ABSTRACT

In 2004, Slovenia started a new siting procedure for a Low and Intermediate Level Waste (LILW) repository. At the end of 2009 the Slovenian government approved the Decree on Detailed Plan of National Importance for Krško Vrbina site, with a near-surface silo concept as the future Slovenian LILW repository concept. For the repository, it is very important to establish confidence in the long term safety of the design at the selected site. This is especially important, because as with most LIL short lived waste repositories, the inventory for disposal could include traces of some longer lived radionuclides, which cannot be separated from the shorter-lived activity. The demonstration that the impact of the disposal system is negligible in the long term is the safety case, an important part of which is the safety assessment.

At the beginning of the paper, the methodology will be presented that was used for the preparation of the last iteration of the long-term safety assessment for the planned Slovenian LILW repository. The paper will then proceed with descriptions of components of the safety assessment: the assessment context, preparation of alternative conceptual models, modelling work, and results and their interpretation.

1 INTRODUCTION

The Slovenian agency for radwaste management (ARAO) completed its siting procedure for the LILW repository in 2009. The Vrbina Krško site and its associated near-surface silo disposal concept were approved by Slovenian government, and the licensing phase was started.

The main goal of this phase is to attain confidence that the combination of the repository site and the disposal concept is safe, especially regarding long-term safety. This information is used both in the license application and to support an Environmental Impact Assessment. To obtain the license for the nuclear facility, a Safety Analysis Report must be prepared[1]. The closest synonym to the Slovenian Safety Report in international practice is the Safety Case. Recommendations on the content and preparation of the Safety Case have been issued by International Atomic Energy Agency (IAEA) [2]. One of the important parts of the safety case is the safety assessment, which has the purpose to develop reasonable assurance that the facility will remain within regulatory safety constraints for long times into
the future, as established in regulation. A methodology was developed, and has become an internationally accepted approach to safety assessment. This methodology is sometimes called the ISAM methodology after the programme in which it was formalised[3]. A key property of this methodology is that it is used iteratively to manage the uncertainties and sensitivities in long-term assessments. In the early stages of the planning of the LILW repository the uncertainties are large, and they are progressively reduced in later stages. An important point is that the safety assessment should be prepared for each phase of the LILW repository life cycle – siting, design, construction, operation, closure, and post – closure monitoring. At each stage the confidence in the safety of the repository is progressively improved and refined.

In 2010 ARAO contracted a consortium that includes ENCONET Consulting (Austria), INTERA, Inc. (US and France), Studsvik (Sweden), Facilia AB (Sweden) and IRGO (Slovenia), hereafter called the EISFI team, to carry out a radiological safety assessment for the proposed LILW repository at Vrbina - Krško, Slovenia. In this paper the work carried out during 2011 and 2012 is presented, focusing on the post-closure safety assessment and results [4].

2 VRBINA – KRŠKO SITE AND NEAR SURFACE – SILO DISPOSAL CONCEPT

The Vrbina – Krško site, where the Slovenian LILW repository will be constructed, lies on left bank of the river Sava, approximately 300 m east from Krško NPP (Figure 1).

![Figure 1: Vrbina – Krško site, marked by orange circle (source: Geopedia.si)](image)

The area of the site is covered by about 10 m thick layers of Quaternary gravels with a 5 m thick phreatic aquifer. Beneath this surface layer lies a low permeability deposit of Miocene silts; this Miocene layer is the host formation for the repository. From a hydrogeological point of view, the Miocene layer would ordinarily be described as an aquiclude.

The future LILW repository is planned to be constructed from the surface. The reinforced concrete cylindrical structure, a silo, is to be excavated to a depth of 55 m and the waste is to be disposed in concrete containers in ten layers (Figure 2). Once filled, the silo is to be capped with a concrete “roof” and a 5 m thick clay layer is to be placed on the top of reinforced concrete plate. Above this, gravel is to be backfilled to the surface elevation, matching the hydraulic properties of the Quaternary aquifer.
3 ASSESSMENT CONTEXT

An initial task of the safety assessment is to evaluate the primary regulatory constraints, which are given in JV5 regulations [5]. In Annex 4 of JV5 it is written:

“Following its closure, a repository shall not impose a burden exceeding 0.3 mSv/year on a member of the public under the normal repository-development scenario [5]. In cases of alternative repository-development scenarios, the following measures shall be implemented, depending on the burden imposed on a member of the public:

a. for up to 10 mSv/year, no repository-optimisation measures are required;

b. for above 10 mSv/year, measures to minimize the probability of an alternative repository-development scenario are required;

c. for above 100 mSv/year, measures to minimize the consequences of the alternative repository-development scenario are required.”

In addition to these radiological criteria for the post-closure period, the potential impact of the non-radioactive toxic components present in the waste was evaluated and the limitations from Slovenian regulation for the drinking water were used [6]. Furthermore, to follow the ICRP recommendations [7], an explicit evaluation of the impact on nonhuman biota was included.

Based on good European practice, a period of 300 years of institutional control was taken into account. That means that for this period of time, the closed repository will be considered to be under control, eliminating the potential for inadvertent intrusion.

4 INVENTORY

The radioactive waste planned to be disposed in LILW repository comes from several origins:

- Operational waste from the Krško NPP over its lifetime,
- Decommissioning waste from the Krško NPP,
- Waste generated at Jozef Stefan Institute (operational and decommissioning),
- Waste from Central Interim Storage Facility in Brinje,
- Decommissioning and operational waste from repository itself.

One of the tasks of the project was also to reassess the whole inventory on the basis of the work already done in the past \cite{8,9}, as well as more recent data, findings, and assumptions. The results are presented in following tables.

Table 1: Material inventory by volume \cite{4}

<table>
<thead>
<tr>
<th></th>
<th>Krsko NPP Op. Waste for 2043 Decom. (m³)</th>
<th>Krsko NPP Decom. Waste, 2043 (m³)</th>
<th>JSI (Triga) Decom. Waste (m³)</th>
<th>CIS Forecast, 2050 (m³)</th>
<th>Repository Op. Waste (m³)</th>
<th>Repository Decom. Waste (m³)</th>
<th>Total (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.95E+03</td>
<td>7.82E+03</td>
<td>3.56E+02</td>
<td>6.90E+02</td>
<td>4.30E+01</td>
<td>8.36E+01</td>
<td>1.90E+04</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Radionuclide inventory (Bq) \cite{4}

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.62E+14</td>
<td>2.33E+17</td>
<td>5.13E+12</td>
<td>8.83E+12</td>
<td>1.30E+09</td>
<td>1.14E+11</td>
<td>2.33E+17</td>
<td></td>
</tr>
</tbody>
</table>

5 SCENARIOS

A formal process for identification and justification of scenarios was followed, comprising 4 steps: 
- Identifying Features, Events and Processes (FEPs),
- FEPs screening,
- Describing the relationships between FEPs,
- Arrange everything (FEPs + relationships) in scenarios.

The work resulted in the following scenarios that were included in the safety assessment.

5.1 Nominal scenario

This scenario describes the future evolution of the repository in the absence of unusual or unexpected events and processes, and it can be shortly described as follows.

After closure, the 300 years of institutional control period is retained. The silo is saturated immediately after closure and all engineered barriers start to degrade. A single family dwelling is assumed to be built nearby the site (at 100 m - which is very near), and a water well in the Quaternary sediments is used to supply the family water needs. This is the
primary potential exposure route to humans. In addition, the potential for discharge to the river is evaluated.

5.2 Early failure of engineering

This scenario represents a large number of potential initiating FEPs that may affect the functions of the barriers to isolate the waste. One such FEP is a possible seismic event outside the design basis. This scenario was evaluated in the same way as the nominal scenario, except that all engineered barriers fail quickly after the end of the institutional control period – after one year all the physical properties of the engineered barriers fail. This scenario was assessed as low probability.

5.3 River meander and surface erosion

The potential for discharge to the river in its current location is evaluated as part of the reference scenario. This scenario was included to evaluate the potential for the transport path length to the river to become shorter in time as the river bed meanders. It is not considered geologically credible for there to be sufficient erosion to reach the burial depth of the repository during the 10,000 year performance period, so the main difference between this scenario and the reference scenario with river exposure analysis is a shorter transport path.

5.4 Inadvertent human intrusion

Because of the combination of the disposal concept and the site (disposal depth, location below the depth of water resources) the probability of an intrusion event is very low. The main credible intrusion scenario is exploratory drilling. This scenario was included in the safety assessment, but is emphasized to be very unlikely.

5.5 Changes in hydrological conditions

Many FEPs can be considered that would lead to changes in the hydrological conditions of the site finding, from climate changes to construction of a dam on the river. Some such conditions have the potential to be detrimental to performance, while others might be favorable. The effect of all of these changes would be changes in the magnitude and direction of the flow velocities in the near field and aquifer.

Figure 3: Hydraulic head around the repository site (site is in the middle of the figure) calculated with FEFLOW. Figure excerpted from [4]
6 MODELING FRAMEWORK

The disposal system was divided in three subsystems: repository near field, far field and biosphere. For near-field modeling, to obtain the flow through the silo, the HYDRUS code was used. A valley-scale model for the far field flows was modeled with the FEFLOW code (Figure 3). For transport in the near field, failure of engineered barriers, transport in the far field, and for the biosphere, a system model was implemented in Ecolego. The system level model Ecolego took abstracted flows from the HYDRUS and FEFLOW models as inputs to integrate the modeling into a comprehensive model of the overall system (Figure 4).

![Diagram](image.png)

Figure 4: Illustration of radionuclide transport in ECOLEGO system level model. Figure excerpted from [4]

Ecolego uses a compartment model approach to represent the spatial components of the system; Ecolego’s interface illustrates the compartments and transfers between them as an interaction matrix. Each compartment is homogeneous (i.e. within it, concentrations are uniform and assumed to be instantaneously mixed) and corresponds to a physically separate part of the physical system. Mathematically this results in a set of coupled Ordinary Differential Equations (ODE), each corresponding to a state variable, such as the radionuclide inventory in a system compartment. For each model compartment, several states are defined - one for each radionuclide present in the waste. The compartments are connected to each other using transfer rates, corresponding to transport processes of radionuclides between compartments. These transport processes represent the physical and chemical behavior of the system as it evolves in time and may include parameters which are dependent on the radionuclide, its chemical form and characteristics of the system. Thus the three submodels are linked by simple mass transfer equations.

7 RESULTS

The safety assessment [4] provides a wide range of results for each scenario and conceptual model considered in the safety assessment. Furthermore, sensitivity and uncertainty analyses were performed using both deterministic and probabilistic approaches. The figure below shows the result for the nominal scenario (Figure 5) an assumption that there is a hypothetical well located down gradient in the centerline of the groundwater contamination plume and that the members of the public use just the water from this well for their water supply. Within the 10,000 year time frame the first peak occurs and the radionuclide Ca-41 which generates over 90% of the dose. At very long time periods, on the order of 400,000 years, the analysis shows doses approaching the dose constraint. These doses are the result of the ingrowth of Ra-226 and its progeny from uranium in the inventory.
Figure 5: Nominal results (in Sv/y) for releases including a well receptor, using a probabilistic calculation showing the effect of parameter uncertainty. Figure excerpted from [4]

Figure 6: Nominal scenario results (in Sv/y) for discharge to the river Sava without a well. Figure excerpted from [4]
Doses at such long time periods must be regarded as qualitative and not to be rigorously compared to the dose constraint. Nevertheless, the calculations suggest that, even at extremely long time periods, the doses do not grow to very high values and the system remains passively safe. One of the variants of the nominal scenario, which is more likely, is that potential exposures from releases from the facility would be associated with exposures to river water, without the well present. Results are presented in Figure 6 and we can see that the peak dose is many orders of magnitude below the dose constraint. The Erica software was used to calculate the impact of the repository on non-human biota and calculations show acceptable dose rates to non-human biota at all times in the future. Calculations for non-radioactive toxic materials were performed and results are presented in following table.

Table 3: Comparison of calculated groundwater concentrations to the regulatory limit for non-radioactive toxic contaminants of concern [4]

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Calculated Concentration (µg/L)</th>
<th>Regulatory Limit (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium</td>
<td>12,6</td>
<td>50</td>
</tr>
<tr>
<td>Lead</td>
<td>0,017</td>
<td>10</td>
</tr>
<tr>
<td>Nickel</td>
<td>0,971</td>
<td>20</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0,0003</td>
<td>5</td>
</tr>
<tr>
<td>Selenium</td>
<td>0,0015</td>
<td>10</td>
</tr>
</tbody>
</table>

8 CONCLUSIONS

The post-closure safety assessment has shown that the proposed facility meets the regulatory safety criteria for post-closure safety with good margin for all the analyses conducted. We can conclude that impact of the planned Slovenia LILW repository in Vrbina Krško will have negligible impact on humans and the environment.

REFERENCES