-1} (consistent with Human Intrusion Scenario);
— Consumption of root vegetables = 80 kg y^{-1} (consistent with Human Intrusion Scenario);
— Consumption of chicken = 15 kg y^{-1} (consistent with Human Intrusion Scenario);
— Inadvertent consumption of soil = 3 10^{-2} kg y^{-1} (representative value taken from EPRI report on Yucca Mountain PA [D7]).

Atmosphere:

— Inhalable dust outdoor = 2 10^{-6} kg m^{-3} (high dust loading factor, consistent with EPRI report on Yucca Mountain PA [D7]).

Crop:

— Soil contamination of pasture = 8.0E-3 kg dw soil/kg fw pasture (representative value, consistent with EPRI report on Yucca Mountain PA [D7]);

— Soil contamination of grain = 9E-5 kg dw soil/kg fw grain [D6];
— Soil contamination of root vegetables = 1.5E-4 kg dw soil/kg fw root vegetables [D6];

— Soil contamination of leafy vegetables = 1E-4 kg dw soil/kg fw leafy vegetables [D6].

Topsoil:

— Area = 35 700 m^2 (area of exposed repository – see section D1.1);
— Thickness = 0.3 m (representative value, consistent with EPRI report on Yucca Mountain PA [D7]);
— Water filled porosity = 0.2 (Vaalputs specific data);
— Total porosity = 0.25 (Vaalputs specific data); dry bulk density = 1989 $kg.m^{-3}$ (Vaalputs specific data).

Animal data taken from EPRI report on Yucca Mountain PA [D7] are given in Table D 8.

TABLE D 13 ANIMAL DATA

Animal	**Fodder (kg fw d^{-1})**	**Soil (kg wet weight d^{-1})**
Sheep	7E+0	8E-2
Chicken	3E-1	2E-2

TABLE D 14 TOP SOIL DISTRIBUTION COEFFICIENTS (m^3 kg^{-1}) (1)

Element	**Sandy Soil**
H	1.0E-4
C	1.0E-1
Ni	4.0E-1
Sr	1.3E-2
Tc	1.4E-4
I	1.0E-3
Cs	2.7E-1
Pb	2.7E-1
Po	1.5E-1
Ra	4.9E-1
Ac	4.5E-1
Th	3.0E+0
Pa	5.4E-1
U	3.3E-2
Np	4.1E-3
Pu	5.4E-1
Am	2.0E+0

Note:

(1) Data compiled from [D6] and [D5].

TABLE D 15 TRANSFER COEFFICIENTS TO MUTTON, CHICKEN AND EGGS (days kg^{-1} fresh weight) (1)

Element	Mutton	Chicken	Eggs
H	4.1E-1	0	5.8E+0
C	1.7E+0	0	2.3E+1
Ni	1.2E-1	1.0E-3	1.7E+0
Sr	4.0E-2	8.0E-2	3.0E-1
Tc	8.6E-2	3.0E-2	1.2E+0
I	6.0E-3	1.0E-2	1.6E+0
Cs	3.0E-1	1.0E+1	4.0E-1
Pb	8.8E-2	1.2E+0	1.2E+0
Po	5.0E-2	1.2E+0 (2)	1.2E+0 (2)
Ra	9.9E-2	4.8E-1	2.5E-1
Ac	4.7E-4	6.6E-3	1.6E-2
Th	1.3E-2	1.8E-1	1.8E-1
Pa	3.4E-4	4.1E-3	4.1E-3
U	7.4E-3	1.0E+0	1.0E-1
Np	1.4E-4	1.7E-3	1.7E-2
Pu	1.0E-3	3.0E-3	8.0E-3
Am	2.0E-3	6.0E-3	3.9E-3

Note:

(1) Data compiled from a range of compilations including [D5] and [D6].

(2) Data based on Pb as an analogue.

TABLE D 16 SOIL TO PLANT CONCENTRATION FACTORS (Bq kg^{-1} fresh weight/Bq kg^{-1} dry soil) (1)

Element	Grain and Vegetables	Pasture
H	4.8E+0	5E+0
C	5.5E+0	1E-1
Ni	5.0E-2	2E-2
Sr	3.0E-1	3E+0
Tc	5.0E+0	1E+1
I	2.0E-2	1E-1
Cs	4.0E-2	3E-2
Pb	1.0E-2	1E-2
Po	2.0E-4	2E-4
Ra	4.0E-2	4E-2
Ac	2.5E-3	1E-3
Th	1.0E-3	5E-4
Pa	1.0E-2	4E-2
U	2.5E-3	1E-3
Np	2.0E-2	5E-3
Pu	1.0E-3	1E-3
Am	1.0E-3	5E-3

Note:

(1) Data compiled from a range of compilations including [D5], [D6], [D2] and [D10].

HUMAN INTRUSION SCENARIO

In addition to the general repository information given in section D1.1 and the radionuclide inventory, decay chains, half lives/decay constants, and dose coefficients information (provided in Tables D 1, D 2, D 3, and D 12), the following additional data (incl. [D4] and [D7]) were required for the mathematical models developed by participants.

D-4. DATA FOR LIETAVA'S MODEL

TABLE D 17 DATA FOR DOSE CALCULATIONS FOR SOURCE TERM 1

Parameter	Value	Unit	Reference
ASR - air/soil concentration ratio	2E-6	kg/m^3	1
AF - area factor	1	-	EJ (1)
DF_{air}- annual intake of air	1.8	m^3/h	1
$TH_{cont}(0)$ - initial thickness of contaminated zone	9	m	3
$TH_{cover}(0)$ - initial thickness of cover	2	m	EJ (1)
TH_{root} – root depth	0.3	m	2
$FCD = TH_{cont}(0) / TH_{root}$	30	-	-
ρ_{cont} - density of contaminated soil material	1600	kg/m^3	4
ρ_{cover} - density of cover material	1989	kg/m^3	3
k - empirical constant for the calculation of the depth factor	0.6E-1	m^2/kg	2
ER_{cont} - erosion rate of the contaminated zone	4.3E-4	m/y	1
ER_{cover} - erosion rate of the cover material	4.3E-4	m/y	1
Foundation depth	2.5	m	EJ (1)
t_{cover} - time for the cover removal by erosion	4650	y	EJ (1), 1
t_{in} – time spent indoors	2190	h/y	2
t_{out} – time spent outdoors	4380	h/y	1
t_{site} – time spent out of the site	2190	h/y	1, 2

Note:

(1) Expert judgement

The area factor (AF) for external gamma radiation represents the correction of radiation field from contaminated material to the area and shape of contaminated zone. For the purpose of human intrusion calculation it is assumed that the value of area factor is 1 [D18], because the dwelling is build approximately in the middle of the waste disposal area.

The thickness of contaminated zone corresponds to the internal height of the vaults – 9 m. The thickness of final cover is assumed to be 2 m and is made of material available nearby the site. Empirical constant for the calculation of depth factor is obtained from Table A.3 of [D18] and depends on bulk density of the contaminated material and the thickness of contaminated zone. The erosion rate of both cover and contaminated material in vaults is the same and is consistent with the erosion rate assumed for the design scenario liquid release calculations.

For the house build at the top of the cover it is assumed, that the foundations are at a depth of 2.5 m and so penetrate into the disposal area. Based on the thickness of the cover and the erosion rate the time for cover removal is about 4650 y.

TABLE D 18 DATA FOR INHALATION AND EXTERNAL IRRADIATION DOSE CALCULATIONS FOR SOURCE TERM 2

Parameter	Value	Unit	Reference
ASR - air/soil concentration ratio	2E-6	kg/m^3	1
AF - area factor	1	-	EJ (1)
DF_{air}- annual intake of air	1.8	m^3/h	1
$TH_{cont}(0)$ - initial thickness of contaminated zone	0.05	m	EJ (1)
TH_{mix} - depth of soil mixing layer	0.3	m	EJ (1)
TH_{root} – root depth	0.3	m	2
FCD $=TH_{cont}(0) / TH_{root}$	0.17	-	-
ρ_{cont} – densit=y of contaminated soil material	1600	kg/m^3	4
ρ_{cover} - density of cover material	1989	kg/m^3	3
ER_{cont} - erosion rate of the contaminated zone	4.7E-4	m/y	1
ER_{cover} - erosion rate of the cover material	4.7E-4	m/y	1
t_{out} – time spent outdoors	2190	h/y	2

Note:

(1) Expert judgement

Most data [D7, D18 and D20] in Table D 18 are identical with data for source term 1. By constructing a house at the top of the cover, some radioactive material will be excavated and after mixing with clean material it will be spread out in the vicinity of the house and used for the agricultural production. It is assumed, that:

- The area of the house is 150 m^2; and
- The depth of foundation is 2.5 m; i.e. it penetrates about 0.5 m into the vault.

The properties of contaminated site is calculated as follows:

— 4 people eat a total of 60 kg/y of chicken meat;
— Assuming each chicken produces 3 kg of meat, 20 chickens are required per year, add on another 10 chickens/hens for egg production, gives a total of 30 chickens/hens;
— Each chicken/hen eats 109.5 kg/y so 3285 kg of grain are required;
— 3285 kg of grain requires 8212.5 m^2 of land (assuming a yield of 0.4 kg/m^2);
— Including land for vegetable production, the total area for agricultural production of around 9000 m^2;
— The thickness of contaminated soil is about 0.05 m (calculated from the total amount of excavated soil and the area of garden); and
— The time spent at the contaminated soil by agricultural activities represents only the half of the total time spent outdoors.

It is assumed, that the losses of radioactive contaminants from excavated materials are due to the erosion and transport by infiltrating water. The site specific precipitation rate is 0.018 m/y. The garden is also irrigated by clean, uncontaminated water by the rate of 0.2 m/y. The runoff coefficient used for the calculation is 0.2 (default value of RESRAD code).

TABLE D 19 DATA FOR INGESTION DOSE CALCULATIONS FOR SOURCE TERM 2

Parameter	**Value**	**Unit**	**Reference**
DF_{plant} – leafy/root vegetable consumption rate	40/80	kg fw/y	3/3
DF_{meat} – meat/eggs consumption rate (chickens/hens)	15/20	kg fw/y	3/1
DF_{fodder} – fodder consumption rate (chickens/hens)	109.5	kg fw/y	3
DFA_{soil} - soil consumption rate (chickens/hens)	7.3	kg fw/y	3
v_{dep}- dust deposition velocity	0-0.001	m/y	2 (1)
$TRANS_{plant}$ – foliage to food transfer coefficient (leafy/root vegetable)	1/0.1	-	2
F_r – fraction of deposited radionuclides retained on the vegetation	0.25	-	2
λ_{weath} – weathering removal constant	20	1/y	2
t_{exp} – time of exposure during the growing season (leafy/root vegetable)	0.25/0.17	y	2
Y - yield (leafy/root vegetable)	1.5/0.7	kg/m^2	2
DF_{soil} - soil consumption rate	0.03	kg/y	3

Note:

(1) 0 m/s for H, C, Ar,Kr; 0.01 m/s for F, Br, I, Cl and 0.001 m/s for all remaining elements [D20]

TABLE D 20 ELEMENT SPECIFIC INPUT DATA

Element	B (1), (2) (-)	K_d top soil (cm^3/g)	K_d unsat. (cm^3/g)	K_d satur. (cm^3/g)	$TRANS_{leafy}$ (-)	$TRANS_{root}$ (-)	$TRANS_{meat}$ (d/kg)	$TRANS_{egg}$ (d/kg)
H	4.8	0.1	0	0	2.3E-2	4.8E+0	N/A	5.8E+0
C	5.5	100	5	5	5.8E-1	5.5E+0	0	2.3E+1
Ni	5E-2	400	400	400	3.7E-1	5.0E-2	1.0E-3	1.7E+0
Sr	0.3	13	8.8	5.5	2.0E-1	3.0E-1	8.0E-2	3.0E-1
Tc	5	0.14	0.1	0.1	2.8E-1	5.0E+0	3.0E-2	1.2E+0
I	2E-2	1	1	1	6.1E-1	2.0E-2	1.0E-2	1.6E+0
Cs	4E-2	270	540	260	1.9E-1	4.0E-2	1.0E+1	4.0E-1
Pb	1E-2	270	300	300	2.2E-1	1.0E-2	1.2E+0	1.2E+0
Ra	4E-2	490	500	500	1.8E-1	4.0E-2	4.8E-1	2.5E-1
Ac	2.5E-3	450	340	340	4.5E-1	2.5E-3	6.6E-3	1.6E-2
Th	1E-3	3000	3000	3000	3.8E-2	1.0E-3	1.8E-1	1.8E-1
Pa	1E-2	540	340	340	4.5E-1	1.0E-2	4.1E-3	4.1E-3
U	2.5E-3	33	2.5	3	3.6E-1	2.5E-3	1.0E+0	1.0E-1
Np	2E-2	4.1	340	340	4.5E-1	2.0E-2	1.7E-3	1.7E-2
Pu	1E-3	540	340	340	3.6E-1	1.0E-3	3.0E-3	8.0E-3
Am	1E-3	2000	340	340	2.8E-1	1.0E-3	6.0E-3	3.9E-3
References	7	5	5	5	1-4	1	1, 6	1, 2

Notes:

(1) RESRAD default values

(2) It is assumed, that the same food/soil concentration ratios can be used for root, leafy vegetables and grain

D-5. DATA FOR LITTLE'S MODEL

Appropriate data values specified by Peter Lietava (section D4.1) were used for the parameters in Little's mathematical model (section C4.2). The only addition data required related to soil contamination on the crops. Consistent with Ashton and Sumerling [D6], the following values were assumed for the soil contamination on the crops (kg dry weight soil kg^{-1} fresh weight of crop): 9E-5 (grain); 1E-4 (leafy vegetables); and 1.5E-4 (root vegetables). It is assumed that the soil to plant concentration factor for grain and leafy vegetables is the same as for root vegetables.

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APPENDIX E: DATA USED FOR RADON TEST CASE: SECOND ITERATION

E-1. RADIONUCLIDE DATA

TABLE E.1. RADIONUCLIDE HALF-LIVES AND DECAY CONSTANTS

Radionuclide	Half-life (y)	Decay Constant (y^{-1})
H-3	1.24E+01	5.59E-02
C-14	5.73E+03	1.21E-04
Cl-36	3.01E+05	2.30E-06
Co-60	5.27E+00	1.32E-01
Se-75	3.28E-01	2.11E+00
Sr-90	2.91E+01	2.38E-02
Cs-137	3.00E+01	2.31E-02
Eu-152	1.33E+01	5.20E-02
Tm-170	3.52E-01	1.97E+00
Ir-192	2.03E-01	3.42E+00
Po-210	3.79E-01	1.83E+00
Ra-226	1.60E+03	4.33E-04
Th-232	1.41E+10	4.92E-11
Pu-239	2.41E+04	2.88E-05

TABLE E.2. DECAY PRODUCTS, THEIR HALF-LIVES AND DECAY CONSTANTS

Radionuclide	Half Life (y)	Decay Constant (y^{-1})
Eu-152		
Gd-152	1.08E+14*	6.42E-15*
Ra-226		
Rn-222	1.05E-02	6.60E+01
Pb-210	2.23E+01	3.11E-02
Po-210	3.79E-01	1.83E+00
Th-232		
Ra-228	5.75E+00	1.21E-01
Th-228	1.91E+00	3.63E-01
Pu-239		
U-235	7.04E+08	9.85E-10
Pa-231	3.28E+04	2.12E-05
Ac-227	2.18E+01	3.18E-02

* In this assessment it is assumed as a stable element.

All data for tables 11.1 –11.2 are taken from [E1].

All short lived daughters with a half-life less than 30 days (except for ^{222}Rn) are assumed to be in secular equilibrium with their parents.

E-2. GENERAL DATA

Infiltration – 0.12 m/y (33% of the average precipitation amount);
Saturated zone hydraulic conductivity - 0.8*365 m/y;
Hydraulic gradient – 1/100 (-);
Effective porosity in the groundwater – 0.4;

Moisture content in an unsaturated zone – 0.2;
Longitudinal dispersivity in the groundwater - 0.32*L_total^0.83 [E2];

Transverse dispersivity in the groundwater – 0.1*Longitudinal dispersivity [E2].

Bulk density:

— Unsaturated zone - 1910 kg/m^3;
— Vault, packed clay, soil – 2000 kg/m^3.

The distance to outlet:

— Design Scenario – 2000 m;
— Aquifer Contamination – 500 m;
— River flow rate – 10^6 m^3/y [E3];
— Erosion rate - 2.10^{-4} m/y [E3].

TABLE E.3. COMPARTMENT DIMENSIONS

Compartment	**Length**	**Width**	**Depth**
Vault A (B)	16.25	5.5	3.5
Vault AB	16.25*2+1	5.5	3.5
Vault C	16.25*2	5.5*3	3.5
PackedClay, UnsatZone			
(for AB case)	16.25*2+1	5.5	
(for C case)	16.25*2	5.5*3	
PackedClay			0.5
UnsatZone			
Design Scenario			7
Alternative Scenarios			70
GroundWater			
Design Scenario	L_total/12	((5.5)^2+24*0.1*Dispersivity*L_total/12*Comp.Number)^0.5	3
Aquifer Contamination	L_total/9	((5.5)^2+24*0.1*Dispersivity*L_total/9*Comp.Number)^0.5	13
RiverWater	1000	2	2
SoilComp	1	1	0.3
SinkComp	1	1	1

TABLE E.4. DISPOSAL FACILITY AND GEOSPHERE DISTRIBUTION COEFFICIENTS

	Distribution coefficients, m^3/kg [E3-E6]					
Nuclide	**Vault**	**Packed clay**	**Unsaturated zone**	**Groundwater**	**River water**	**Soil**
H-3	0	0	0	0	3.00E-05	1.00E-04
C-14	2	0.001	0.005	0.005	0.1	0.1
Cl-36	0	1.00E-03*	3.00E-05	3.00E-05	5.00E-03*	1.40E-04*
Co-60	0.1	0.5	0.015	0.015	5	0.06
Sr-90	0.005	0.1	0.015	0.015	1	0.013
Cs-137	0.001	2	0.3	0.3	1	0.27
Eu-152	2**	0.092**	1	1	5**	0.24**
Pb-210	2	0.5	0.3	0.3	10	0.27
Po-210	2	3	0.15	0.15	10	0.15
Rn-222	0	0	0	0	0	0
Ra-226	0.2	9	0.5	0.5	0.5	0.49
Ac-227	2	7.6	0.34	0.34	10	0.45
Ra-228	0.2	9	0.5	0.5	0.5	0.49
Th-228	2	6	3	3	10	3
Pa-231	2	7.6	0.34	0.34	5	0.54
Th-232	2	6	3	3	10	3
U-235	2	0.046	0.56	0.56	0.05	0.033
Pu-239	2	7.6	0.34	0.34	100	0.54

*Assumed value the same as for Tc [E4]

**Sm used as an analogue

TABLE E.5. TRANSFER COEFFICIENTS FOR COW PRODUCTS (MEAT AND MILK) IN D/KG (MEAT) AND D/L (MILK) [E3, E4]

Element	**Meat**	**Milk**
H	2.9E-2	1.5E-2
C	1.2E-1	1.0E-2
Cl	2.0E-2	1.7E-2
Co	1.0E-2	3.0E-4
Sr	8.0E-3	2.8E-3
Cs	5.0E-2	7.9E-3
Eu	4.7E-4	2.0E-5
Ra	9.0E-4	1.3E-3
Pu	1.0E-5	1.1E-6
Th	2.7E-3	5.0E-6
Pb	4.0E-4	3.0E-4
U	3.0E-4	4.0E-4
Pa	5.0E-5	5.0E-6
Ac	1.6E-4	4.0E-7
Po	5.0E-3	3.4E-4

TABLE E.6. CONCENTRATION FACTORS FOR ALL CROPS (INC. PASTURE ETC.) AND CONTAMINANTS (IN BQ/KG WET (FRESH) WEIGHT OF CROP PER BQ/KG DRY WEIGHT OF SOIL) [E3, E4]

Nuclide	Grain	Green	Root	Pasture
H	5.0E+00	5.0E+00	5.0E+00	5.0E+00
C	1.0E-01	1.0E-01	1.0E-01	1.0E-01
Cl	5.0E+00	5.0E+00	5.0E+00	5.0E+00
Co	3.0E-02	3.0E-02	3.0E-02	6.0E-03
Sr	8.0E-02	3.0E+00	9.0E-02	3.0E+00
Cs	2.0E-02	3.0E-02	3.0E-02	3.0E-02
Eu	1.0E-03	1.0E-03	1.8E-03	1.0E-02
Pb	1.0E-02	1.0E-02	1.0E-02	1.0E-02
Po	2.0E-04	2.0E-04	2.0E-04	2.0E-04
Ra	4.0E-02	4.0E-02	4.0E-02	4.0E-02
Ac	1.0E-03	1.0E-03	1.0E-03	1.0E-03
Th	5.0E-04	5.0E-04	5.0E-04	5.0E-04
Pa	4.0E-02	4.0E-02	4.0E-02	4.0E-02
U	1.0E-04	1.0E-03	1.0E-03	1.0E-03
Pu	3.0E-05	1.0E-04	1.0E-03	1.0E-03

TABLE E.7. CONCENTRATION RATIOS (M^3 KG^{-1}) FOR FRESHWATER FISH [E3], FOR CL, EU [E4]

Element	Concentration Ratio
H	1E-3
C	5E+1
Cl	5E-2
Co	3E-1
Sr	6E-2
Cs	2E+0
Eu	3E-2
Pb	3E-1
Po	5E-2
Ra	5E-2
Ac	3E-2
Th	1E-1
Pa	1E-2
U	1E-2
Pu	3E-2

TABLE E.8. DOSE COEFFICIENTS FOR INGESTION, INHALATION AND EXTERNAL IRRADIATION [E3]

Radionuclide	**Ingestion**	**Inhalation**	**External irradiation from soil [E7]**	**External irradiation from immersion in water [E8]**
	(Sv Bq^{-1})	(Sv Bq^{-1})	(Sv.h^{-1}.Bq^{-1}.kg)	(Sv h^{-1} /Bq m^{-3})
^{3}H	1.8E-11	2.6E-10	0	0
^{14}C	5.8E-10	5.8E-09	0	1.6E-18
^{36}Cl	9.3E-10	7.3E-09	7.5E-14	1.6E-16
^{60}Co	3.5E-09	3.1E-08	5.5E-10	9.9E-13
^{90}Sr	3.1E-08	1.6E-07	2.1E-12	1.4E-15
^{137}Cs	1.3E-08	3.9E-08	1.2E-10	2.1E-13
^{152}Eu	1.4E-09	4.2E-08	3.0E-10	4.4E-13
^{210}Pb	6.9E-07	5.7E-06	2.5E-13	7.0E-16
^{210}Po	1.2E-06	4.3E-06	1.9E-15	3.3E-18
^{226}Ra	2.8E-07	9.5E-06	5.7E-10	6.9E-13
^{228}Ra	6.9E-07	1.6E-05	1.6E-10	3.7E-13
^{227}Ac	1.2E-06	5.7E-04	6.0E-11	1.5E-13
^{228}Th	1.4E-07	4.4E-05	3.2E-10	6.3E-13
^{232}Th	2.3E-07	1.1E-04	9.4E-15	1.4E-16
^{231}Pa	7.1E-07	1.4E-04	6.1E-12	1.4E-14
^{235}U	4.7E-08	8.5E-06	1.9E-11	6.2E-14
^{239}Pu	2.5E-07	1.2E-04	4.6E-15	3.5E-17

TABLE E.9. COEFFICIENTS FOR TRANSFER OF RADIONUCLIDES FROM EXTERNAL SURFACES BY WEATHERING (Y^{-1}) [E4]

Crop	**Coefficients for transfer**	**Element**
Grain	51 8.4	Pu All other elements
Green vegetables	51 18	Pu All other elements
Root vegetables	18	All elements
Pasture	18	All elements

TABLE E.10. FRACTION OF ACTIVITY TRANSFERRED FROM EXTERNAL TO INTERNAL PLANT SURFACES (-) [E9]

Nuclide	Translocation factor for crop			Pasture
	Grain	Green	Root	
H	0.01	0.023	0.02	0.023
C	0.16	0.58	0.4	0.58
Cl	0.088	0.19	0.19	0.19
Co	0.08	0.18	0.17	0.18
Sr	0.12	0.2	0.14	0.2
Cs	0.088	0.19	0.3	0.19
Eu	0.13	0.28	0.29	0.28
Pb	0.1	0.22	0.22	0.22
Po	0.1	0.22	0.22	0.22
Ra	0.08	0.18	0.099	0.18
Ac	0.2	0.45	0.29	0.45
Th	0.13	0.038	0.29	0.038
Pa	0.2	0.45	0.29	0.45
U	0.16	0.36	0.043	0.36
Pu	0.16	0.36	0.043	0.36

E-3. HUMAN EXPOSURE DATA

Data taken from [E3] unless stated otherwise.

Design scenario, aquifer contamination scenario

Human behaviour:

— Average adult breathing rate = 1 $m^3.h^{-1}$;
— Drinking water consumption = 0.73 $m^3.y^{-1}$;
— Consumption of freshwater fish 2 $kg.y^{-1}$;
— Consumption of grain = 148 $kg.y^{-1}$;
— Consumption of root vegetables = 235 $kg.y^{-1}$;
— Consumption of green vegetables = 62 $kg.y^{-1}$;
— Consumption of cow milk = 330 $kg.y^{-1}$;
— Consumption of cow meat = 95 $kg.y^{-1}$;
— Inadvertent consumption of soil = 3 10^{-2} kg. y^{-1};
— Airborne dust loading during occupational activities = 10^{-6} $kg.m^{-3}$;
— Occupancy factor for high airborne dust concentrations = 0.034 $y.y^{-1}$;
— Occupancy time in the water = 300 $h.y^{-1}$ [E10].

Plants:

— Irrigation rate per crop 300 mm;
— Root zone thickness = 0.30 m;
— Interception factor = 0.33;
— Soil contamination on crops = 0.002 kg dry weight soil/kg wet weight crop;
— Yield of grain = 0.4 $kg.m^{-2}$ (wet weight);
— Yield of root vegetables = 3.5 $kg.m^{-2}$ (wet weight);
— Yield of green vegetables = 3 $kg.m^{-2}$ (wet weight);

— Yield of pasture = 1.7 kg.m^{-2} (wet weight).

Cattle:

— Daily water consumption = 0.06 m^{3}.day$^{-1;}$
— Daily soil consumption = 0.6 kg.day^{-1};
— Daily pasture intake (wet) = 55 kg.day^{-1};
— Average body weight = 500 kg;
— Average milk production = 5500 kg.y$^{-1;}$
— Cattle density on agricultural land = 100 animals.km^{-2}.

Atmosphere:

— Inhalable dust loading under normal residential conditions = 2.10^{-8} kg.m^{-3}.

Farming scenario

Dilution factor of the radioactive waste in the non-radioactive materials is 0.3. With regard the external exposure, a shielding factor of 0.1 for indoor activities is introduced.

Human behaviour:

— Breathing rate indoor = 0.75 m^{3}.h^{-1};
— Breathing rate outdoor = 1 m^{3}.h^{-1};
— Time spent indoor = 6575 h y$^{-1;}$
— Time spent outdoor = 2192 h y$^{-1;}$
— Consumption of root vegetables = 118 kg.y^{-1};
— Consumption of green vegetables = 31 kg.y^{-1};
— Inadvertent consumption of soil = 3 10^{-2} kg.y$^{-1;}$
— No irrigation of crops or consumption of contaminated water by humans and animals.

Atmosphere:

— Inhalable dust indoor = 1 10^{-8} kg.m^{-3};
— Inhalable dust outdoor = 2 10^{-8} kg.m^{-3}.

Excavation scenario

A road is supposed to be constructed through the facility.

Work speed:

— Average speed = 10 km in 6 months (20 km per year);
— Maximum distance to cross the facility = 33.5 m;
— Exposure duration: 14.7 h (33.5 m of radioactive material require 0.0017 y = 14.7 h at the average speed defined above).

- Breathing rate = 1.2 m^{3} h$^{-1;}$
- Inadvertent consumption of soil rate = 3.4 10^{-5} kg h$^{-1;}$

- Dut level: 1 mg.m^{-3} available for inhalation;
- N shielding with respect to external exposure;

- Dilution factor = 0.3;
- Minimum time before the construction of a road through the vault system = 300 y.

Dose due to radon and its daughters

Human behaviour:

— Breathing rate = 0.75 $m^3.h^{-1}$;
— Time spent indoor = 6575 h y^{-1}.

Building features:

— Ratio of surface : volume = 0.2 m^{-1};
— Air removal rate = 8741 y^{-1}.

Disposal features:

— Vault emanation factor = 0.03 [–];
— Vault cover thickness = 1.5 m.

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APPENDIX F: DESCRIPTION OF THE GOLDSIM'S MODEL USED FOR THE BOREHOLE TEST CASE FARMER SCENARIO

The opening screen of the GoldSim model is shown in Fig. F.1; while the model components are shown in Fig. F.2.

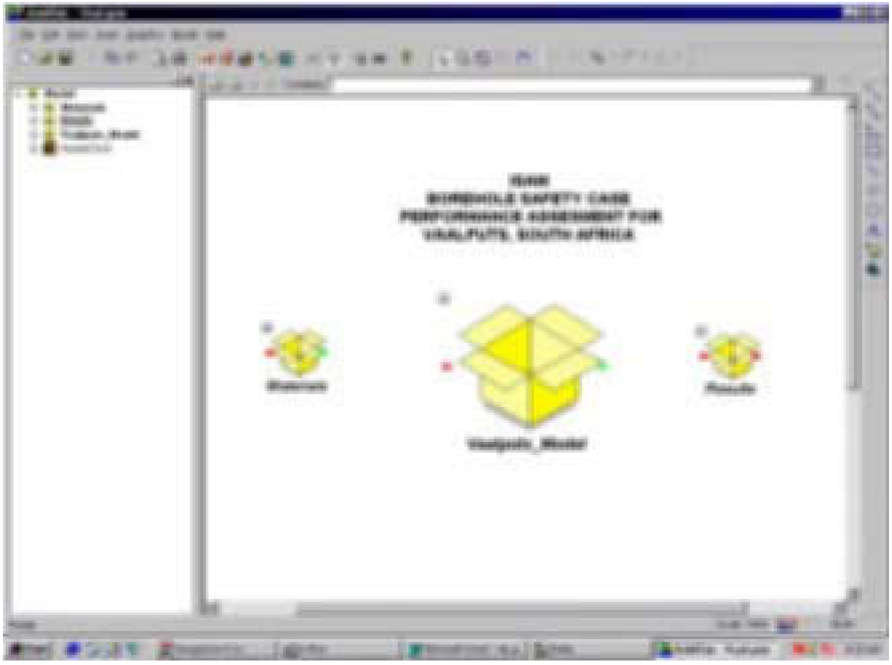

FIG. F.1. GoldSim Opening Screen for the Borehole Test Case Farming Scenario.

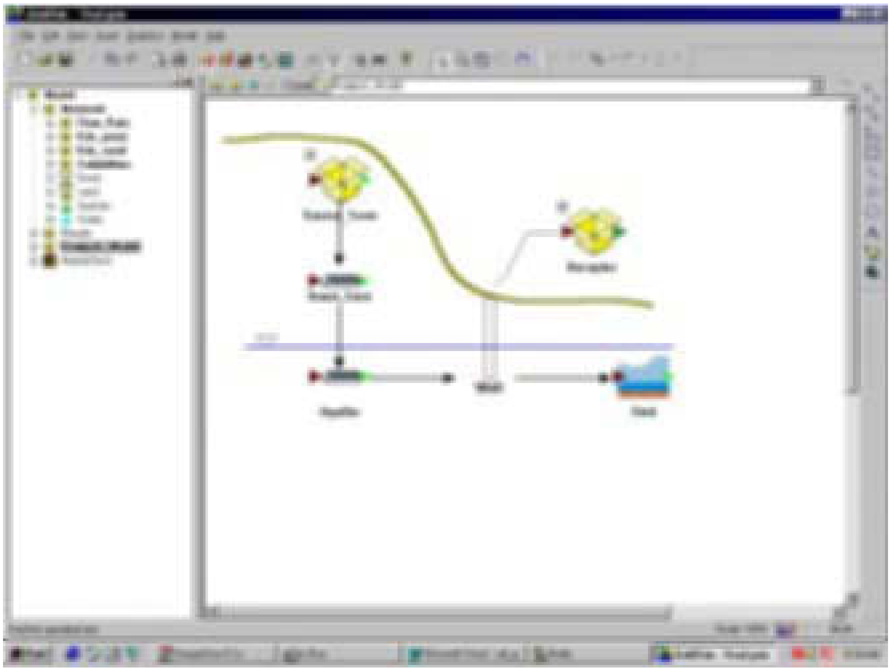

FIG. F.2. Model Components for the Borehole Test Case Farming Scenario.

F-1. SOURCE TERM

The Source element of the Transport Module is used to simulate the release of radionuclides from the borehole. The initial radionuclide inventory for the assessment is defined by specifying the name and atomic weight and half-life of each radionuclide, as well as its daughter products. Source simulates radionuclide decay and generation of daughter products by considering the parent-daughter relationship for each radionuclide. The inventory is discretised into user-specified number of packages or containers. Container degradation is modelled by defining failure distributions for single or double barriers or no barriers, and associated duration during which degradation is expected to occur. Waste-form degradation - an option for inventories that may be encapsulated in a matrix - can also be modelled by specifying a matrix degradation rate. Once the mass is exposed to infiltrating water, radionuclides are dissolved into the soil water (constrained by radionuclide-specific solubility and adsorption) and released to environmental media through advection and/or diffusion. GoldSim simulates these processes by associating a Cell pathway with the Source. The properties of the Cell associated with the Source include the volume and mass of the media, the flow rate if releases are through advection, and the diffusive area for diffusive mass flux to or from other elements. Figure F.3 shows a GoldSim screen including elements for material properties, while Fig. F.4 shows the elements describing the source.

FIG. F.3. Assigning Material Properties in GoldSim for the Borehole Test Case Farmer Scenario.

F-2. GEOSPHERE TRANSPORT

Environmental media such as unsaturated soils, aquifers, lakes, sediments, and atmosphere can be represented in GoldSim by Cell and Pipe pathways. A network of Cell pathways, which is mathematically equivalent to a finite difference network of nodes, can simulate a three dimensional geosphere transport problem. GoldSim solves the advective-dispersive transport equation for the network of pathways representing the physical domain and computes the mass transfers as a function of time. The Cell pathway can move fluids and solids by specifying the properties and the processes that control the mass movement: flow rates for advective transport and diffusion coefficients and geometric factors for diffusive transport must be specified. The Cell pathway allows for partitioning of species among multiple fluid and solid media that are specified for the Cell, as well as setting solubility limits for the species. Pipe pathway represents a stream tube whose geometry is defined by specifying a length, cross-sectional area, and perimeter. It can transport a single fluid only. GoldSim's Pipe pathway can solve a wide range of advectively dominated transport problems using Laplace transforms, including one-dimensional advection, longitudinal dispersion, retardation, decay, ingrowth, and matrix diffusion. One-dimensional unsaturated and saturated zone transport can be readily simulated by Pipe pathways.

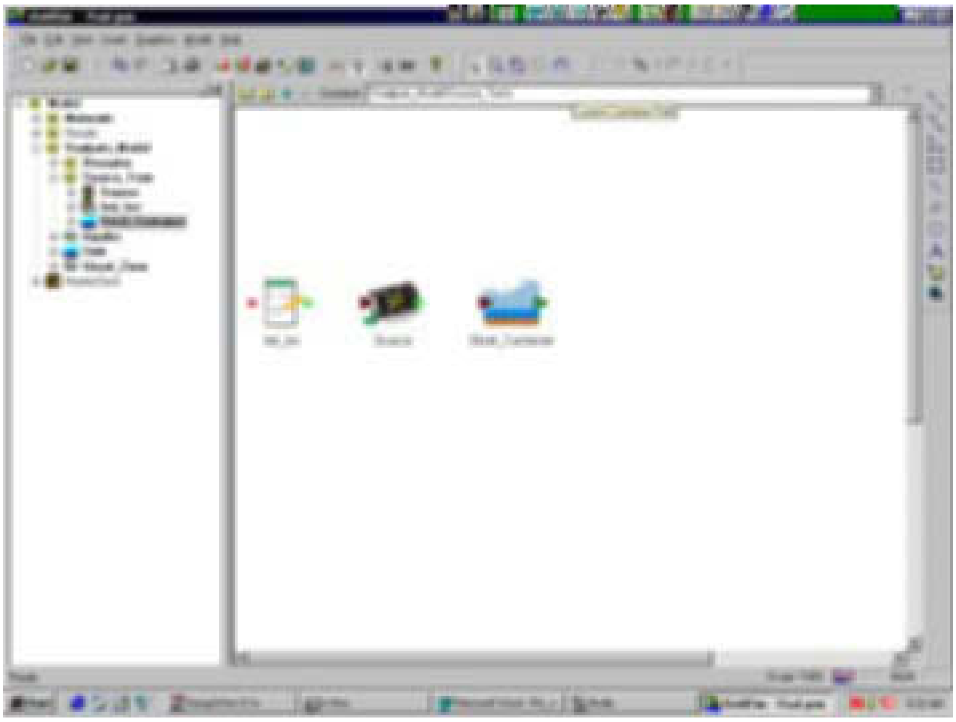

FIG. F.4. Describing the Source Term in GoldSim Elements for the Borehole Test Case Farmer Scenario.

The model for the Borehole Test Case represented the unsaturated zone and the aquifer using a Pipe pathway for each.

F-3. DOSE ASSESSMENT

The receptor (member of the potential exposure group) is assumed to be an adult who resides by the Borehole Disposal site and pumps water from the aquifer. The total effective dose equivalent (TEDE) to the receptor is calculated considering various exposures routes (ingestion of water, meat, and eggs) using GoldSim's large array of mathematical functions.

The TEDE for the scenario is computed by summing the product of the scenario dose conversion factor (SDCF) and the radionuclide concentration in water for all the radionuclides. The SDCF is the sum of the three pathways dose conversion factors (PDCF) - drinking water, mutton ingestion, and poultry ingestion including eggs. The PDCF for drinking water is calculated multiplying the receptor's drinking water intake rate by the dose conversion factor (DCF). The PDCF for mutton consumption is calculated as a product of four factors: the DCF, a transfer factor, the water intake rate by sheep, and the mutton ingestion rate by the potential exposure group member. The PDCF for poultry consumption is calculated as the sum of the PDCFs for poultry and eggs. Each is computed as the product of four factors: the dose conversion factor, water intake rate by poultry, transfer factor for poultry or eggs, and the poultry or egg ingestion rate by the receptor. Various GoldSim elements used in the dose assessment are shown in the screenshot in Fig. F.5: a data element containing the DCFs; GoldSim containers for transfer factors and ingestion rates, and function elements used to calculate the PDCFs. The SDCF is obtained by summing the PDCFs using the summation function sigma shown in Fig. F.5.

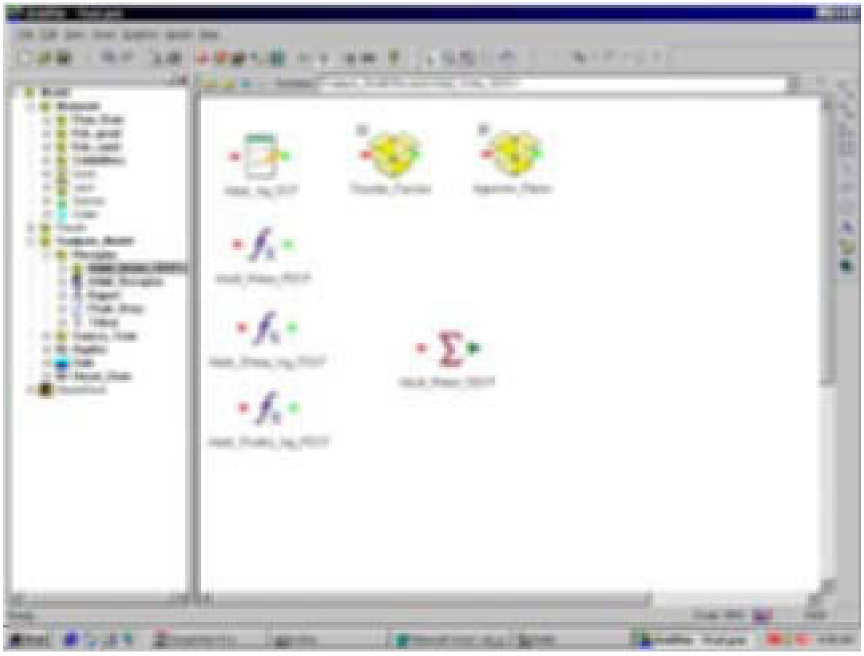

FIG. F.5. GoldSim Elements for Dose Calculations for the Borehole Test Case Farmer Scenario.

F-4. PROBABILISTIC APPROACH TO MODELLING

Figures F.6 to F.8 show stochastic elements describing the dose assessment parameters as probability distributions. The probabilistic approach to assessment modelling explicitly considers the uncertainty in features, events, and processes. Since inputs to an assessment of a disposal system are generally uncertain, any prediction of future performance of the system based on uncertain inputs will be uncertain. GoldSim provides the capability to address uncertainty explicitly: by specifying model input parameters as probability distributions, parameter uncertainty is directly incorporated into the simulations, yielding probability distributions of model outputs. Furthermore, consequences of disruptive events whose time of occurrence and magnitude are uncertain can also be simulated. GoldSim provides several options of discrete or continuous probability distributions. GoldSim uses Monte Carlo simulation framework for propagating uncertainty through the system to the predicted performance. In a Monte Carlo simulation, the system simulations are repeated for a large number of times: each simulation uses a different set of input parameters that are sampled randomly from their respective probability distributions. Each simulation is an equally likely realisation of the system. The results of these realisations are then assembled into probability distributions of outcomes. For the Borehole Test Case, the scenario TEDE is derived as a probability distribution. The expected value of the TEDE distribution (mean or median) can then be compared against the regulatory dose constraint to show compliance.

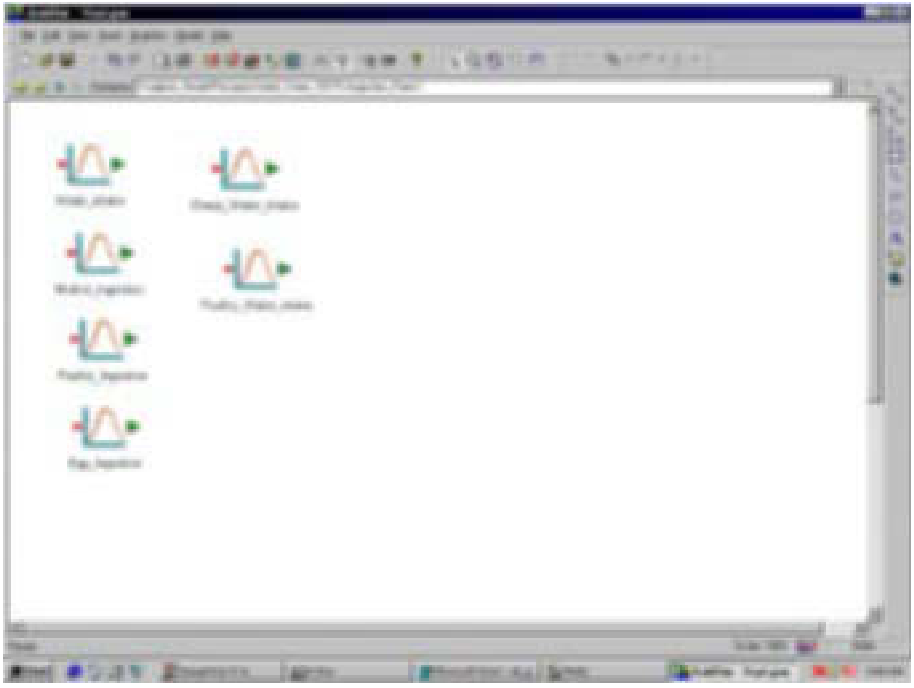

FIG. F.6. Stochastic GoldSim Elements for Intake Rates for the Borehole Test Case Farmer Scenario.

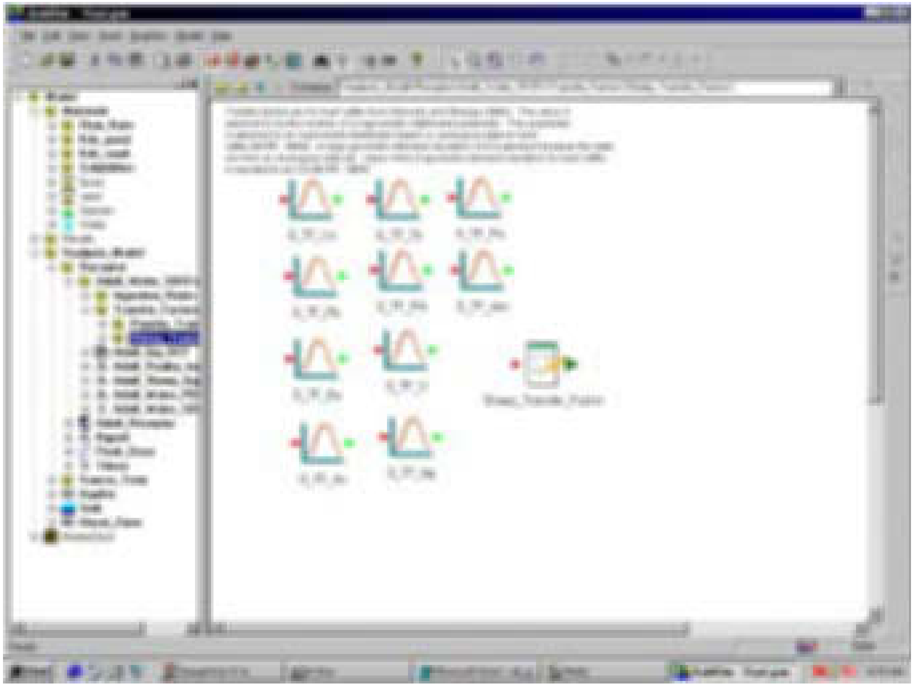

FIG. F.7 Sheep Transfer Factor Calculations Using Stochastic Elements for the Borehole Test Case Farmer Scenario.

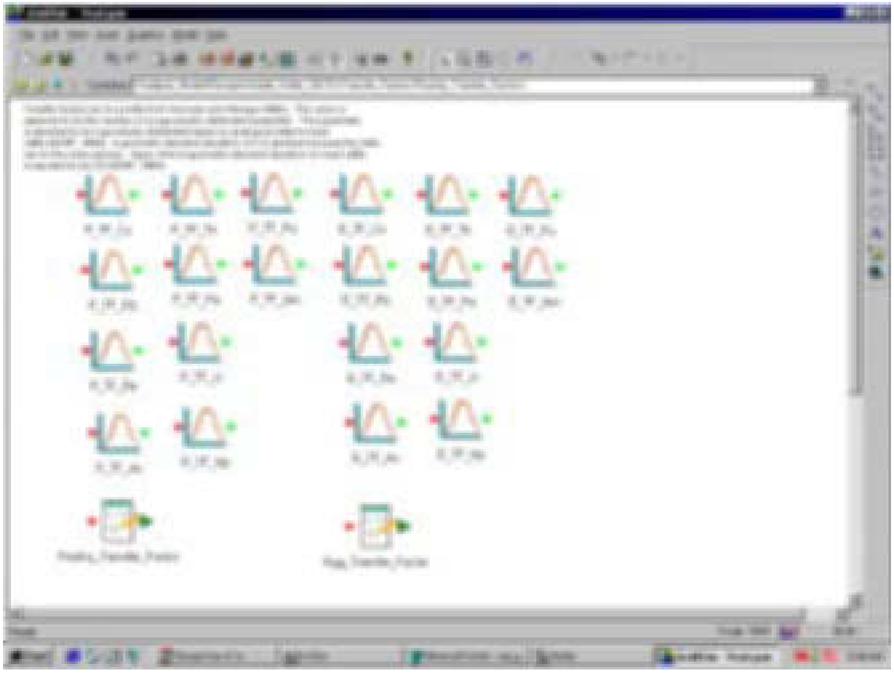

FIG. F.8. Egg and Poultry Transfer Factor Calculations Using Stochastic Elements for the Borehole Test Case Farmer Scenario.

ABBREVIATIONS AND ACRONYMS

ALARA	As Low As Reasonably Achievable
APE	Asphalt Propylene Concrete
BIOMASS	BIOsphere Modelling and ASSessment project
BIOMOVS	Biosphere Model Validation Study
CFR	Code of Federal Regulations (USA)
DSIN	Direction de la Sûreté des Installations Nucléaires (France)
EFEPs	External FEPs
EGE	Engineering and Geological Elements
FEPs	Features, Events and Processes
FSAR	Final Safety Analysis Report
GIS	Geographical Information System
HLW	High Level Waste
ICRP	International Commission on Radiological Protection
IFEPS	International FEPs
IHI	Inadvertent Human Intrusion
IM	Interaction Matrix
IRUS	Intrusion Resistant Underground Structure
ISAM	Improvement of Long term Safety Assessment Methodologies for Near Surface Waste Disposal Facilities
LDE	Leading Diagonal Elements
LHS	Latin Hypercube Sampling
LILW	Low and Intermediate Level Waste
LLW	Low Level Waste
NSARS	Near Surface radioactive Waste Disposal Safety Assessment Reliability Study
ODE	Off-Diagonal Elements
OECD	Organisation for Economic Co-operation and Development
PA	Performance Assessment
PAGIS	Performance Assessment of Geological Isolation Systems
PCRSA	Post Closure Radiological Safety Assessment
PDF	Probabilistic Distribution Functions
PID	Process Influence Diagram
PSAR	Preliminary Safety Analysis Report
RAW	Radioactive Waste

SITE-94	Deep Repository Performance Assessment Project, SKI (Sweden)
SRS	Simple Radon Sampling
WIPP	Waste Isolation Pilot Plant

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RELATED MEETINGS

Consultancy to assist in developing the ISAM CRP,
Vienna, Austria
20–24 May 1996

Consultancy to assist in developing the ISAM CRP
Vienna, Austria
18–22 November 1996

Consultancy to assist in launching the ISAM CRP
Vienna, Austria
16–18 April 1997

Consultancy to prepare for the 1st ISAM Research Co-ordination Meeting
Vienna, Austria
19–21 November 1997

1st ISAM Research Co-ordination Meeting (RCM)
Vienna, Austria
24–28 November 1997

Consultancy to assist in implementing the ISAM Work Programme
Risley, United Kingdom
23–27 February 1998

1st ISAM Working Groups Meeting
Rio de Janeiro, Brazil
27–31 July 1998

Consultancy to assist in implementing the ISAM Work Programme,
Risley, United Kingdom
16–20 November 1998

2nd ISAM RCM, Plenary and Working Group Meetings
Vienna, Austria
1–5 February 1999

2nd ISAM Working Groups Meeting
Madrid, Spain
28 June–2 July 1999

Consultancy to assist in implementing the ISAM Work Programme
Risley, United Kingdom
15–19 November 1999

3rd ISAM RCM, Plenary and Working Group Meetings
Vienna, Austria
25–29 September 2000

Consultancy to assist in implementing the ISAM Work Programme
Vienna, Austria
9–11 April 2001

Final Meeting of the ISAM Co-ordinating Group
Vienna, Austria
29 October–2 November 2001