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Development of a Computer Code for Low-and Intermediate-Level Radioactive Waste Disposal Safety Assessment

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Abstract - A safety assessment code, called SAGE (Safety Assessment Groundwater Evaluation), has been developed to describe post-closure radionuclide releases and potential radiological doses for low- and intermediate-level radioactive waste (LILW) disposal in an engineered vault facility in Korea. The conceptual model implemented in the code is focused on the release of radionuclide from a gradually degrading engineered barrier system to an underlying unsaturated zone, thence to a saturated groundwater zone. The radionuclide transport equations are solved by spatially discretizing the disposal system into a series of compartments. Mass transfer between compartments is by diffusion/dispersion and advection. In all compartments, radionuclides are decayed either as a single-member chain or as multi-member chains. The biosphere is represented as a set of steady-state, radionuclide-specific pathway dose conversion factors that are multiplied by the appropriate release rate from the far field for each pathway. The code has the capability to treat input parameters either deterministically or probabilistically. Parameter input is achieved through a user-friendly Graphical User Interface. An application is presented, which is compared against safety assessment results from the other computer codes, to benchmark the reliability of system-level conceptual modeling of the code.

Key words : probabilistic safety assessment code, radionuclide releases, low-and intermediate-level radioactive waste disposal

INTRODUCTION

Korean national policy for the radioactive waste management is to open a low-and intermediate-level waste (LILW) repository by 2008. At this time, a site has not yet been chosen for the disposal of Korean LILW, and a preferred near-surface disposal method, either disposal in rock caverns or disposal in engineered concrete vaults, is to be determined in consideration of site conditions. The application of the near-surface disposal option requires the implementation of measures that provide protection of human health and the environment now and in the future. As an effort to ensure safety of a disposal facility, a comprehensive safety assessment system needs to be established. Within this safety assessment framework, a new customized computer code is developed to be used for evaluation of the engineered vault disposal concept for LILW disposal in Korea. The computer code has been named Safety Assessment for Groundwater Evaluation (SAGE). The conceptual model in the code is focused on releases from a gradually degrading engineered barrier system to an underlying unsaturated zone, thence to a saturated groundwater zone. Doses can be calculated for several biosphere systems including drinking contaminated groundwater, and subsequent contamination of foods, rivers, lakes, or the ocean by that groundwater. The flexibility of the code will permit both generic analyses in support of design and site development activities, and straightforward modification to permit site-specific and design-specific safety assessments of a real facility as progress is made toward implementation of a disposal site.

In this paper, safety assessment methodology taken for LILW near-surface disposal, and the overall scheme, conceptual model and features implemented in the developed code are described, along with application of the code to an international safety case.

SAFETY ASSESSMENT METHODOLOGY FOR LILW NEAR-SURFACE DISPOSAL

Safety assessment is an analysis to evaluate the performance and/or safety of a system, followed by comparison of the results of such analysis with appropriate standards or criteria. The use of the safety assessment approach allows for practical decisions on issues related to the safety of the disposal system in a clear, comprehensive, well-documented, and defensible manner. A variety of safety assessment approaches have been developed and applied for the assessment of near-surface disposal facilities. The safety assessment methodology for the current project, as shown in Figure 1, is based on currently accepted international approaches.[1] This approach is consistent with current international recommendations on the structure and content of safety assessments, which in turn have been developed over many years in a number of countries.[2]

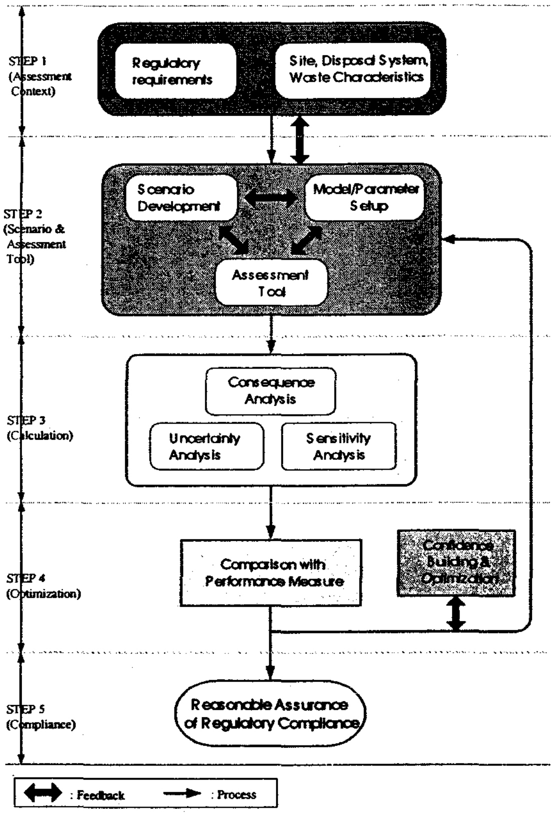

Fig. 1. Safety assessment methodology for LILW disposal

DEVELOPMENT OF A SAFETY ASSESSMENT CODE

The overall scheme of the code for safety assessment is shown in Figure 2. The safety assessment models have been divided into three categories: Near field, Far field, and Biosphere models. The code has modular structure having the capability to treat input parameters either deterministically or probabilistically. The code has been written to easily interface with more detailed codes for specific parts of the safety assessment. In this way, the code's capabilities

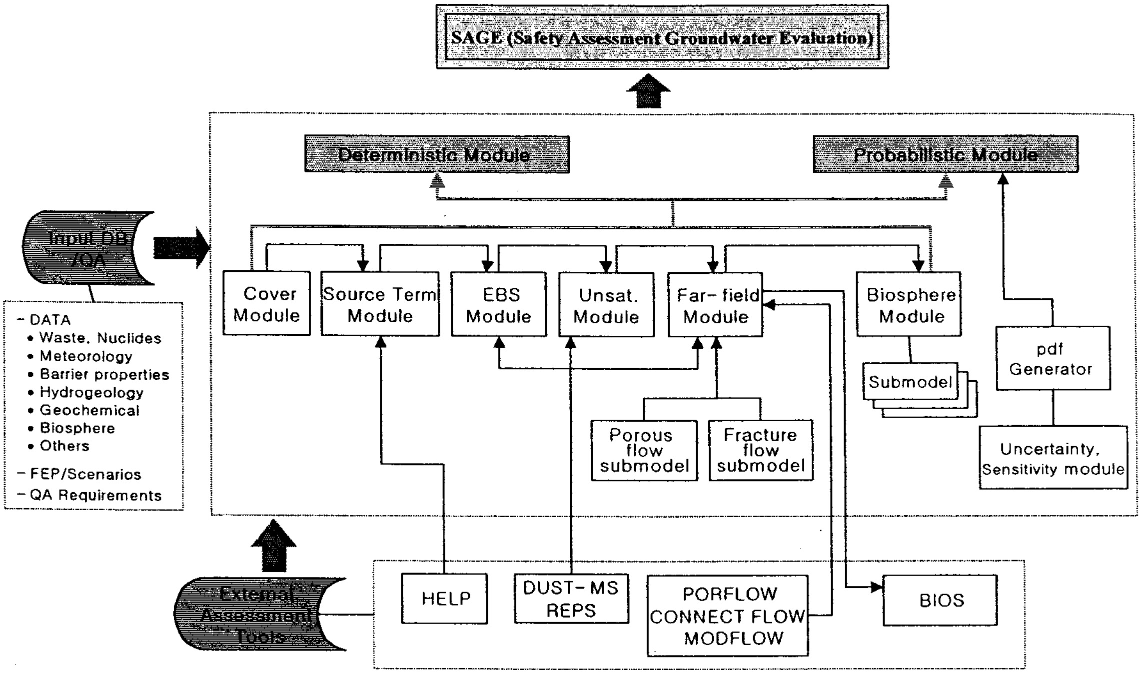

Fig. 2. Overall scheme of the safety assessment code.

can be significantly expanded as needed.

Safety assessment of waste disposal systems requires efficient and robust numerical solution schemes. The compartment model approach adopted by several waste management programs is one such method, and is considered suitable for safety assessment calculations.[3,4] In SAGE, the conceptual model is focused on the release of radionuclide from a gradually degrading engineered barrier system (EBS) to an underlying unsaturated zone (UZ), thence to a saturated groundwater zone (SZ). The radionuclide transport equations are solved by spatially discretizing the system into a series of compartments. For the purpose of the implementation of SAGE, the near field of the disposal system includes: waste form and packaging, near field below the waste form, and UZ, as shown in Figure 3. The EBS and UZ can be further divided into a number of sub-compartments. Because the UZ is often relatively thin and adjacent to the disposal facility, it is included in the near field for modeling convenience.

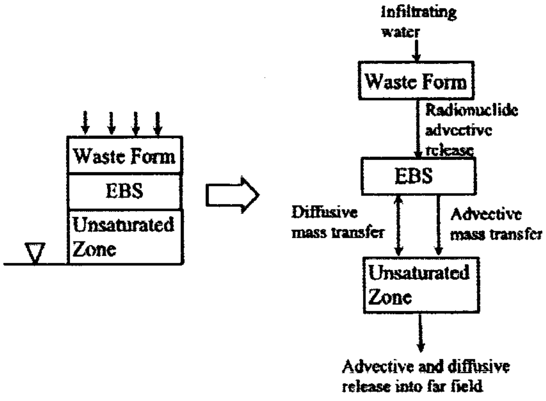

Fig. 3. Illustration of the compartment model for the near field.

Figure 3 also shows mass transfer relationships between compartments. Mass transfer of radionuclides from one compartment to the other is by diffusion/dispersion and advection. The Waste-Form compartment represents the source of radionuclides released during the post-closure period of the disposal facility. The release of radionuclides is caused by the failure of multi-layered cover system and water contact thereafter. The initiation of release is assumed to happen when water drips into the waste facility through failed cover system. The rate of infiltrating water through this compartment is treated as either linear or piecewise step function with time in order to simulate gradual degradation of the cover system. The EBS compartment receives advective release rates of radionuclides from the Waste-Form compartment and transfers radionuclides to the UZ compartments via diffusion/dispersion and advection. The UZ compartment represents unsaturated soils between the EBS and the SZ.

In SAGE, the SZ represents a layer of soils below the water table that carries radionuclides from the overlying contaminated unsaturated soils to the well that represents the biosphere. To types of media are considered as possibilities in the SZ: soils (or weathered rock) and fractured rock. For the purpose of performance assessment, radionuclide transport in the far field is conceptualized as a series of connected compartments shown in Figure 4. This conceptualization is used for both the soil and the fractured rock far-field options, although the mathematical models for the two medium types, however, are different. This conceptualization is consistent with contemporary approaches in low-level waste safety assessments.[1] Radionuclides are released from UZ into SZ via diffusion/dispersion and advection. The spatial discretization will be in the direction parallel to groundwater flow. In all compartments, radionuclides are decayed either as a single-member chain or as multi-member chains. Transport of radionuclides in the EBS, UZ, and SZ compartments will be attenuated by assuming linear equilibrium sorption. Elemental solubility limit is considered in the near field.

The biosphere compartments are assumed to be located at the end of the geosphere and to have an infinite dilution effect on radionuclide concentrations transferred from the geosphere. The code calculates the rates of radionuclides released from the geosphere into the biosphere. The release rates then are converted to dose rates according to biosphere exposure pathways. The biosphere compartments represent well, soil, river, lake, and sea. The biosphere can be represented as a set of steady-state, radionuclide-specific pathway dose conversion factors that are multiplied by the appropriate release rate from the far field for each pathway. In present version of SAGE, the biosphere is treated in a generic manner, since there is not a current site chosen for disposal in Korea. The potential exists for selection of a site that would involve potential releases to groundwater alone, or with subsequent releases to surface water bodies, which may be rivers, ponds, lakes, or the ocean. Since specific interactions between groundwater and surface water vary widely on a site-specific basis,[5] only simple, generic modeling approaches are included in the code. These generic approaches will be easily adaptable to site-specific conditions when the situation merits. In addition, the code has the functionality to edit user-specified dose conversion factors.

SAGE has been implemented to function within a Microsoft Windows compatible Graphical User Interface (GUI). This GUI simplifies input of parameters needed to run the code, facilitates analyses using probabilistic distributions of input parameters, and simplifies examination of results. The distribution functions such as normal, log-normal, uniform, log-uniform, etc. are available to take distribution parameters as inputs or to generate a series of performance assessment calculation input data files by Latin Hypercube Sampling processing. Upon completion of assessment calculations, SAGE calculates the time-dependent total dose rates for each realization. Average dose rates vs. time are also calculated. Cumulative distribution functions (CDF) plotting for peak dose rates and scattered plots showing effects of parameter variation on peak dose rates can be created. On the CDF plots, the calculated mean, median, and variance values for the peak dose rates are also shown.

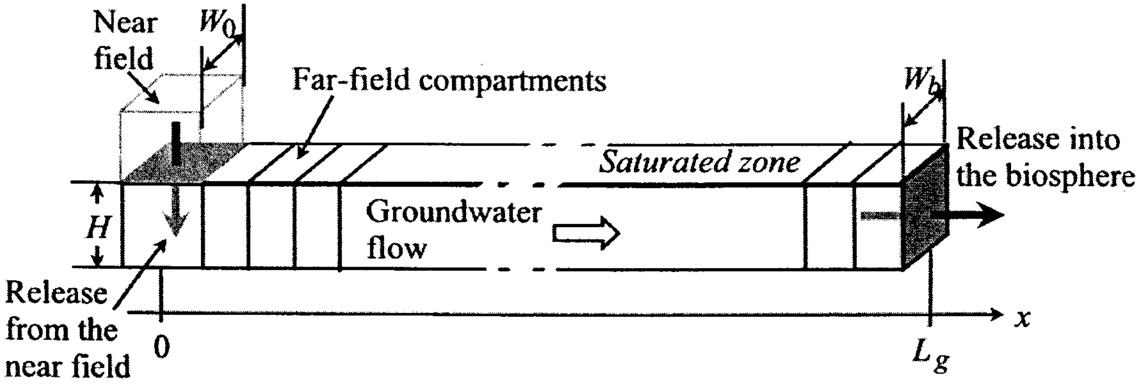

Fig. 4. Illustration of the far-field compartment model.

From a technical perspective, the code has been tested extensively against existing analyses of LILW disposal facilities and other computer codes. These benchmark analyses provide a high degree of confidence that the code has been implemented correctly, and that the results generated using the code have a high degree of reliability. An example of one of the benchmark analyses is described in next section.

APPLICATION

To benchmark SAGE against existing system-level analyses, the radiological impacts of radionuclides on a critical human group has been evaluated for a hypothetical near-surface radioactive waste disposal facility in Vaalputs, South Africa as a part of the IAEA coordinated research program on improvement of safety assessment methodologies (ISAM).[6] The analysis deals with the drinking water scenario from a well, which is considered to provide conservative results. The parameters for the modeling of source-term, geosphere and biosphere are mainly obtained from the site-specific data. The results from the SAGE calculation have been compared with those from other computer codes for the same facility and scenario.

The disposal facility was defined as a set of 20 concrete vaults located above ground level and has a total of about 750,000 drums. The waste disposal area contains two lines of 10 vaults. The approximate dimensions of the disposal area are 170 by 210 m giving a surface area of 35,700 m^2. Each vault has internal dimensions of 9 m high by 20.5 m wide by 83 m long allowing concrete cubes to be stacked 4 high x 17 x 69.

It has been assumed that the near-field barriers degrade with time. The drums were assumed to remain intact for 100 years and the concrete was assumed to physically fail after 300 years of closure and chemically degrade over a 1,000-year period from site closure. The cap was assumed to be maintained during the 100-year active institutional control period but then starts to degrade so that it allows the 50 % of total precipitation. After 500 years it no longer limits the rate of water infiltration. Furthermore, the near field was assumed to be degraded chemically after 500 years so that the distribution coefficient for the degraded vault is used for safety assessment. In order to consider changing K_d's in the vault as a function of time, an initial calculation is conducted using the initial K_d values in the vault. It was determined that there is little release during this initial time period, so the steady-state K_d's were used in SAGE calculation.

For flow in the UZ, it was assumed that there are a series of fractures below the disposal facility and that an equivalent porous medium approximation can be made to represent flow and transport in the zone. The UZ is made up of a sequence of four lithologies. In the SZ, it is assumed that the water that has percolated down from the UZ is intercepted by a series of fractures. Groundwater is abstracted from a well that is 200 m away from the boundary of the disposal area. It was assumed that the series of fractures in the SZ that intercept the percolating water from the disposal facility can be represented by a single streamtube. The streamtube yields 2,160 m^3. Based on site-specific data, a yield of 8,300 m^3 is assumed from the well. It was therefore assumed that the remaining 6,140 m^3 is derived from other fractures that carry uncontaminated water. The consumption of drinking water was determined as 0.8 m^3/yr from the site-specific data. As the safety case specifies dispersion coefficients, while SAGE uses a diffusion formulation, an approximate value for diffusion coefficient was determined by calculating the dispersion coefficient from flow and dispersivity, and choosing a diffusion coefficient approximately equal to the dispersion coefficient.

Despite the differences in the conceptual models underlying the three published analyses of the safety case, good agreement is achieved in comparing peak releases into the aquifer. A comparison of prior analyses in the literature[7] with SAGE results is shown in Table 1 for releases into the aquifer, and in Table 2 for well concentrations. Figure 5 shows time-dependent radionuclide concentration in the well water.

Table 1. Comparison of peak flux rates to the aquifer from published values[7] and SAGE.

Nuclides	C. L. Kim(KHNP)		R. Little(Quintessa)		SAGE	
	Time (yr)	Peak Flux (Bq/yr)	Time (yr)	Peak Flux (Bq/yr)	Time (yr)	Peak Flux (Bq/yr)
C-14	31,000	3.3E5	30,000	3.7E5	30,000	4.7E5
Tc-99	2,500	1.8E7	2,500	1.9E7	2,100	4.1E7
I-129	6,900	1.3E6	8,000	1.4E6	6,800	1.5E6
U-234	65,000	5.2E5	40,000	4.1E5	43,000	4.9E5
U-238	65,000	5.2E5	50,000	4.6E5	43,000	4.9E5

Table 2. Comparison of peak concentrations in the well from published values[7] and SAGE.

Nuclides	C. L. Kim(KHNP)		R. Little(Quintessa)		SAGE	
	Time (yr)	Peak Concentration (Bq m^{-3})	Time (yr)	Peak Concentration (Bq m^{-3})	Time (yr)	Peak Concentration (Bq m^{-3})
C-14	31,000	6.7E1	30,000	4.4E1	34,000	3.6E1
Tc-99	2,500	3.7E3	2,500	2.2E3	1,700	1.5E3
I-129	7,000	2.7E2	8,000	1.7E2	7,400	1.7E2
U-234	73,000	1.3E2	50,000	5.5E1	41,000	5.8E1
U-238	59,000	1.1E2	50,000	5.5E1	41,000	5.8E1

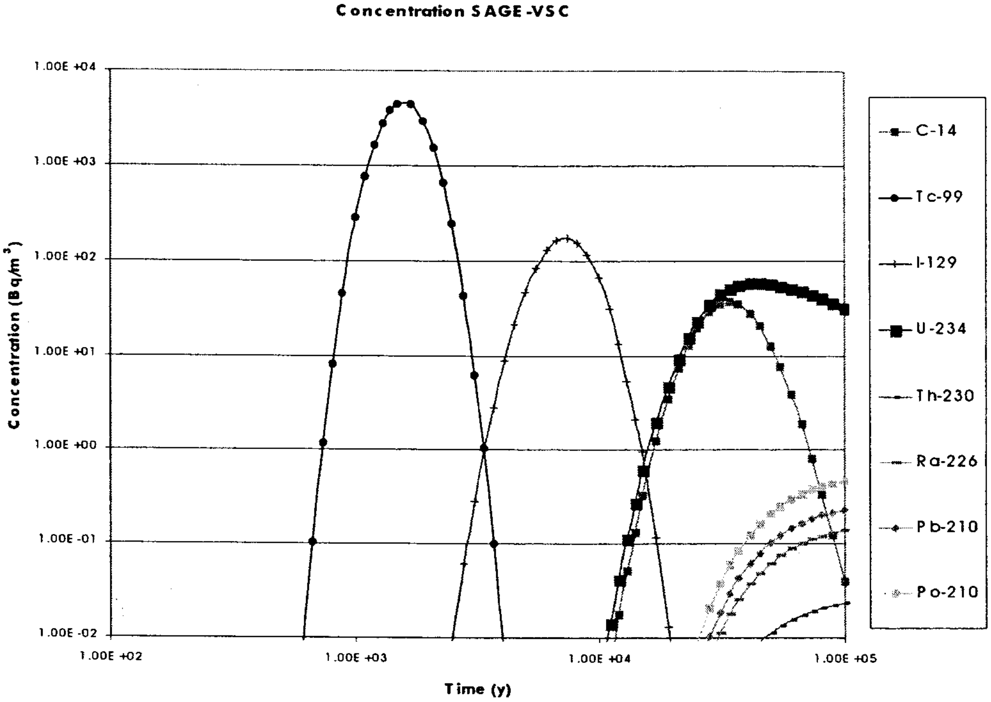

Fig. 5. Radionuclide concentration in the well water for IAEA vault safety case.

CONCLUSIONS

This paper described a new computer code, SAGE, developed as a tool for use in safety assessments of the Korean concept for LILW disposal. SAGE has been developed to provide functionality in evaluation releases to groundwater as part of a total safety assessment for development and licensing of a LILW engineered concrete vault disposal facility. Basic models for near field, far field, and biosphere have been included in the conceptual model, and the compartment modeling approach is described in this paper.

The SAGE Framework has been written with a Windows-compatible Graphical User Interface (GUI) to facilitate input of parameters into the assessment codes, and to interface with the LHS code for probabilistic sampling. Interfaces have also been provided to allow alternative conceptual models to be used for portions of the analysis, and their results incorporated in the SAGE analysis.

The functionality of SAGE has been tested, and the code has been benchmarked against a number of situations to ensure that the implementation is correct. In all cases SAGE compared extremely well with the benchmark analysis. A brief discussion of the application of SAGE compared to a system-level safety assessment analyses has also been provided. SAGE compares well with existing codes for conducting LILW safety assessments, and is anticipated to have significant benefits over those codes when used in a regulatory setting.

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