BOREHOLE DISPOSAL OF SPENT SOURCES: IMPROVING SAFETY ASSESSMENT METHODOLOGIES THROUGH INTERNATIONAL EVALUATION

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ABSTRACT

In 1997, the International Atomic Energy Agency undertook a Coordinated Research Programme to review and enhance postclosure safety assessment approaches and tools for near-surface waste disposal facilities. The new Programme was appropriately called Improvement of Safety Assessment Methodologies (ISAM). One objective of the ISAM Programme is international application of the elements of the safety assessment approach to three test cases. Specifically, methodologies developed under three work groups-- scenario generation and justification, modeling and data, and confidence building□□□are applied to three safety cases: (1) an engineered VAULT disposal design; (2) a RADON type facility, such as that in Russia; and (3) a disposal BOREHOLE design studied as an Africa region project. This paper focuses on the application of the methods developed in ISAM to the later Borehole Safety Case (BSC). The BSC is based on the Borehole Disposal of Spent Sources concept intended to provide African countries with a solution for the long-term management of their spent sources. The BSC is being considered for intermediate-depth borehole disposal, 40 to 100 meters, of an inventory ranging from short- to long-lived radionuclides. The hypothetical geosphere and biosphere

characteristics for the safety assessment are derived from the arid Vaalputs radioactive waste disposal site in western South Africa. Preliminary results for safety assessment of the farmer and hunter-gatherer scenarios are presented.

INTRODUCTION

In 1997, the International Atomic Energy Agency (IAEA) undertook a Coordinated Research Programme (CRP) to review and enhance post-closure safety assessment approaches and tools for near-surface waste disposal facilities. Safety assessments are conducted to provide confidence to the stakeholders that the facility is sited properly and engineered to ensure safety to humans and the environment over long time periods, often exceeding 1,000 years. The new CRP was appropriately called Improvement of Safety Assessment Methodologies (ISAM). The main objectives of the ISAM Programme are:

- To provide 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
- To enhance the approaches and tools used
- To provide participants with practical experience in the implementation of the approaches and tools
- To build confidence in the approaches and tools used

Methodologies were developed under three work groups: scenario generation and justification, modeling and data, and confidence building. International application of the elements of the safety assessment approach (Fig. 1) were demonstrated in three test cases:

1. An engineered VAULT disposal design
2. A RADON type facility, such as that in Russia
3. A disposal BOREHOLE design studied as an Africa region project

This paper focuses on the application of the elements of the safety assessment process (Fig. 1) and the methods developed in ISAM to the later Borehole Safety Case (BSC). The BSC is based on the Borehole disposal of Spent Sources (BOSS) concept under development through the IAEA (1), intended to provide African countries with a solution for the long-term management of their spent radiation sources. The hypothetical geosphere and biosphere characteristics for the safety assessment are derived from the arid Vaalputs radioactive waste disposal site in western South Africa (Fig. 2).

Briefly, the first element in the safety assessment approach (Fig. 1) is to define the assessment context. Consideration of site selection, licensing requirements, dose thresholds, risk exposures, compliance periods, and so on, are taken into account in establishing Element 1. The disposal system is described in Element 2, linked to site-specific or regulatory-defined exposure pathways and receptors in Element 3. Exposure scenarios are converted to their conceptual and mathematical equivalents in Element 4, and modeling simulations are conducted in Element 5. Model results are analyzed in Element 6, and compared to the performance criteria in Element 7 to determine adequacy of the safety assessment in Element 8. If one can demonstrate compliance against the criteria with the results of the analyses, one exits the flowchart, otherwise, modifications to the assessment components occur in Element 10. The approach is iterated as required.

The purpose of this paper is to discuss how the safety assessment approach for the BSC was implemented in an international forum, how scenarios were determined, determination of conceptual and mathematical model components, and how results compare to the assessment criteria. Members of the BSC represent a diverse, international scientific and technical group from seven countries, including, South Africa, the United States, Italy, Israel, Egypt, China, and Australia.

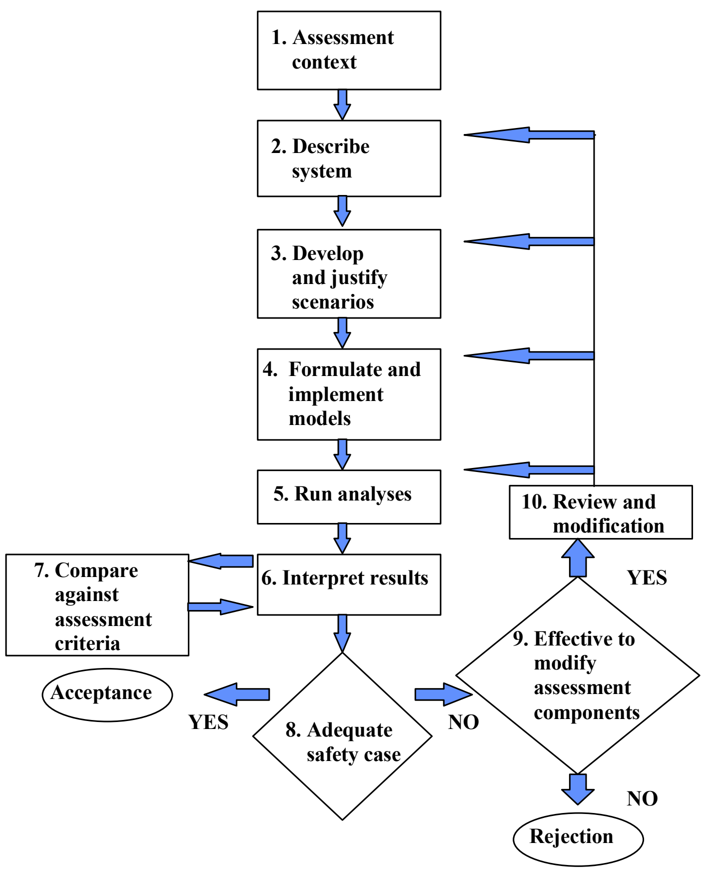

Fig. 1. Safety Assessment Process

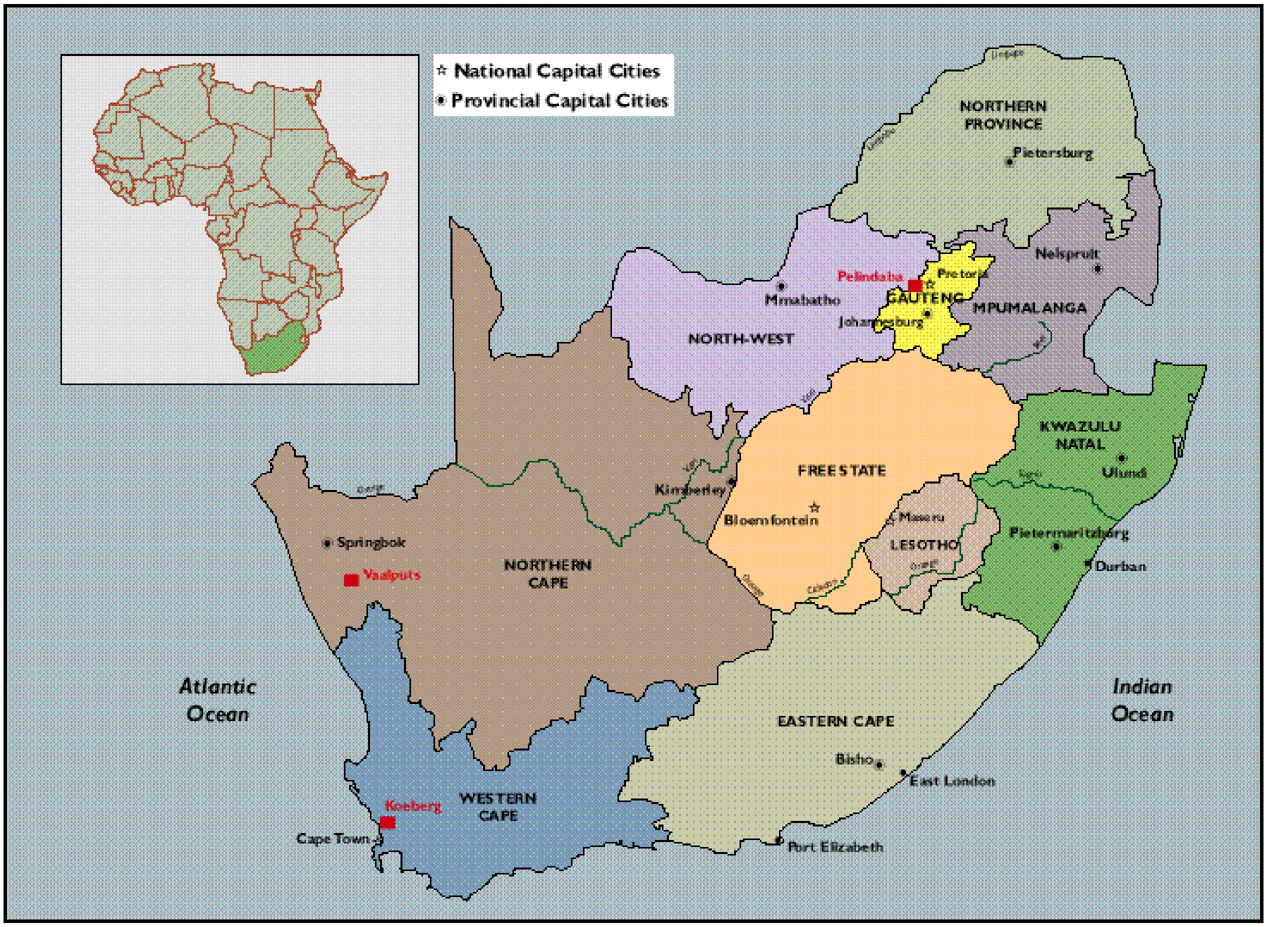

Fig. 2. Location of Vaalputs in the Northern Cape Province of South Africa

ASSESSMENT CONTEXT

The assessment context defines the scope and content of the BSC assessment; the target audience includes government officials, the Site Operator, regulators, the public, and technical or scientific staff and reviewers. The regulatory framework assumes international (2; ICRP 60) and "as low as reasonably achievable" principles.

The assessment will be limited to two land use conditions: (1) continued current use of small farms in the area and agricultural activity, and (2) reversion to a traditional hunter-gatherer life style, such as that of bushman living 500 kilometers (km) from the site. An effective dose limit of 1 milliSievert (mSv) per year (3; ICRP 77) is used, excluding natural background radiation and medical procedures. An individual dose constraint of 0.3 mSv per year is applied to account for the potential that an individual may be exposed to more one source or practice.

A passive and active institutional control period of 30 years is assumed, because some African countries have had recent and dramatic changes in governmental control. In such cases, institutional memory and control may be short; it is conservatively assumed that no institutional control will exist after 30 years. Following closure, estimated impacts should be considered against the 0.3 mSv per year dose limit. Radioactive wastes will be managed so that impacts to future generations will not be greater than the relevant impacts that are acceptable today

Regulatory guidance requires that there is no cut-off limit beyond which impacts need not be considered. The assessment period for the BSC is 10,000 years; this period does not preclude calculation to peak dose. Finally, the BSC is being considered for intermediate-depth borehole disposal, 40 to 100 meters (m), of an inventory ranging from short- to long-lived radionuclides. For this study, surface processes and events, such as erosion and inadvertent intrusion scenarios, are dismissed from the analysis that would normally be treated in a conventional near-surface safety assessment.

Isolation of the waste from the accessible environment does not depend on the actions of future generations to maintain the integrity of the disposal system. Therefore, issues such as retrievability, remedial action and monitoring after site closure are not be considered.

DISPOSAL SYSTEM DESCRIPTION

The disposal system consists of the waste, the engineered facility, and natural barriers expected to contain and isolate the waste. The system description also includes all the necessary information about the near-field landscape. The near-field describes the release of radionuclides from the waste package and the borehole into the far-field where the radionuclides are transported through the environmental media to reach the receptors.

Waste Inventory

The inventory adopted for the BSC is derived from Algeria, with the addition of two sources from Ghana. A typical inventory of sealed radiation sources used in medicine, industry, and education is presented in Table I. It consists of short-lived radionuclides such as ^{192}Ir as well as long-lived radionuclides such as ^{226}Ra. The addition of ^{109}Cd and ^{99m}Tc are from Ghana.

Table I. Typical Inventory for the Borehole Safety 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 5µm 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 µm thickness	Static Electricity Removal

The sealed sources are high integrity capsules that may carry highly concentrated activity depending upon the type of application as shown in Table I. Gamma sources (e.g., ^{60}Co, ^{137}Cs, and ^{241} Am) are used in industry for material control, radiotherapy and sterilization. Beta sources (e.g., ^{90}Sr) are used in clinical therapy. Alpha sources (e.g., ^{226}Ra and isotopes of Pu) are used in analytical applications and as heat sources. Neutron sources (e.g., ^{241}Am) are used in various analytical practices.

Disposal Facility Design

The borehole disposal concept relies on an integrated system of engineered barriers to dispose the sealed sources safely and economically. The design satisfies the following objectives:

- Accommodate the disposal of spent sources in suitable waste packages
- Enhance the site's ability to isolate and contain the waste, thus minimizing releases in the long-run
- Allow flexibility and ease in operations

- Minimize the need for post-closure site maintenance
- Minimize the potential for human intrusion

Important features of the engineered barrier include: the waste form and packaging, the emplacement of the waste packages in the borehole, the borehole casing, and the backfill around the packages. The sealed sources consist of high-integrity capsules containing a specific radionuclide in concentrated form. These capsules will be introduced to cement, then emplaced in a 304-stainless-steel container with a thickness of 3.05 millimeter (mm; 114-mm outside diameter and 250-mm length), and sealed with a lid. Prior to emplacement in the container, radium-sealed sources that are broken or leaking will be placed into 304-stainless-steel capsules of 21.3-mm diameter and 110-mm length, with a wall thickness of 2.77 mm.

The stainless steel container is expected to isolate the waste about 5,000 years before leaks develop. Corrosion rates are expected to be low; corrosion rate of stainless steel under alkaline, anaerobic conditions range from 0.3 to 1.0 micrometer per year. However, crevice corrosion can occur in groundwater with high chlorine content. The cementitious waste form provides an effective physical, chemical, and hydrologic barrier to release once the container loses its integrity and contacts water.

Of concern to the BCS assessment is safe isolation of long-lived isotopes such as ^{226}Ra. Consequently, it is assumed that ^{226}Ra will not be mixed with short-lived isotopes in the same container. Packages will contain homogeneous inventory. Containers are stacked in the borehole vertically, with a container in every one-meter zone, then backfilled with cement. The containers with the long-lived radionuclides are placed deeper in the hole. Ten containers can potentially be placed into a borehole.

The waste package is lowered into a borehole constructed in bedrock in two configurations: first, in the unsaturated zone at a depth of 45 m, which is 10 m above the piezeometric level, and second, in the saturated zone to a depth of 100 m. The first design configuration in the unsaturated zone (i.e. the conceptual model shown in Fig. 2) has been evaluated; it is described in detail in the later Model Implementation and Analysis section.

The borehole is constructed using the percussion drilling method, to a diameter of 305 mm through the weathered zone, and will be telescoped to 254-mm diameter in the hard rock zone. A 300-mm casing is installed through the weathered zone to keep loose material from sloughing. A 203-mm PVC casing is fit to the bottom of the borehole, where it is driven through a wet cement plug. Due to possible corrosiveness of the water and soil, the borehole casing material is PVC.

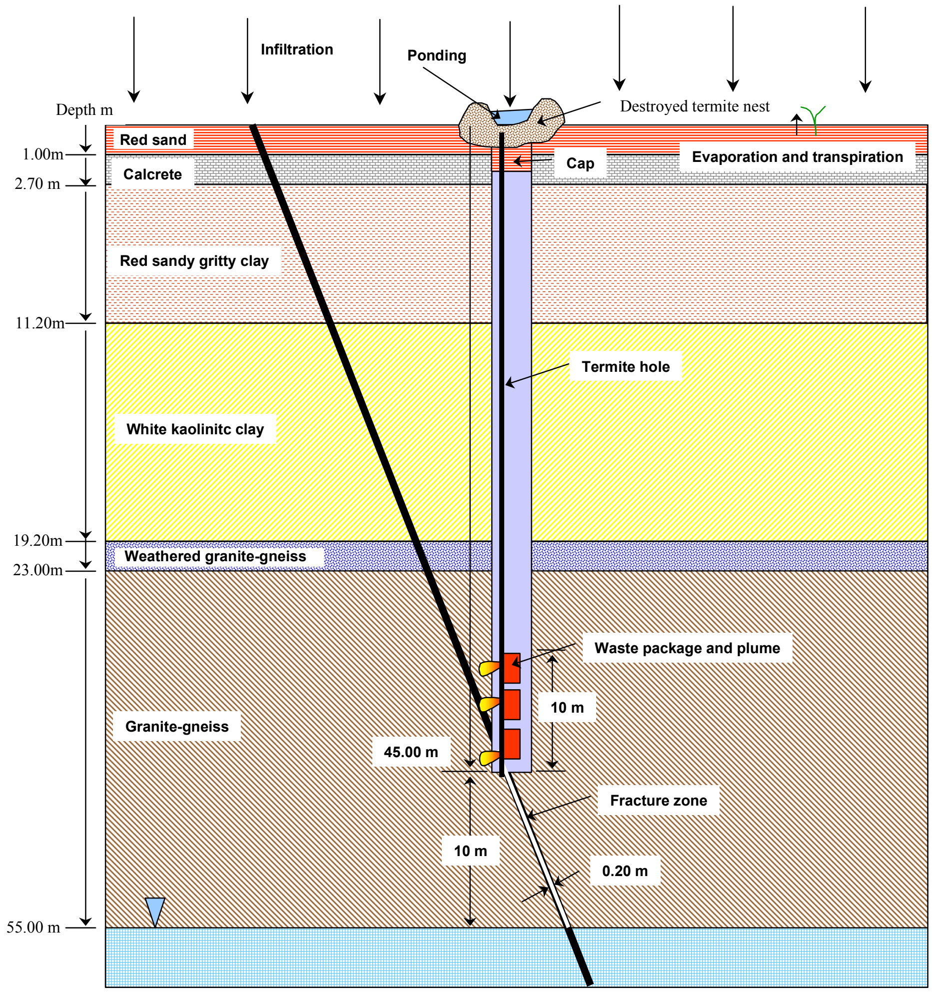

Fig. 3. Conceptual Model of the Disposal Facility

Hydrogeologic Setting

The Vaalputs facility is located in the Northern Cape province of South Africa on a high plateau at the edge of the western side of the escarpment that divides the inland and the coastal plains (Fig. 2). No permanent human habitation exists within 20 km of the site. The area is known for its dry, arid to semiarid desert conditions. Average annual rainfall is 80 mm; pan evaporation is 2,412 mm, indicating very high potential evaporation. Granite-gneisses and metavolcanics overlie the crystalline bedrock of Precambrian age (Fig. 3). The bedrock has been folded, thrusted, and fractured due to large-scale tectonism. The groundwater aquifer is located in the weathered and fractured bedrock. Fault zones control flow in the upper saturated zone with characteristically higher hydraulic conductivity than the underlying hard granite zone, where the matrix impedes, flow but fractures facilitate it. The water table is about 50 m below the ground surface at the facility. The regional and local groundwater gradients are small, and consequently, so are the groundwater velocities.

The unsaturated zone is between 15- to 30-m thick. It is quite heterogeneous, with irregular layers of sand, red clay, white clay, calcrete, and weathered and fresh granite. The moisture content varies from 0.1 to 0.3. Both laboratory test and field pumping test have been performed to characterize the conductivity of the unsaturated zone as well as the saturated zone. The distribution of fractures in the saturated zone has been partially characterized through geophysical techniques.

The ecosystem near the facility has also been thoroughly studied and described--flora and fauna are typical of a semi-arid environment, including open shrub and grass communities. Animals trapped within the proximal ecosystem include rodents, jackal, and rabbits. Of particular interest to the radionuclide release scenario for the bounding analysis are burrowing insects such as ants, termites, and scorpions. Termites in particular occupy a pivotal position in the food chain and release pathway, creating nests and burrows at depths potentially extending to the water table.

SCENARIO GENERATION AND JUSTIFICATION

The BSC report contains an explanation of scenario generation and justification for the post-closure safety assessment to address the uncertainties associated with the evolution of the system over time. Two critical groups, or receptors, were defined for the BSC based on land use conditions discussed in the Assessment Context section: a present day farmer, and a traditional hunter-gatherer. Four potential exposure scenarios were defined for discussion and justification for the subsequent analysis:

1. Assuming present land use patterns of small farms and agricultural activity, a farmer with an extraction well for drinking and irrigation would be exposed through pathways of ingestion, inhalation, and other external factors.
2. Assuming present land use patterns, a farmer living near a discharge salt pan would be exposed through pathways of ingestion, inhalation, and dermal soil contact.
3. Assuming a revision to traditional human behavior, a hunter-gatherer eating termites would be exposed through pathways of ingestion and dermal soil contact.
4. Inadvertent human intrusion (IHI) with variations of exposure scenarios.

In the interest of brevity, this paper focuses on exposure scenarios 1 and 3, as more likely to occur, as well as conservative and bounding scenarios for the BSC assessment. An inadvertent human intruder that would drill a borehole, or water well, into a contaminated plume emanating from the disposal borehole was removed from consideration. An expert elicitation (4) completed at the Nevada Test Site demonstrates the low probability of IHI occurrence at similar remote, desert waste sites. The very low probability of penetrating the disposal borehole is attributed primarily to the small borehole footprint, the remoteness of the site to inhabited areas, and predicted future land uses that do not include drilling or boring.

The ISAM futures, events, and processes (FEPs) list, derived from the U.S. Nuclear Energy Agency's international electronic FEPs database, was screened for relevant internal and external factors influencing the assessment and construction of the conceptual model. Interaction matrixes, together with the screened FEPs list, were used to develop the BSC conceptual model. Although details of the FEPs screening and matrix development are beyond the scope of this paper due to length, the process was extensive and critical in establishing a consensus among international members to reach consensus on the elements and processes of the conceptual model.

MODEL DEVELOPMENT

An interaction matrix (Table II) was constructed as an audit tool to develop the conceptual model for the total system performance: the near-field, geosphere, and biosphere interactions. The leading diagonal elements of the interaction matrix include: waste package, unsaturated zone, saturated zone, soil, atmosphere, flora, fauna, human activities, and exposure group. Processes that occur between the diagonal elements are noted for inclusion in the modeling process. The conceptual model developed for the assessment is illustrated in Fig. 3. The conceptual model for the BSC assessment is shown as a flowchart in Fig. 4. Interaction matrixes for the near-field, geosphere, and biosphere were further developed, supporting the total system performance (excluded here due to report length).

The next step was to perform source-pathway-receptor analyses for the farmer and hunter-gatherer scenarios. Near- and far-field modeling was performed for both. In the bounding case for the hunter-gatherer, it is assumed that termites nest atop the borehole to facilitate contaminated soil transport to the surface for exposure pathway analysis. An extended assumption is that a gum tree grows beside the borehole, the roots invade the backfill and waste material, uptaking radionuclides. Finally, it is assumed that the waste borehole penetrates a permeable fracture zone facilitating surface infiltration to the waste package level. Corrosion occurs, facilitating radionuclide transport and migration of contaminated groundwater to the farmer's water well for ingestion and irrigation.

MODEL IMPLEMENTATION AND ANALYSIS

Farmer Scenario

The GoldSim code, developed by Golder Associates (5, 6) was used in the mathematical implementation of the conceptual model of the groundwater pathway for the farmer scenario. The model simulates the following:

- The release of radionuclides from the waste packages in the borehole
- Their transport through the unsaturated zone to the water table
- Their transport in the saturated zone to a borehole near the site

- The dose to the farmer-receptor who uses borehole water for drinking, and consumes sheep, poultry, and eggs that are contaminated by the borehole water

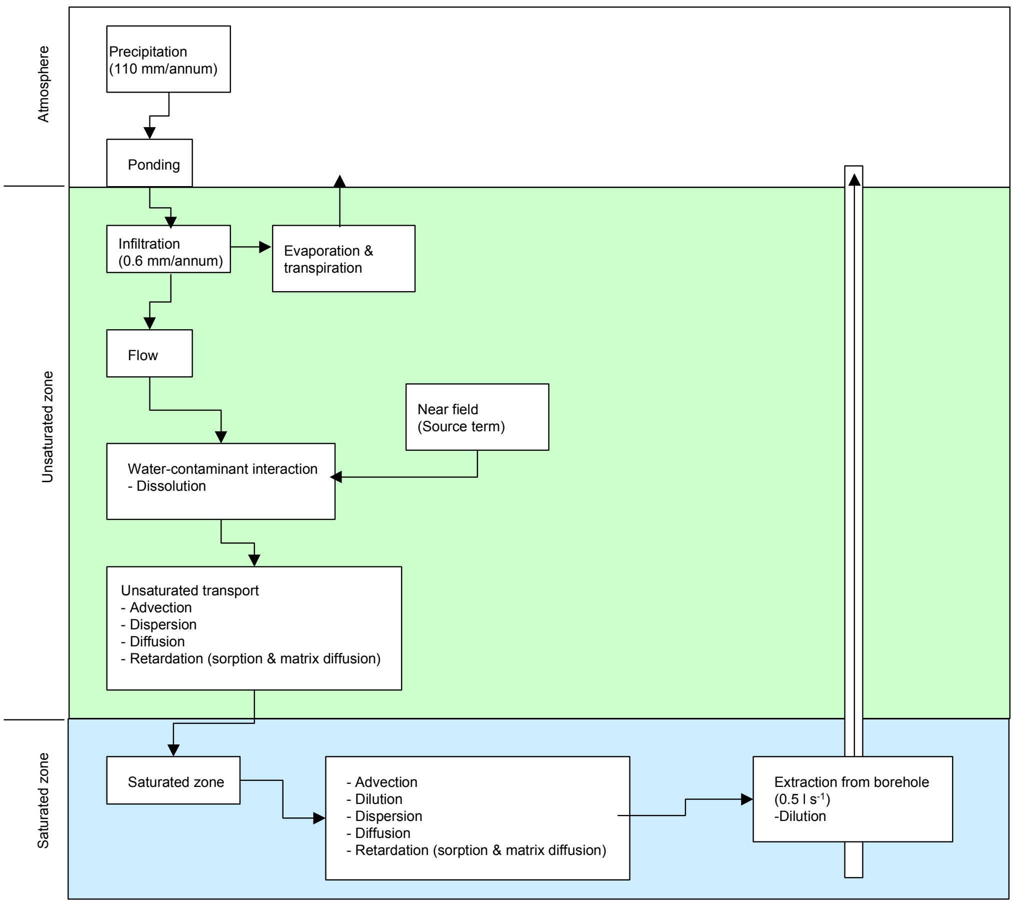

Fig. 4. The Geosphere Conceptual Model

Table II. The Total System Performance Interaction Matrix

	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)**

The key flow and transport assumptions are the following:

- A steady-state flow field
- The recharge rate is equal to the average infiltration rate
- Flow is one-dimensional through a homogeneous high-permeability zone (i.e. a fracture zone)
- No dispersion or diffusion is assumed
- Radionuclides are subject to decay and sorption

The radionuclide inventory is assumed to be evenly distributed into ten stainless steel containers stacked vertically one meter apart in a borehole. The engineered container is described in the earlier Disposal Facility Design section. A concrete-bentonite slurry fills the space between the borehole and the container; no credit is taken for the backfill in this analysis.

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 density of 2,000 $kg.m^{-3}$ for concrete), and 1.5E-03 m^3 of water (assuming a moisture content of 0.06 when the container is breached). Steel containers are unlikely to fail due to corrosion within 10,000 years after closure, given the borehole conditions at Vaalputs site (7). 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.

Because of uncertainties associated with release, flow, and transport parametirization, a probabilistic approach was adopted for the modeling (Monte Carlo simulation). Several parameters were assigned probability distributions including recharge, soil moisture in the unsaturated zone, solubilities, and sorption. A recharge distribution was derived assuming five percent of the annual precipitation infiltrates the ground surface and becomes recharge. The annual recharge rate is assumed normally distributed with a mean of 6.3 mm/yr and a standard deviation of 1 mm/yr, derived from a 13-year record at Vaalputs (1986-1998). The minimum and the maximum of the distribution were set at 2.3 mm/yr and 10 mm/yr respectively. The soil moisture distribution was derived from the recharge values and the soil moisture retention characteristics for a sandy soil type.

Radionuclide-specific solubility and distribution coefficients (K_d) are assumed to have uniform distributions, parameters of which are shown in Table 4. 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 (8,9,10). The K_ds are adopted from the United States Department Of Energy's Residual Radioactive Material Guidelines (RESRAD) dose assessment program (11). The expected values of the K_d distributions shown in Table 4 are for a sandy type material. Since there is no consistent set of K_d data available from cementatious materials with high pH conditions typical of the borehole environment at the Vaalputs site, K_ds for a sandy material are used instead, leading to a conservative analysis. The minimum and maximum of the K_d distribution are assumed to cover a range equal to the expected value of the distribution.
The receptor was assumed to pump water from a well annually at a rate of 91.25 m^3 (12)
The dose conversion factors, which are assumed constants, are given in Table 5. The poultry transfer factors are assumed lognormally distributed with the median values shown in Table VI (12). A geometric standard deviation of 3 is assumed. Upper limit of geometric standard deviation for beef cattle is reported to be 3.8 (13). The mutton transfer factors are assumed lognormally distributed with the median values shown in Table VI (12). A geometric standard

deviation of 4 is assumed. The intake rate distributions for water, mutton, poultry and eggs are shown in Table VII.

Monte Carlo simulations were performed using Latin Hypercube sampling, specifying 100 realizations. 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.

Table IV. Solubility Limits and Distribution Coefficients

Radionuclide	**Solubility (mg/l)**		**K_d - Sand (m^3/kg)**	
	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

Table V. Dose Conversion Factors

Radionuclide	**Dose Conversion Factor ($Sv.Bq^{-1}$)**
^{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 VI. Transfer Factors

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
229Th	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 VII. Intake Rates Used in the Farmer Scenario of the BSC Assessment

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
Mutton (kg.a^{-1})	Triangular	31	15	62
Poulty (kg.a^{-1})	Triangular	9.5	4.5	19
Eggs (kg.a^{-1})	Triangular	15	7.5	30

Radionuclides including ^{237}Np, ^{233}U, ^{229}Th, ^{235}U, ^{231}Pa, and ^{227}Ac show breakthrough within the 10,000- Fig. 5. TEDE for the Farmer Scenario

year simulation period. The concentrations show an increasing trend with peak concentrations well beyond the 10,000-year simulation period. The maximum total effective dose equivalent (TEDE) occurs in 10,000 years after the facility closure. Most of the TEDE is attributed to ^{237}Np and ^{233}U. The time history of the farmer scenario TEDE is shown in Fig. 5. The mean, median, 95 percentile, and 5 percentile of the TEDE distribution are shown in the figure. The TEDE distribution at 10,000 years (in mSv.a-1) has a mean of 9.4E-07, a median of 8.8E-07, a 95 percentile of 2.0E-06, and a 5 percentile of 5.0E-08. The results indicate that all TEDE realizations are well below the compliance criterion of 0.3 mSv per year.

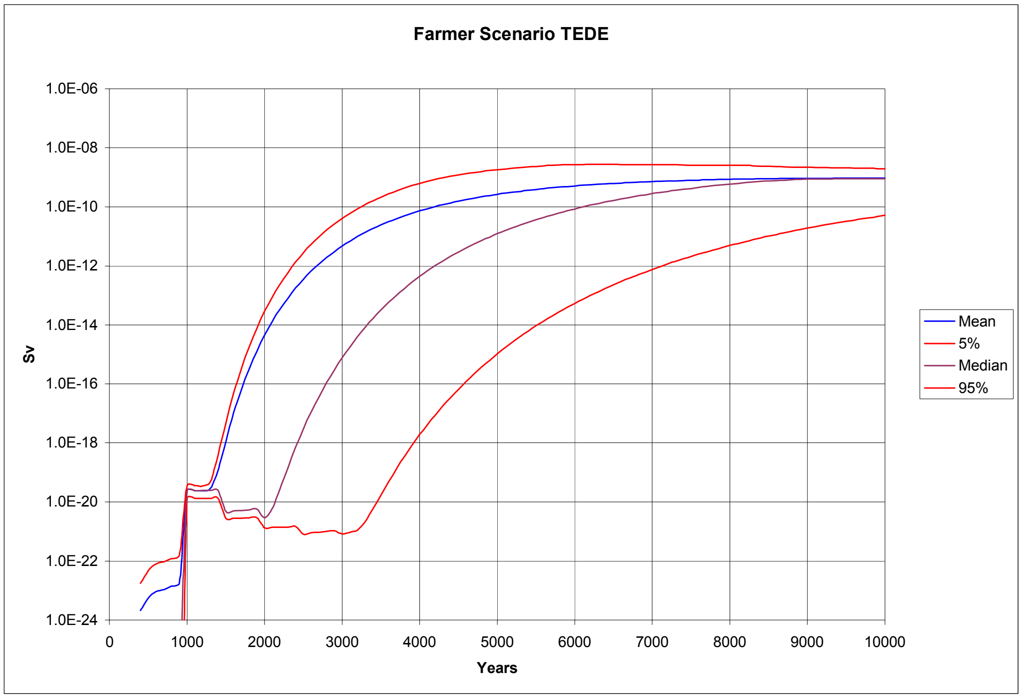

Fig. 5. TEDE for the Farmer Scenario

Hunter-Gatherer Scenario

For comparative purposes, results of the conservative and bounding hunter-gatherer scenario are presented here; details of the model implementation and analysis are beyond the scope of this paper. The scenario assumes that termites built their nest on top of the borehole and dig tunnels through the borehole to the water table. In the process, termites contact contaminated soils because of the breached containers and bring contaminated soil to the ground surface. Also activity bioaccumulates in the termites. The hunter-gatherer, who collects termites for consumption, receives dose due to external irradiation as well as ingestion.

Results of the hunter-gatherer scenario dose model show high values for the insect consumption pathway, peaking at 3.5 mSv per year. These results are highly uncertain because the amount of termites consumed, bioaccumulation of activity in termites, amount of contaminated soil brought to the ground surface, and the dose conversion factors are not known.

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