Probabilistic Risk Assessment for the Design and Operation of a Radioactive Waste Disposal Facility – 14617

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ABSTRACT

In Germany, a Probabilistic Risk Assessment has been applied as part of the operational safety assessment during the conceptual design of a radioactive waste disposal facility already some 20 years ago. The Probabilistic Risk Assessment underpins the low risk assumptions made in the conceptual design of a geological disposal facility and aims to calculate the frequency of occurrence of events which may lead to an increase of radiation exposure of the operating personnel and of events which may lead to release of radioactive materials into the environment.

The Probabilistic Risk Assessment covered the complete sequence of operations, from the arrival of the waste package on surface, through the shaft transport, and finally to its final disposal underground. The considered geological disposal facility was designed to receive heat generating waste as well as non-heat generating waste. Therefore, different disposal techniques and different sizes and types of waste packages were taken into consideration during the analysis.

For the Probabilistic Risk Assessment, fault trees were built and evaluated separately for each disposal technique and type of waste. The results were calculated as frequency of occurrence per waste package cycle and in a second step, using the number of waste packages expected to be disposed in the facility, as frequency of occurrence per operating year.

DBE TECHNOLOGY GmbH is presently continuing the work. The current work focuses mainly on improving the quality of the results and on modeling the sequence of operations in the geological disposal facilities in order to bring the utilization and relevance of this technique to a similar level to the one in the nuclear power plants.

INTRODUCTION

Since risk-informed approaches have been introduced as an additional mean to assess the safety of nuclear facilities, their significance has constantly been growing. This is also true in the case of radioactive waste repositories, even though efforts mainly focus on the long-term safety of repositories. But for the operation of Low and Intermediate Level Radioactive Waste (LILW) disposal facilities, risk-informed approaches have been applied in recent years; and with High-Level Radioactive Waste (HLW) programs becoming more developed, operational safety of geological disposal facilities is getting higher attention.

In Germany, a Probabilistic Risk Assessment has been applied as part of the operational safety assessment during the conceptual design of a geological disposal facility already 20 years ago.
The Probabilistic Risk Assessment was carried out with the aim of bringing additional information to the deterministic safety evaluation in a similar way as it was done in the nuclear power plants. The scope of the work covered the complete sequence of operations carried out for each type of waste package expected to be disposed of in the geological disposal facility. Consequently, the

reliability of all the relevant equipment necessary for the transport, handling and disposal of the waste packages was carefully assessed.

The Probabilistic Risk Assessment analyzed the possibility of safety relevant situations which may have an impact on the operation of the facility, its operating personnel, and on the environment, and calculated the frequencies of occurrence of such situations. For this purpose two events were determined:

- Increase of radiation exposure of the operating personnel.
- Release of radioactive materials into the environment.

DESCRIPTION OF THE FACILITY

The considered conceptual design for a geological disposal facility foresaw the construction of two shafts and the possibility of receiving radioactive waste packages with heat generating waste and also waste packages with negligible heat generating waste at the same time. The most appropriate designs of containers for such wastes have been taken into account. Moreover, three different disposal techniques were considered:

- Drift disposal;
- Borehole disposal; and
- Mixed borehole and drift disposal.

The scope of the work covered the complete sequence of operations, which were structured in three main areas in order to structure the work in a reasonable manner:

- On-surface operations;
- Shaft transport; and
- Underground operations.

The complete sequence of operations considered in the analysis is represented in the Fig. 1.

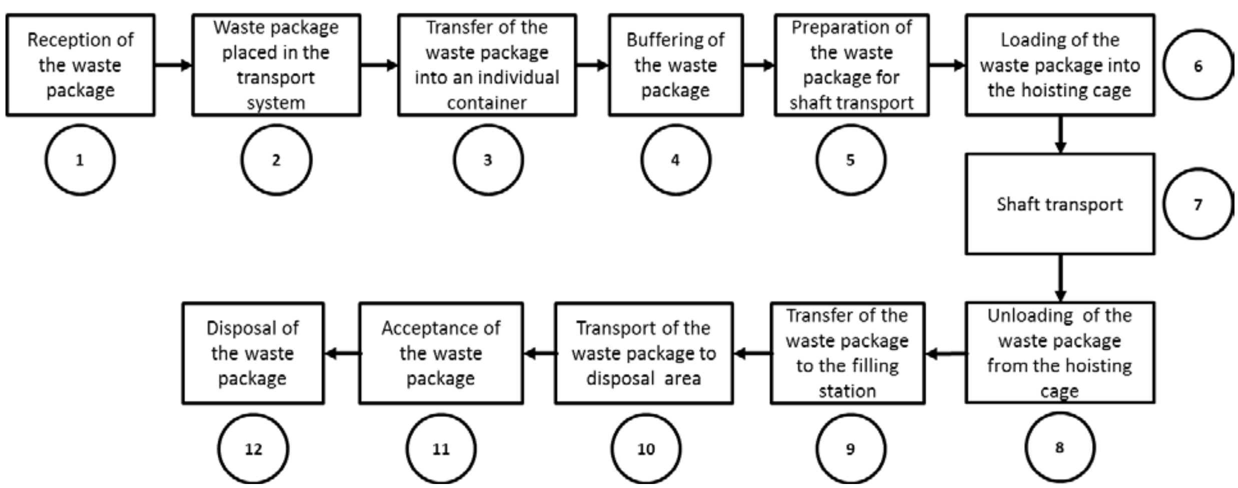

Fig. 1. Sequence of operations

Each of the twelve main operations is formed by a sequence of sub-operations, which defined the operations carried out and the components and equipment utilized in a more precise manner.

SELECTION OF SAFETY-RELEVANT SCENARIOS

The condition necessary for an increase of radiation exposure of the operating personnel was defined as a forced long stay of the operating personnel within a distance of approximately 5 m from the waste package. This event may result from a blocked waste package during one of the operational steps and requires that the operating personnel work close to the waste package in order to unblock the situation. The same approach was used for both types of waste packages, heat generating waste and non-heat generating waste.

On the other hand, a release of radioactive material into the environment may result from sustainable damage of the waste package container. These situations may happen if the waste package container crashes onto an unyielding surface or if a heavy load falls onto the container and the kinetic energy involved is sufficiently high.

According to the results of the experimental tests carried out by the Federal Institute for Materials Research and Testing, the required kinetic energy in order to damage the containers containing heat generating waste may be only produced by a free fall of the waste package from a height of more than 9 m. For the containers containing non-heat generating waste, the height has to be higher than 1.2 m. In this analysis, loads resulting from collisions of the containers against vehicles or other equipment were not considered.

METHODOLOGY

Fault trees were used for the determination of the frequency of occurrence of the two events, “Increase of radiation exposure of the operating personnel” and “Release of radioactive material into the environment”.
At the top of the fault trees, there were the two mentioned events, defined as TOP-events, which were connected to the Basic-events, at the bottom of the fault trees, through combinations of logic gates “AND” and/or “OR”, which modeled the possible combinations of undesired events that may lead to the TOP-events.

The fault trees were assessed in a quantitative manner using the minimum cut sets, which provided the minimum conditions necessary for the occurrence of the TOP-events. For the quantitative assessment, and therefore for the calculation of the frequencies of occurrence of the TOP-events of each fault tree, reliability data for the Basic-events were needed.

Twenty years ago the availability of reliability data of the components to be used in such a facility was very limited. For this reason, most of the frequencies of occurrence regarding the failures of the components were taken from comparable fields or were estimated.

The creation and evaluation of the fault trees was done separately for each disposal concept and for each type of waste package, in total 16 different fault trees were created. For this reason, and in order to facilitate the understanding of the structure of the fault trees and to facilitate the analysis of the results, a matrix, see Table I, was created.

TABLE I: Fault trees overview

<table>
<tr><th rowspan="2">Event</th><th rowspan="2">Area</th><th colspan="3">Waste with heat generation</th><th>Waste with negligible heat generation</th></tr>
<tr><th>Mixed borehole and drift disposal</th><th>Drift disposal</th><th>Borehole disposal</th><th>Drift disposal</th></tr>
<tr><td rowspan="3">Increased radiation exposure of the operating personnel</td><td>On-surface</td><td>Fault Tree 1</td><td>Fault Tree 2</td><td>Fault Tree 3</td><td>Fault Tree 4</td></tr>
<tr><td>Shaft</td><td colspan="4">Fault Tree 5</td></tr>
<tr><td>Underground</td><td>Fault Tree 6</td><td>Fault Tree 7</td><td>Fault Tree 8</td><td>Fault Tree 9</td></tr>
<tr><td rowspan="3">Release of radioactive material</td><td>On-surface</td><td>Fault Tree 10</td><td>Not applicable</td><td>Fault Tree 11</td><td>Fault Tree 12</td></tr>
<tr><td>Shaft</td><td colspan="4">Fault Tree 13</td></tr>
<tr><td>Underground</td><td>Fault Tree 14</td><td>Not applicable</td><td>Fault Tree 15</td><td>Fault Tree 16</td></tr>
</table>

The assessment of the fault trees was carried out based on the duration of the whole sequence of operations of each waste package and, therefore, calculating the probabilities of failure of the components, based on their operating time. This approach resulted in the frequencies of occurrence of the two mentioned TOP-events per waste package cycle.

In a further step and due to the fact that the expected number of each type of waste package per year was known, it was also possible to calculate the frequency of occurrence of the two TOP-events per operating year. The result was provided by multiplying the frequencies of occurrence per waste package cycle and the expected number of waste packages per year.

As the uncertainty of the data regarding the failure rates of the components used for the calculations had to be taken into consideration, a Monte-Carlo simulation was used and the following parameters were calculated:

- Expected value (Mean);
- Median;
- The below 5% percentile; and
- The above 95% percentile.

RESULTS

The resulting frequencies of occurrence, expressed as expected values, for the event “Increase of radiation exposure of the operating personnel” were between 6.5*10-3 and 3 per operating year, while the resulting frequencies of occurrence for the event “Release of radioactive materials into the environment” were between 6.5*10-11 and 1.8*10-2 per operating year. The wide range of values resulted, as commented before, because different frequencies of occurrence were determined for each type of container and for each disposal technique.

It is relevant to remark that these results do not include any statement regarding the duration of the radiation exposure, i. e. the health impact cannot be determined since the duration of radiation exposure, which has got a decisive influence on the health, is neglected. Similarly, the quantity of radioactive material released into the environment was also not assessed – only the occurrence of a release independently of the quantity was determined.

CURRENT WORK

The work carried out in Germany twenty years ago is being continued in order to improve the quality of the results and to provide an additional tool to the safety assessments of geological disposal facilities, as is already done for nuclear power plants.

Currently, DBE TECHNOLOGY GmbH is working on a research and development project, promoted by the Project Management Agency Karlsruhe (PTKA) called “Safety studies on the shaft transport of heavy loads up to 175 t (SULa)” in which the methodology used and the results obtained during the last twenty years as well as the current Probabilistic Risk Assessment methodology used for the German nuclear power plants will be analyzed in detail in order to determine the best methodology for assessing the safety of the shaft transport facility of a geological disposal facility.

However, from our point of view, in order to bring the Probabilistic Risk Assessment of the geological disposal facilities to a level similar to the one used for the nuclear power plants, there are also other themes to be developed during the next years.

Modeling of the Facility

The current work of the DBE TECHNOLOGY GmbH in this field focuses on the standardization and the modeling of the sequence of operations to be followed by the waste packages in the geological disposal facilities, based on the work performed in Germany during the last twenty years, but also considering the current conceptual designs of these facilities.

The main objective of this work consists, firstly, in defining a modular structure, containing the main activities, and, then, linking each of these modules with their respective fault trees, and then with the reliability data of the implied components and systems.

This basic structured model could be the basis of future Probabilistic Risk Assessments of facilities with different conceptual designs. From our point of view, and taking into consideration that the operations of most of such facilities are similar, having well-defined models for the main operations would reduce considerably the effort of performing a Probabilistic Risk Assessment during the conceptual design of the facilities and, moreover, different conceptual designs could be compared in an low-effort manner using the appropriate modules according to the characteristics of each specific design. It is important to remark, that as far as part of the operations in the underground disposal facilities and in the surface disposal facilities are similar, most of the modules could be also used to assess conceptual designs for surface disposal facilities.

Presentation of Results

As explained before in this paper, the results obtained in the analysis performed in Germany twenty years ago, did not provide any measure regarding the extent of radiation exposure to the operating personnel, or regarding the quantity of radioactive material released to the environment.

Presenting the results in such a manner, it is not possible to evaluate the impact of the risks analyzed and, for example, to evaluate the need of modifying the design. Hence, from our point of view, one further step is necessary.

In order to go one step further, different end states will be defined by the level of the potential load of radiation exposure of the operating personnel and by the potential quantity of radioactive material released to the environment. These end-states may be defined according to ranges of measures, which may be determined taking into consideration relevant international standards regarding the radiation exposure of operating personnel and regarding the release of radioactive material into the environment of such facilities. For example, in Germany, the Radiation Protection Ordinance [1] limits the effective dose of the occupationally exposed persons to 20 mSv during one calendar year, therefore a potential end-state might describe increase of radiation exposure up to 20 mSv per year and another end-state might be defined as increase of radiation exposure of more than 20 mSv per year.

For this purpose, event trees will be built to represent the evolution of the initiating events, which may lead to the different end-states, in a similar manner as is being currently done in the Probabilistic Risk Assessment of nuclear power plants.

Design Tool

Finally, the Probabilistic Risk Assessment may be also used as a design tool. Due to the requirements defined by the national policies and the international standards, safety requirements are usually well known before the start of the detailed design of the facilities. The modular structure described before would facilitate the design of the components by creating a direct relation between the results of the Probabilistic Risk Assessment and the specifications of the components. For example, it may be possible to select the most appropriate materials of the components according to their impact on the safety of each operation.

CONCLUSIONS

As expected before the start of the analysis, the frequencies of occurrence obtained for the event "Release of radioactive materials to the environment" were considerably smaller than the frequencies of occurrence obtained for the event "Increase of radiation exposure of the operating personnel". The sequence of the operations was designed in order to minimize the number of possible situations, which may result in the two safety relevant events, but the design of the containers was the main reason for the difference between the results of the two events. The design of the containers reduced considerably the number of situations which may result in a "Release of radioactive materials to the environment" since most of the operations could be designed in order to avoid such situations (e.g. avoiding operations where the containers could fall from relevant heights).

It was also noted that the frequency of occurrence for the event "Release of radioactive materials to the environment" of the waste packages with non-heat generating waste was considerably higher than the one obtained for the waste packages with heat generating waste. Here, the reason of the difference between the values may be found in the design and the characteristics of the containers used for one type of waste and for the other. As the containers used for non-heat generating waste may be sufficiently damaged after a free fall from a height higher than 1.2m, which is considerably lower than the 9 m required for the containers used for the heat generating waste, a higher number of possible situations during the sequence of operations shall be considered, and therefore the frequency of occurrence is also higher.

Finally, it can be stated that during the upcoming months further research and development work in this area is required with the objectives of improving the quality of the results and of bringing the Probabilistic Risk Assessment of geological disposal facilities to a level of utilization and importance similar to the one of the nuclear power plants.

REFERENCES

1. Federal Office for Radiation Protection, Ordinance on the Protection against Damage and Injuries Caused by Ionizing Radiation (Radiation Protection Ordinance), Edition 02/12, Paragraph 55.