Performance Assessment Methodology and Preliminary Results for Low-Level Radioactive Waste Disposal in Taiwan

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ABSTRACT

Sandia National Laboratories (SNL) and Taiwan's Institute for Nuclear Energy Research (INER) have teamed together to evaluate several candidate sites for Low-Level Radioactive Waste (LLW) disposal in Taiwan. Taiwan currently has three nuclear power plants, with another under construction. Taiwan also has a research reactor, as well as medical and industrial wastes to contend with. Eventually the reactors will be decommissioned. Operational and decommissioning wastes will need to be disposed in a licensed disposal facility starting in 2014. Taiwan has adopted regulations similar to the U.S. Nuclear Regulatory Commission's (NRC's) low-level radioactive waste rules (10 CFR 61) to govern the disposal of LLW.

Taiwan has proposed several potential sites for the final disposal of LLW that is now in temporary storage on Lanyu Island and on-site at operating nuclear power plants, and for waste generated in the future through 2045. The planned final disposal facility will have a capacity of approximately 966,000 55-gallon drums. Taiwan is in the process of evaluating the best candidate site to pursue for licensing. Amongst these proposed sites there are basically two disposal concepts: shallow land burial and cavern disposal. A representative potential site for shallow land burial is located on a small island in the Taiwan Strait with basalt bedrock and interbedded sedimentary rocks. An engineered cover system would be constructed to limit infiltration for shallow land burial. A representative potential site for cavern disposal is located along the southeastern coast of Taiwan in a tunnel system that would be about 500 to 800 m below the surface. Bedrock at this site consists of argillite and meta-sedimentary rocks.

Performance assessment analyses will be performed to evaluate future performance of the facility and the potential dose/risk to exposed populations. Preliminary performance assessment analyses will be used in the site-selection process and to aid in design of the disposal system. Final performance assessment analyses will be used in the regulatory process of licensing a site. The SNL/INER team has developed a performance assessment methodology that is used to simulate processes associated with the potential release of radionuclides to evaluate these sites. The following software codes are utilized in the performance assessment methodology: GoldSim (to implement a probabilistic analysis that will explicitly address uncertainties); the NRC's Breach, Leach, and Transport – Multiple Species (BLT-MS) code (to simulate waste-container

degradation, waste-form leaching, and transport through the host rock); the Finite Element Heat and Mass Transfer code (FEHM) (to simulate groundwater flow and estimate flow velocities); the Hydrologic Evaluation of Landfill Performance Model (HELP) code (to evaluate infiltration through the disposal cover); the AMBER code (to evaluate human health exposures); and the NRC's Disposal Unit Source Term – Multiple Species (DUST-MS) code (to screen applicable radionuclides). Preliminary results of the evaluations of the two disposal concept sites are presented.

INTRODUCTION

Taiwan is in need of a permanent disposal facility for their low-level radioactive waste (LLW). There are multiple sources of LLW in Taiwan. Currently, Taiwan has three nuclear power plants and a fourth under construction. These power plants generate LLW and will eventually be decommissioned, thereby creating additional waste for disposal. The INER operates an experimental research reactor that generates waste, which is undergoing decommissioning. Medical and industrial LLW are also being generated. Taiwan is temporarily storing some of their LLW on an island called Lanyu off the southeast coast of Taiwan. The waste stored on Lanyu will be transported to the permanent disposal facility when it becomes operational beginning in 2014. Most of the LLW that has or will be produced is Class A, but Class B, C, and some Greater Than Class C (GTCC) waste are also present.

To date, Taiwan has not licensed a LLW disposal facility. The Taiwanese government looked to other countries for regulatory guidelines for LLW disposal. They have put regulations in place that are predominantly based on U.S. standards. In particular, Taiwan has adopted much of the language from the U.S. Nuclear Regulatory Commission's (NRC's) low-level radioactive waste rules (10 CFR 61) to govern the disposal of LLW.

One of the key products that must be produced in order to license a LLW disposal facility is a performance assessment of the post-operational behavior of the facility [1]. A performance assessment is intended to address the behavior of the facility in relation to how it meets specific performance criteria in the regulations. One such criteria stipulates that the releases of radioactive material to the environment through groundwater, surface water, air, soil, plants, or animals shall not exceed a maximum allowable dose to the whole body that is greater than 25 millirems per year [0.25 milliSeiverts]. The performance assessment must address uncertainties in the analysis, given the complexity of the source term packaging, breaching of containers, leaching of waste forms, and transport of contaminants to potentially exposed individuals.

Taiwan has been engaged in a siting process to select a potential LLW disposal site for over a decade. Among several responsibilities, Taiwan's Institute of Nuclear Energy Research (INER) has been charged with the responsibility of producing the performance assessment for the licensing activity. Through an arrangement with Lockheed-Martin Corporation, Sandia National Laboratories (SNL) is assisting INER in developing their performance assessment capabilities. SNL has extensive experience in the area of performance assessment. SNL has been a technical assistance contractor to the NRC for developing their guidelines for LLW performance assessment, as well as the lead lab for the performance assessment activities that were instrumental in getting the Waste Isolation Pilot Plant (WIPP) operational, and a key contributor to the total system performance assessment activities on the Yucca Mountain Project for high-level radioactive waste disposal.

This paper provides an overview of the performance assessment activities performed to date for evaluating candidate sites for Taiwan's LLW disposal facility, as well as associated licensing activities.

WASTE INVENTORY

Taiwan has a need to dispose of LLW from the following sources:

- Operational wastes from four nuclear power plants;
- Operational wastes from nuclear research facilities;
- Operational wastes from medical applications;
- Operational wastes from industrial applications;
- Decommissioning waste from four nuclear power plants; and
- Decommissioning waste from nuclear research facilities.

In terms of the volume of waste, INER estimates that there will be approximately 216,000 drums of solidified operational waste, about 70,000 drums of non-solidified operational waste, and about 680,000 drums of decommissioning waste. In terms of the total activity of the radionuclides in the waste inventory, INER estimates approximately 25,400 curies will be disposed. The principal radionuclides of concern, those that contribute approximately 99% of the activity in the waste streams, are: Ni-63, Cs-137, C-14, Co-60, Ba-137m, Sr-90, Y-90, H-3, Pu-239, Pu-240, and Am-241. Two other radionuclides of concern are Tc-99 and I-129, not because of there relative amounts of activity, but because of their mobility in terms of fate and transport in the subsurface and their long half-lives.

OVERVIEW OF POTENTIAL DISPOSAL SITES

Taiwan began a process of evaluating potential LLW disposal site locations in 1992. A companion paper in these proceedings provides an overview of Taiwan's site selection efforts [3]. There has been strong public opposition to some of the proposed locations, which has contributed to the lengthy siting process. At this time, Taiwan has narrowed the search to four candidate sites. INER is tasked with evaluating these four sites for potential compliance with the LLW rules and recommending the best site for licensing.

Two basic design concepts have been proposed for the four sites under consideration. One site, number 7, is located on a small island in the Taiwan Strait off the west coast of Taiwan. The waste disposal configuration at this site consists of shallow land burial of the waste in concrete lined trenches. Three separate groupings of trenches are proposed on two of the upland areas of the island. An engineered cover system would be constructed to limit infiltration for shallow land burial. The island is predominantly basaltic bedrock with interbedded sedimentary rocks. Sites 6, 8, and 9 have a very different disposal configuration. Each of these sites is located along the southeastern coast of Taiwan and would consist of a tunnel system that would be about 500 to 800 m below the surface. These sites are referred to as cavern disposal sites. Bedrock at these sites consists of argillite and meta-sedimentary rocks.

PERFORMANCE ASSESSMENT METHODOLOGY

As mentioned above, SNL is providing technical support to INER in support of the performance assessment activities for site selection and licensing. SNL has considerable experience in performance assessment, both for LLW and for high-level radioactive waste disposal. The performance assessment methodology being employed for Taiwan's needs is consistent with that recommended by the NRC [1]. The following steps are integral to a defensible performance assessment:

1. Evaluate existing data
2. Develop features, events and processes (FEPs) and scenarios
3. Develop conceptual model(s), assumptions, and parameter distributions
4. Formulate mathematical models and select computer codes for implementation
5. Conduct consequence modeling
6. Perform sensitivity analyses
7. Evaluate disposal site adequacy

At this point if the site does not meet the performance objectives, the decision makers must evaluate the need for additional site characterization data, formulating alternative conceptual models, redesigning the facility, or abandoning this design/facility in favor of another.

One area that SNL has particular strength in, and is assisting INER with, is the consequence modeling. SNL promotes the use of probabilistic methods in order to quantify uncertainties in meeting the performance objectives. Uncertainty analysis provides the decision makers with more powerful information by which they can base their decisions. It also lends more power to the sensitivity analyses, which in turn help justify the adequacy and importance of the data and parameter distributions that describe the site and its associated processes.

CONCEPTUAL MODEL CONSIDERATIONS

As mentioned above, none of the potential LLW disposal sites has been characterized adequately due to local opposition. Therefore, the preliminary performance assessment analyses will rely heavily on limited data and documented assumptions. Some of the more important assumptions are summarized below for the two types of candidate sites, the shallow land burial and cavern disposal concepts.

For all the sites under consideration the waste will likely be contained in carbon steel drums, galvanized steel drums, or concrete over-pack containers. Some of the LLW may be mixed with cement for solidification within the drums and containers. The drums or containers will be placed in concrete lined trenches or tunnels. It is anticipated that the drums will be subject to localized (i.e., pitting) and general corrosion processes. The concrete containers will be subject to general corrosion processes. These processes will cause the drums and containers to fail at different rates over different time periods.

Once the containers have failed the waste inside them will be potentially subject to several leaching processes. These processes will likely include:

- Rinsing mechanisms, whereby infiltrating groundwater coming in contact with the waste causes radionuclides to be leached advectively with the water;
- Diffusion mechanisms; and
- Dissolution processes.

In addition, the radionuclides may be subject to solubility constraints, as well as radioactive decay and ingrowth including daughter products. Once the radionuclides have been leached from the waste forms, they are subject to advective-dispersive transport processes in the host rock at each site.

For the shallow land burial site, potential site 7, it is known that the water table is fairly shallow, probably within several meters of the land surface. With a proposed cover system over the disposal units, the infiltration potential should be below the background recharge rate directly over the facilities. A potential for unsaturated flow conditions may exist within the source area, thereby decreasing the leaching potential of the waste form upon failure of the containment system relative to saturated flow conditions. Any potential transport of radionuclides out of the facility would be into the saturated rock lying beneath the site. The bedrock at this site consists of basalt and interbedded sandstone and mudstone. Conceptually, the flow and transport through this bedrock could be represented by two different processes. First, it could be considered as an equivalent porous media subject to advective-dispersive transport processes. Second, matrix diffusion could be considered important, whereby radionuclides diffuse both into and out of the secondary porosity of the bedrock due to the nature of the fracture-matrix interactions.

For the cavern disposal sites, such as potential site 6, it is quite likely that the tunnel systems will be located in saturated bedrock. The bedrock at this site consists of fractured argillite and meta-sedimentary rocks. Similar to potential site 7, the flow and transport through this bedrock could be represented by two different processes: as an equivalent porous media subject to advective-dispersive transport processes, or as matrix diffusion.

MATHEMATICAL AND COMPUTER MODEL CONSIDERATIONS

In considering the development of a mathematical and computer model to use in these performance assessment analyses, the conceptual model assumptions mentioned above are critical. A need exists to simulate the breaching (i.e., pitting and corrosion) processes associated with container failure, followed by the leaching (i.e., rinse, diffusion, and dissolution) processes of the waste form, and finally the flow and transport of radionuclides within the host rock to the accessible environment (e.g., a drinking water well). The flow and transport within the host rock may be considered by either of two conceptual models, equivalent porous media or matrix diffusion. In addition to the processes just summarized, the selected model must be capable of implementing an uncertainty analysis. All of these processes are under consideration through the implementation of the following computer models.

SNL has developed a methodology that involves the use of the Breach, Leach, and Transport – Multiple Species (BLT-MS) code [4] to implement the majority of the processes outlined above. BLT-MS is a finite-element based code developed by Brookhaven National Laboratories (BNL) for the Nuclear Regulatory Commission (NRC) specifically for LLW compliance analyses. SNL has a need of a probabilistic version of the code to evaluate uncertainties. BLT-MS has been integrated with the GoldSim code in order to implement a probabilistic model.

The BLT-MS code and its preprocessor (used to develop/modify input files) were developed in the mid-1990’s. They are FORTRAN codes that have been compiled to run under DOS or a DOS-emulator. SNL has developed Windows-based versions of these codes for ease of use with modern desktop computers. However, modifications to the input/output constructs of the model are necessary to integrate the code with GoldSim.

In implementing a probabilistic version of BLT-MS, decisions needed to be made regarding what input constructs would be considered to be uncertain. In the extreme, each realization of a probabilistic analysis could have a unique finite-element mesh, source term configuration, and parameter uncertainties. The input/output requirements, as well as the computational burden, could get prohibitively complex if this much flexibility were built into the tool. Therefore, some simplifying assumptions were made in order to make the code integration more practical.

It is quite common in probabilistic analyses that involve the potential to address spatial variability that the physical aspects of the problem are fixed, such as the model boundaries and finite-element mesh configuration. If there is a question about the design of the finite-element mesh and the boundary conditions, then this should be evaluated in terms of potential conceptual model uncertainty and additional model configurations contemplated to address this uncertainty explicitly. Therefore, it is recommended that a fixed, deterministic approach be taken for the design of the finite-element mesh and the specification of boundary node types (i.e., Cauchy, Neumann, or Dirichlet boundary conditions).

In addition to the overall configuration of the finite-element mesh and boundary conditions, it is also advantageous to fix the locations of the source term containers. If the elements containing containers are allowed to vary with each realization of a probabilistic analysis then the dependent specifications for container types, waste form types and breach/leach processes becomes much more intensive in terms of data configuration and formatting. In practice, any given site under consideration will have a proposed engineering design layout of the disposal area, so the physical configuration of the source term could be fixed based on this design. This still allows the user flexibility with the specifications of container types and waste form types for any of the specified containers. Therefore, the physical source-term configuration (e.g., elements containing containers) will be fixed/deterministic for any given probabilistic analysis, but the characteristics of each of the containers may be uncertain.

In summary, the input parameters that will remain fixed, or deterministic, are:

- Finite-element mesh design parameters/specifications;

- Material property assignments within the finite element mesh (although the characteristics of each material may be uncertain, the element assignments will remain fixed for a given material type);
- Finite element nodes for boundary conditions, including keeping the type of boundary condition fixed for a given node (i.e., Cauchy vs Neumann vs Dirichlet);
- Flow field Darcy velocities;
- Number of isotopic species (because specifying different decay chains for each model realization would be burdensome);
- Number of decay chains and branching fractions;
- Number of container types; and
- Number of waste types.

In general, the parameter sets that will be considered uncertain are in these areas:

- Initial concentrations within the source term;
- Breaching characteristics for any given container type;
- Leaching characteristics for any given waste type;
- Transport characteristics of the host rock/soil; and

The BLT-MS code does not explicitly simulate flow in the host rock. A separate computer model is needed to simulate flow and estimate Darcy flow velocities, which would then be input to the BLT-MS code. The Finite Element Heat and Mass Transfer code (FEHM) [5] was selected to simulate groundwater flow and estimate Darcy flow velocities. For potential site 7, there is a need to simulate infiltration through the cover material as well. The Hydrologic Evaluation of Landfill Performance Model (HELP) code [6] was selected to evaluate infiltration through the disposal cover. To simulate the potential health effects (i.e., dose) to any potentially exposed individuals, INER plans to use the AMBER code.

As mentioned above, there are two alternative conceptual models for transport of radionuclides in the host rock at each site. The equivalent porous media conceptual model can be implemented through the use of the BLT-MS transport module. The matrix-diffusion conceptual model can be implemented with the GoldSim model, which includes capabilities to simulate one-dimensional matrix-diffusion transport.

When BLT-MS is integrated into GoldSim in order to implement an uncertainty analysis capability, several Dynamic Link Libraries (DLLs) are created to accommodate interactions between the codes.

PRELIMINARY GROUNDWATER FLOW ANALYSES

Groundwater flow is an important pathway by which radionuclides could be released to a possible future receptor. Preliminary groundwater flow models were constructed for both potential sites and used to evaluate the flow directions and specific discharge from the repository locations to the receptor. In addition, the groundwater flow model at potential site #6 was used to estimate the groundwater flow rate through the repository horizon. Given the general lack of site-specific hydrological data, these groundwater flow models are conceptual in nature and are not calibrated to specific information on the potential sites.

Potential site #6 is representative of the cavern disposal concept for LLW in Taiwan. The site is located in the southeastern mountain area near the coastline of the Pacific Ocean and has high topographic relief (Fig. 1). Average annual precipitation is about 2.4 m/year, with surface drainage occurring along several streams near the site. Bedrock geology consists of fractured argillite and meta-sedimentary rocks.

A three-dimensional finite-element model of groundwater flow at potential site #6 was constructed using the FEHM software code [5]. A triangular element grid was generated to conform to the boundaries of the model domain and was projected in the vertical direction from 500 m below sea level to the topographic surface, forming a total of 70498 elements. No-flow lateral boundaries were specified approximately along ridge crests on the landward sides of the model domain. The ocean shoreline along the southeast margin of the model was set as a constant-head boundary with head equal to sea level and the lower boundary of the model was assumed to have no flow. The upper boundary of the model was specified flux as groundwater recharge, with the exception of nodes along streams (Fig. 1), which were assigned as head-dependent boundaries.

The resulting simulated steady-state groundwater flow field for potential site #6 indicates generally southeasterly flow toward the constant-head boundary of the ocean shoreline, as indicated by the contour map of simulated head shown in the lower plot of Fig. 1. The groundwater flow model also indicates upward flow near and discharge to the reaches of streams at lower elevations. Solute transport modeling indicates that contaminants released from the potential repository would be discharged to the ocean and to reaches of the main streams near the repository. Groundwater flow rates along a cross section through the three-dimensional flow model down gradient of the repository were extracted for simulations of radionuclide release and transport with the BLT software code in the performance assessment analyses.

Potential site #7 is representative of the near surface disposal concept for LLW in Taiwan. The site is located on an island in the Taiwan Strait and is shown in the topographic map of Fig. 2. The preliminary design concept is to develop three disposal units that would be capped by layered covers to limit infiltration through the waste. Average annual precipitation is about 0.95 m/year. Bedrock geology consists of basalt and interbedded sandstone and mudstone.

A three-dimensional finite-element model of groundwater flow at potential site #7 was constructed using the FEHM software code [5]. A triangular element grid was generated to conform to the shoreline of the island and was projected from an assumed interface with underlying salt water, up to the topographic surface, forming a total of 211732 elements. Constant-head boundary conditions were assigned at the shoreline of the model, extending to a depth of 20 m below sea level. Groundwater flux corresponding to recharge was specified at the upper boundary of the model. A lower value of recharge was specified below the disposal units, corresponding to the diminished infiltration through the disposal unit covers estimated using the HELP software code [5], as described below. No-flow conditions were assumed at the lower boundary of the groundwater flow model. Geological heterogeneity was incorporated in the flow model for potential site #7 as a lens of sedimentary rocks between predominantly basalt units near sea level in the center of the island.

The resulting simulated steady-state groundwater flow field for potential site #7 indicates generally outward flow toward the constant-head boundary of the ocean shoreline, as indicated by the contour map of simulated head shown in the right plot of Fig. 2. Strong downward vertical hydraulic gradients in the basalt indicate downward flow in the basalt. Generally horizontal outward flow is simulated to occur in the sedimentary geological unit, as indicated by the contours of head in Fig. 2. Groundwater flow rates were extracted from a southeasterly oriented cross section originating from the disposal unit on the east northeast side of the island. These estimated two-dimensional groundwater flow vectors were exported to the BLT software code in the performance assessment analyses.

Infiltration through the layered landfill covers over the disposal units at potential site #7 was estimated using the HELP software code [6]. The quasi-two-dimensional water routing model of infiltration implemented with the HELP software uses a synthetic weather record, based on estimates of average values of precipitation, temperature, wind speed, and relative humidity. A preliminary cover design concept and estimates of material properties were specified in the model. The resulting preliminary estimate of percolation flux through the cover and into the waste zone was 45 mm/year.

PRELIMINARY PERFORMANCE ASSESSMENT RESULTS

The GoldSim/BLT-MS code has been assembled and is being used for preliminary performance assessment analyses. It is premature to report any formal results. However, some insights have been gleaned from these preliminary results. As mentioned above, the primary radionuclides of interest in the analysis are Ni-63, Cs-137, C-14, Co-60, Ba-137m, Sr-90, Y-90, H-3, Pu-239, Pu-240, Am-241, Tc-99 and I-129. Three radionuclides have emerged from the preliminary analyses with predicted concentrations well above the other contaminants, which are: C-14, Tc-99, and I-129. The primary reason for concern with these radionuclides is that they are relatively mobile and do not sorb readily within the waste forms or host rock. In addition, they are relatively long lived. Additional analyses are needed before any substantial conclusions are drawn from this analysis. In addition, there is a need for additional site characterization data. Future work will also include sensitivity analyses.

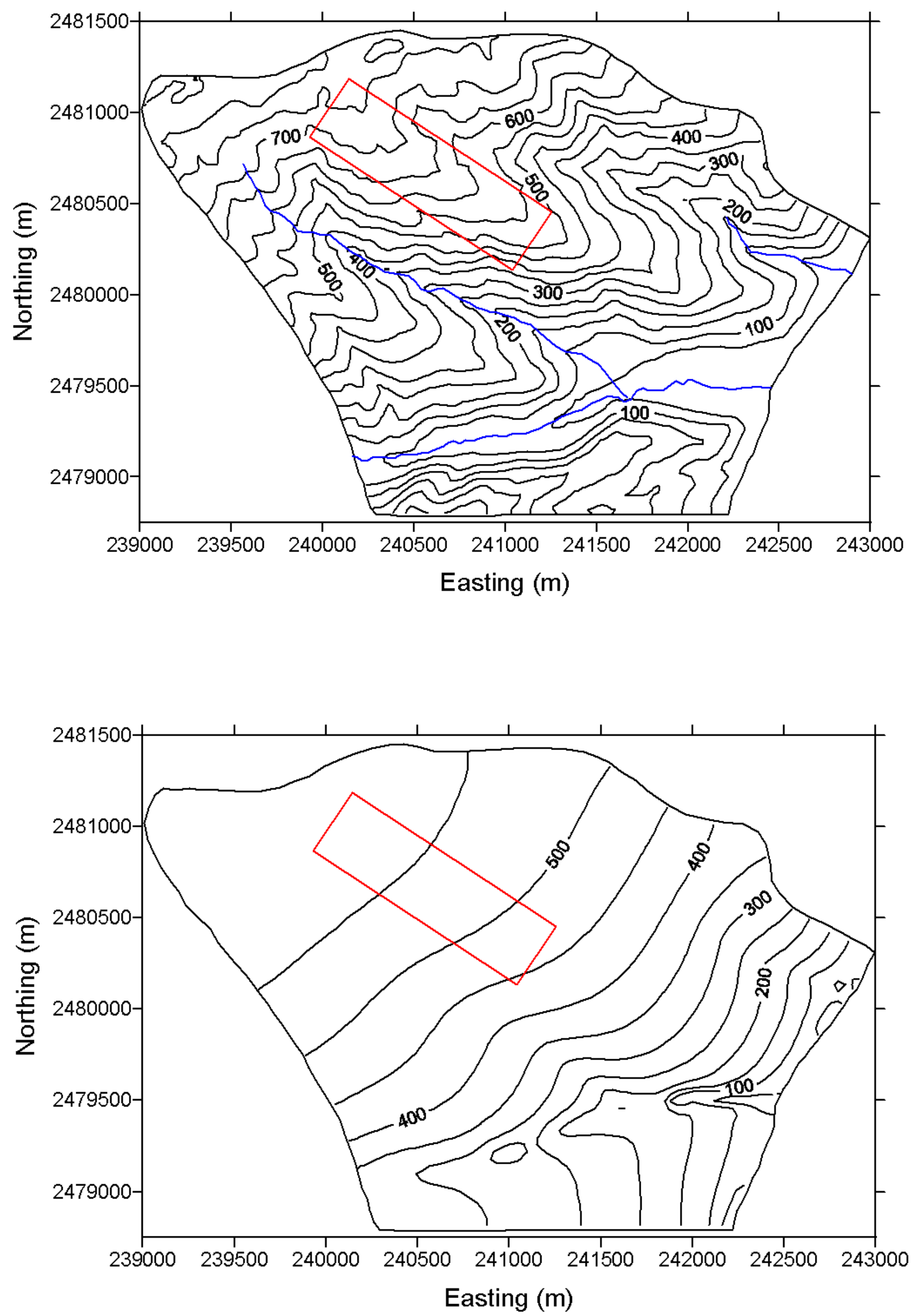

Fig. 1. Topographic map of elevation (meters) of the groundwater flow model domain (above) and simulated head (meters) at sea-level elevation in the groundwater flow model (below) for potential site #6. Streams are shown with blue lines and the potential cavern repository outline is shown in red

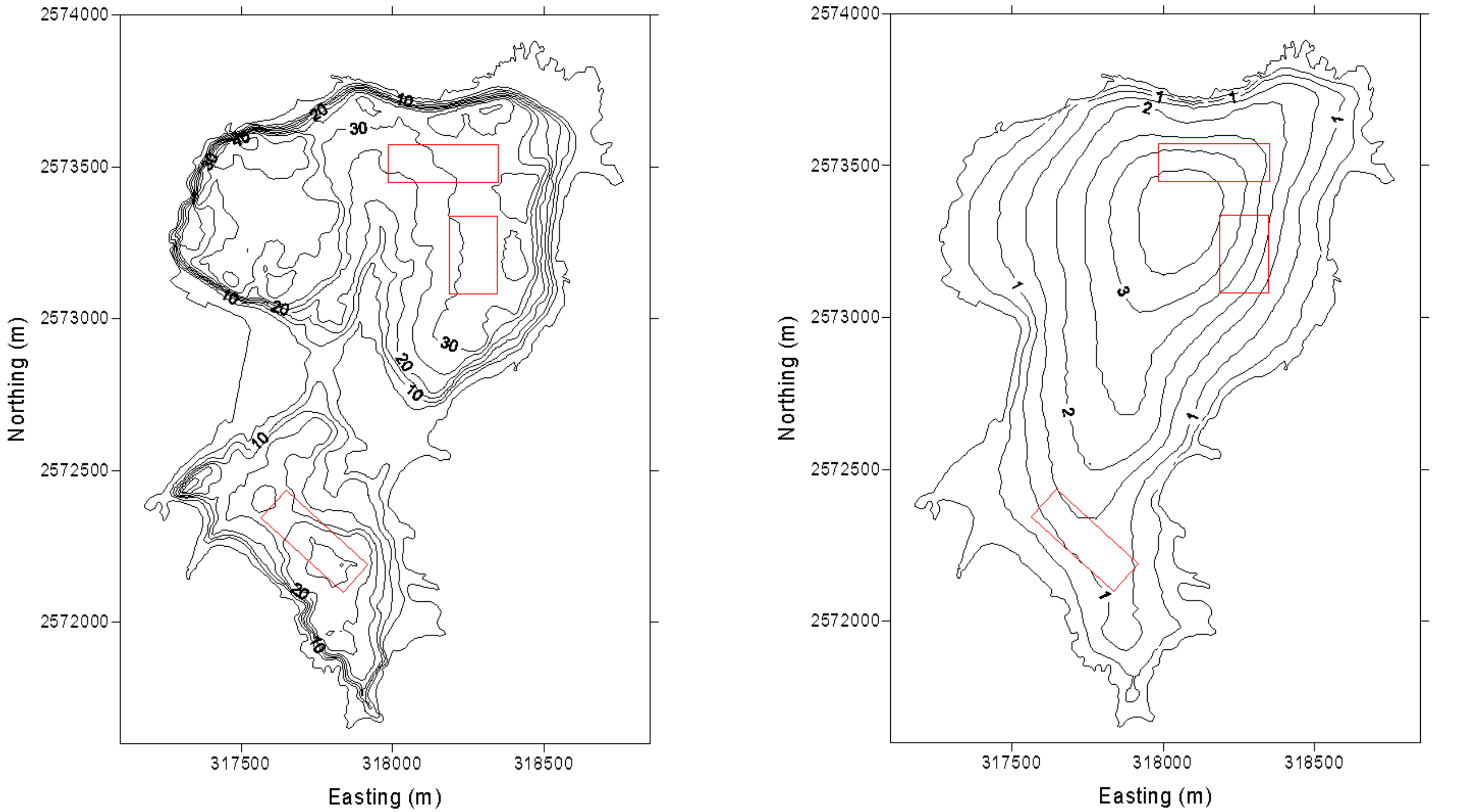

Fig. 2. Topographic map of the island (left) and simulated head at sea-level elevation in the groundwater flow model (right) for potential site #7. The potential near-surface repository disposal units are shown in red.

CONCLUSION

SNL and Taiwan's INER are collaborating on performance assessment activities for siting a LLW disposal facility in Taiwan. A probabilistic model has been developed using a suite of codes, including BLT-MS and GoldSim, in order to implement this methodology. Using this integrated code suite, uncertainty analyses are being performed in order to simulate the breach, leach and transport processes associated with potential failure of the proposed facilities. In addition, other codes such as FEHM and HELP are being employed to supplement the analyses in order to simulate groundwater flow at the proposed sites. Preliminary results suggest that mobile, long-lived radionuclides are of potential concern.

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