Safety Assessment for the Kozloduy National Disposal Facility in Bulgaria - 13507

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ABSTRACT

Due to the early decommissioning of four Water-Water Energy Reactors (WWER) 440-V230 reactors at the Nuclear Power Plant (NPP) near the city of Kozloduy in Bulgaria, large amounts of low and intermediate radioactive waste will arise much earlier than initially scheduled. In order to manage the radioactive waste from the early decommissioning, Bulgaria has intensified its efforts to provide a near surface disposal facility at Radiana with the required capacity. To this end, a project was launched and assigned in international competition to a German-Spanish consortium to provide the complete technical planning including the preparation of the Intermediate Safety Assessment Report. Preliminary results of operational and long-term safety show compliance with the Bulgarian regulatory requirements. The long-term calculations carried out for the Radiana site are also a good example of how analysis of safety assessment results can be used for iterative improvements of the assessment by pointing out uncertainties and areas of future investigations to reduce such uncertainties in regard to the potential radiological impact. The computer model used to estimate the long-term evolution of the future repository at Radiana predicted a maximum total annual dose for members of the critical group, which is carried to approximately 80 % by C-14 for a specific ingestion pathway. Based on this result and the outcome of the sensitivity analysis, existing uncertainties were evaluated and areas for reasonable future investigations to reduce these uncertainties were identified.

INTRODUCTION

In Bulgaria, currently the two operating WWER 1000 reactors constitute the backbone of the country's electricity supply system. Four additional units of WWER 440-V230 reactors were also in operation at the same site near the city of Kozloduy, on the shore of the Danube River, in Northern Bulgaria. These four smaller reactor units were phased out on request of the European Union (EU) as a condition of the treaty for the accession of the country to the EU.

The decommissioning was to be carried out ahead of the originally planned schedule. The early decommissioning has a significant economic impact for Bulgaria, so that the European Union established a compensation mechanism to support the country among others in dealing with the NPP decommissioning, the Kozloduy International Decommissioning Support Fund (KIDSF). The early decommissioning has also an important impact on the planned waste management operations in Bulgaria, which originally were based on the concept of interim storage at the NPP and management of the operational waste together with the decommissioning waste after the end of the plant service life.

According to Resolution No. 683 of the Council of Ministers dated 25 July 2005, the State Enterprise for Radioactive Waste (SERAW) is required to construct the Bulgarian National Disposal Facility (NDF) for low and intermediate level short-lived radioactive waste (termed Category 2a radioactive waste under Bulgarian regulations). These wastes will include operational wastes from other nuclear power stations in Bulgaria (existing and planned), research reactors, hospitals and industrial enterprises but will primarily arise from the former operation and from decommissioning of Units 1-4 of the Kozloduy Nuclear Power Plant (KNPP). Consequently, the project "Technical Design and ISAR preparation for National Disposal Facility" has been financed from the KIDSF. The project is aimed at providing the complete technical planning of a near-surface repository for all the waste accumulated and expected to arise from operation and decommissioning of the Bulgarian NPPs. The planning is carried out in compliance with the requirements of Bulgarian planning law for nuclear facilities licensing. The contract for this work was assigned to a consortium of Westinghouse Electric Spain SAU, DBE TECHNOLOGY GmbH (Germany), and ENRESA (Spain).

A site for the NDF had been selected and pre-design studies had been carried out to identify possible technical solutions for the construction of a near-surface disposal facility following the international state of art before the start of the current project.

The work carried out during the early phase of the project included the preparation of several conceptual design alternatives, which were evaluated in regard to operational safety, long-term safety, environmental impact, constructability and operability. The design alternatives were compared with each other with a multi-attribute analysis and the most favorable was selected. Currently, the design work focuses on producing the technical design documentation for the preferred alternative necessary for initiating the licensing procedure, which is scheduled to start in early 2013: the Technical Design documentation and an Intermediate Safety Analysis Report (ISAR) following requirements set up by the nuclear regulator.

The following sections give a brief overview of the planned repository and describe the computer model developed to simulate the long-term evolution of the repository and its potential radiological impact. The main results of the long-term calculations are summarized and discussed in relation to recommendations for further investigations to be carried out for the future Final Safety Analysis Report.

DESCRIPTION OF THE REPOSITORY SITE

The Radiana site, selected as location for the planned NDF, has been thoroughly investigated during the last four decades with the basic result that the Radiana site geological characteristics were appropriate for the NDF.

Geographic Location

The Radiana site is located in northern Bulgaria, in the village of Hurlets, municipality of Kozloduy (district of Vratsa) at about 200 km to the north of the Capital Sofia by road and some 5 km to the south-east of the town of Kozloduy. The Danube River which forms a frontier with Romania flows approximately four kilometers to the north of the selected site. The site lies in the immediate vicinity of the KNPP, located between two roads, one to the north, which connects the town of Kozloduy with the NPP, and one to the south, Road No 11, which connects the village of Hurlets to the town of Kozloduy (see Fig. 1).

Fig. 1: General Site Location

The geometry of the site is almost rectangular with approximate dimensions of 1250 m x 470 m, limited by the two parallel roads, of which the southern road is located at a higher elevation than the northern road. The contour lines of the topography run roughly parallel to the two roads except in a small flat area at the lower part of the site.

Climate

The site falls within a moderate continental climate zone characterized by warm summers and cold winters, a large annual variation in air temperature, maximum precipitation during the spring and summer months and varying winter snow cover.

The climate in the area is influenced by humid ocean air from the West and Northwest and by continental air masses coming from the West and Northeast. The Stara Planina mountain chain impedes the penetration of warm Mediterranean air from the South.

Geology

The Radiana site lies on the right bank of the River Danube, in a region of typical hilly-plain low-land morphology. The elevation of the terrain in this zone varies between 25 and 130 m. The basin is occupied by Quaternary formations and Miocene - Pliocene (Neogene) sediments. Quaternary sediments, represented by lake-river, alluvial, river and aeolian-alluvial deposits, cover nearly the complete region around Radiana. Directly at the Radiana site the Pliocene has a thickness of 25 – 55 m and the Miocene has a thickness of more than 700 m and is found underneath, immediately on top of the Mesozoic basement.

In morphological terms, the Radiana site is located in almost flat land of the second non-flooded terrace (T2) of the right bank of the Danube River and in the adjacent inclined slope of the sixth (T6) terrace. The elevation difference between the terraces is about 54 m.

The area that has been selected as future site for the NDF is the upper terrace, T6, situated in the slope part with elevations ranging between 58 and 98 meters, with a gradient of 10 - 12º. It occupies the southern part of the site and has a width of about 300 m. The substratum of T6 is excavated in Pliocene clays at an elevation of 50 to 53 m, covered with alluvial gravel with a thickness of 2 - 7 m. The alluvial gravel is covered by a loess complex which thickness varies between 41- 42 m in the highest part of the slope and of 6 – 7 m in the lower part.

For stability reasons, the upper collapsible Loess layers will be excavated before repository construction and partly replaced by a 5 m thick foundation layer of compacted Loess-Cement mixture.

A detailed description of site geological and hydrological condition can be found in [1].

Hydrogeology

The main hydrogeological units that have been identified in the geological profiles of the site are the unsaturated zone and the two aquifers. The unsaturated zone consists of 15-25 m of loess-like clay, sandy clay and gravelly sandy clay and of the sediments of the Brusarska Formation – silty clay and clayey sand. The two aquifers are divided into an upper slightly permeable and a lower strongly permeable layer which are separated by a sandy-clayey complex of the Brusarska Formation (aquitard).

The upper slightly permeable layer is present within the sediments of the Brusarska Formation at an elevation of about 38 - 43 m in the area of the upper site (within the range of 35 - 50 m below the ground surface). In general, this layer is inhomogeneous due to the heterogeneous structure of the Brusarska Formation. The groundwater flow inside this aquifer is to the North-Northeast and the water is entirely drained into the first non-floodplain terrace T1, where Kozloduy NPP is situated, and from there into the Danube River.

The lower strongly permeable layer is formed in the sandy sediments of the Archarska Formation (with the top part at elevation of approximately 0 m). The groundwater flow in the lower aquifer has the general direction to the North-Northwest and has a hydraulic conductivity that is considerably higher than for the upper aquifer. For the post-closure safety assessment, it has been conservatively assumed that no contaminants will migrate from the upper aquifer inside the Brusarska into the lower aquifer. Therefore the lower aquifer has not been included in the model for the long-term calculations.

GENERAL CHARACTERISTICS OF THE NDF

The objective of the NDF is to provide capacity for the disposal of conditioned short-lived low and intermediate wastes in a modular multi-barrier engineered near surface repository. For this purpose, the concept realized in Centre de l'Aube – France and El Cabril – Spain has been chosen as prototype for the future repository at Radiana. The technical solution for the NDF is to provide a modular multi-barrier engineered system, which is supplemented by the natural barrier of the surrounding sedimentary layers, which enhance the retardation of radionuclide transport towards the biosphere. The main engineered barriers will be the waste packages, the disposal cells and the engineered cover.

The NDF is designed to accept conditioned waste in reinforced concrete containers with outer dimensions of 1.95 m x 1.95 m x 1.95 m. Disposal of large radioactive waste and/or free bulk materials is not envisaged so far.

The NDF layout design comprises 66 cells for waste package disposal. These disposal cells are located on three equal platforms with 22 cells each and their related systems. The cells are arranged in two lanes of 11 cells. Each cell is a monolithic rectangular box with a total capacity for 288 waste packages, subdivided by two inner walls made of reinforced concrete into three cavities, each offering space for 96 waste packages in four layers of 8x3 containers.

The engineered cover will be composed of several layers of natural materials with different safety functions to minimize water infiltration and restrict intrusion by humans and animals or plants. Its design has not been finalized, but will be subject to a large scale experiment during operational times. The main design criteria for the long term multilayer engineered barrier that were considered for the assumed post-closure evolution of the repository are summarized below:

- Durability: the duration of its functionality will be 300 years. The design will take into account repair work during the post-closure period of 300 years.
- Bio-intrusion: protection will be provided by barriers to avoid the action of small animals and deep rooting of vegetation.

- Wind or run-off erosion will be reduced to < 0.5 kg/m²/yr.
- Restriction of hydraulic conductivity will be provided by a clay layer, with a minimum thickness of 1.0 m and a permeability ≤ 10^{-16} m².
- The total thickness of the multilayer engineered barrier is 3 m.

The design of the NDF incorporates an underground inspection gallery equipped with a water infiltration control network designed to collect water accumulations from the interior part of cells. Water collected by this system will be monitored and either be discharged into the environment, provided its radioactive content is below regulatory limits, or be treated and conditioned appropriately at some off-site facility. At the end of active institutional control, the infiltration control system will be properly closed to prevent its potential later use as fast pathways for radionuclides into the biosphere.

THE EXPECTED WASTE INVENTORY

The proposed NDF will be a facility for disposing of radioactive wastes belonging to Bulgarian Category 2a, defined as "low and intermediate level short-lived waste containing mainly short-lived radionuclides (with a half-life shorter or equal to that of Cs-137) and long-lived alpha emitting radionuclides with specific activity less than or equal to $4.0 \cdot 10^4$ Bq/kg in a single waste package and less than or equal to $4.0 \cdot 10^5$ Bq/kg for the whole volume of waste".

The preliminary assessment of the quantity of radioactive waste, which is to be disposed of at the NDF, amounts to 138,200 m^3 (345,500 tons), considering both the radioactive waste and the volume of the reinforced concrete containers in which it is packed.

The expected total radionuclide inventory of the NDF, which was used for the long-term calculations, was provided by SERAW and is listed in Table I.

Table I: Estimated total inventory of future NDF.

Radionuclide	**Initial total activity (Bq)**	**Radionuclide**	**Initial total activity (Bq)**	**Radionuclide**	**Initial total activity (Bq)**
Ac-227	0.0 E+00	I-129	8.6 E+07	Ra-226	0.0 E+00
Ag-110m	1.7 E+12	Mn-54	-1.1 E+12	Sr-90	3.4 E+11
Am-241	1.3 E+10	Nb-94	-3.3 E+09	Tc-99	1.8 E+09
C-14	2.7 E+12	Nb-95	3.5 E+11	Th-229	0.0 E+00
Cm-242	9.8 E+07	Ni-63	4.4 E+12	Th-230	0.0 E+00
Cm-244	3.0 E+09	Np-237	0.0 E+00	U-233	1.8 E+07
Co-58	7.7 E+11	Pa-231	0.0 E+00	U-234	1.0 E+08
Co-60	1.5 E+13	Pb-210	0.0 E+00	U-235	1.8 E+07
Cs-134	2.0 E+13	Pu-238	5.2 E+09	U-236	0.0 E+00
Cs-137	1.4 E+14	Pu-239	4.35 E+09	U-238	5.3 E+07
Fe-55	1.4 E+13	Pu-240	4.35 E+09	Σ α emitters	3.0E+10
Fe-59	7.9 E+11	Pu-242	3.7 E+07	Σ Total	2.0 E+14

The computer code GoldSim, used for the long-term modeling, calculates radioactive decay as well as the ingrowth of daughter products. The daughter radionuclides that have been included in the estimation of the radiological impact for the ISAR, can be identified from Table I by their zero initial total activity.

SAFETY ASSESSMENT METHODOLOGY

In accordance with internationally widely accepted best practice, the ISAM Methodology [2] developed for safety assessments of near-surface repositories for radioactive waste has been chosen for the operational and the post-closure safety analysis for the National Disposal Facility to identify the relevant exposure paths and evolution scenarios.

For normal operation of the NDF, the identified exposure path is direct irradiation of workers or members of the public by the waste. The most important accidents considered for the operational period were scenarios associated with the drop of a waste package during handling and the fire scenario.

For the normal long-term evolution of the NDF, the only release pathway for radionuclides that has been considered as relevant is the groundwater pathway. The same is valid for the alternative or accident scenarios that have been developed for the long-term assessment, apart from the human intrusion scenarios. The following scenarios were selected for the long-term assessment:

- Normal evolution
- Human intrusion (Road Construction - and Residential Scenario)
- Earthquake
- Climate change (change towards wet or dry climate)
- Crash of airplane

The results of the operational and post-closure scenarios together with the regulatory limits for normal and disturbed evolution of the repository were then used to determine:

- Maximum specific activities of waste to be disposed of at the NDF by radionuclides,
- Maximum total capacity of the NDF by radionuclides,
- Radiological impact from the expected total inventory,
- Areas of future work suited for improving safety conditions or increasing confidence in the outcome of the safety assessment.

Specific activity limits are related to those exposure scenarios where radiological impacts are a function of the specific activity but not of the total activity of the radioactive source. In case of the NDF, this applies to the operational scenarios and the post-closure human intrusion scenarios. In contrast, the total radiological capacity is determined by analysis of the post-closure scenarios where the radiological impact is a function of the total activity disposed of at the NDF, which is given by the post-closure scenarios with exception of the human intrusion scenarios.

The radiological capacity is determined as the maximum activity (Bq) for each nuclide that is allowed to be disposed of in the NDF without exceeding the applicable dose limits for the population, provided that the specific activity limits (Bq/g) of the NDF, derived from the results of the applicable scenarios and the Bulgarian regulations, are met at the same time.

To give a realistic estimate about the radiologic impact that can be expected from the facility after closure, the dose rates resulting from the different scenarios were calculated for the expected specific or total inventory as part of the safety analysis. This is particularly important not only for comparing the calculated dose rates with the regulatory limits but also for identifying those assumptions and data that have the largest influence on evaluating the potential radiological impact. These parameters can be found and analyzed properly only if realistic assumptions about the future total inventory are used for the calculations.

For the purpose of this paper, only this last aspect is addressed in detail.

NORMAL EVOLUTION SCENARIO

Conceptual Model for the Normal Evolution Scenario

The main assumptions forming the basis for the normal evolution scenario are listed below:

- Climate conditions remain essentially the same as today.
- Closure of the repository will be followed by a period of 300 yr of active institutional control during which maintenance of the multilayer engineered cover will be executed.
- After the end of institutional control, the infiltration control system will be backfilled.
- It is assumed that the total inventory is accessible to infiltrating water from the time of failure of the containers (average lifetime 60 yr), that is:
    - No radionuclides are bound in any kind of waste matrix and
    - All infiltration will be equally distributed over the complete waste volume.
- Geosphere conditions will remain as today.
- Construction, closure and performance of technical barriers will be according to design.

Deviations from these assumptions are partly considered by sensitivity analyses or consideration of alternative scenarios.

Surface water pathways do not exist in the direct vicinity and due to the topographical situation of the facility and the high permeability of underlying sediment layers their future existence is highly improbable. Also, it is assumed that there will always be some soil cover and vegetation on top of the disposal cells preventing any direct exposure of radioactive waste to the biosphere. Consequently, the only release pathway for radionuclides from the repository in the normal evolution scenario is the groundwater pathway. The principal distribution of water fluxes expected to develop with time inside the repository near field is visualized in Fig. 2.

From the time of closure, a certain amount of infiltration corresponding to the regional groundwater recharge will reach the engineered cover of the repository, which will reduce the infiltration towards the disposal cells to a design minimum as long as the sealing capacities of the clay layer have not been impaired. Based on design values for the permeability for the clay layer and the concrete slab on top of the disposal cells infiltration into the cells will start at a value of 31.5

mm/yr, corresponding to a permeability of 10^{-9} m/s. With degradation of the clay layer after the end of institutional control and any maintenance activities and degradation of the concrete, this infiltration will increase to a maximum value of 170 mm/yr, corresponding to twice the regional groundwater recharge and approximately 30 % of the annual precipitation.

Once water enters the inner disposal cells, it comes into contact with the containers and depending on the state of the containers also with the waste matrix and its radioactive content. According to the design properties of the containers, any sealing function of the containers is limited to a total of 60 years after production. Considering the boundary conditions of operation and closure activities, it has to be assumed that at the time of closure already 25 % of the containers have lost their sealing capacity and the remaining ones will follow during the next 45 years.

For the calculations of this analysis it is assumed that upon failure of a container its total radionuclide inventory is exposed to the water inside the disposal cell and any retardation is limited to the sorption capacity of the surrounding concrete.

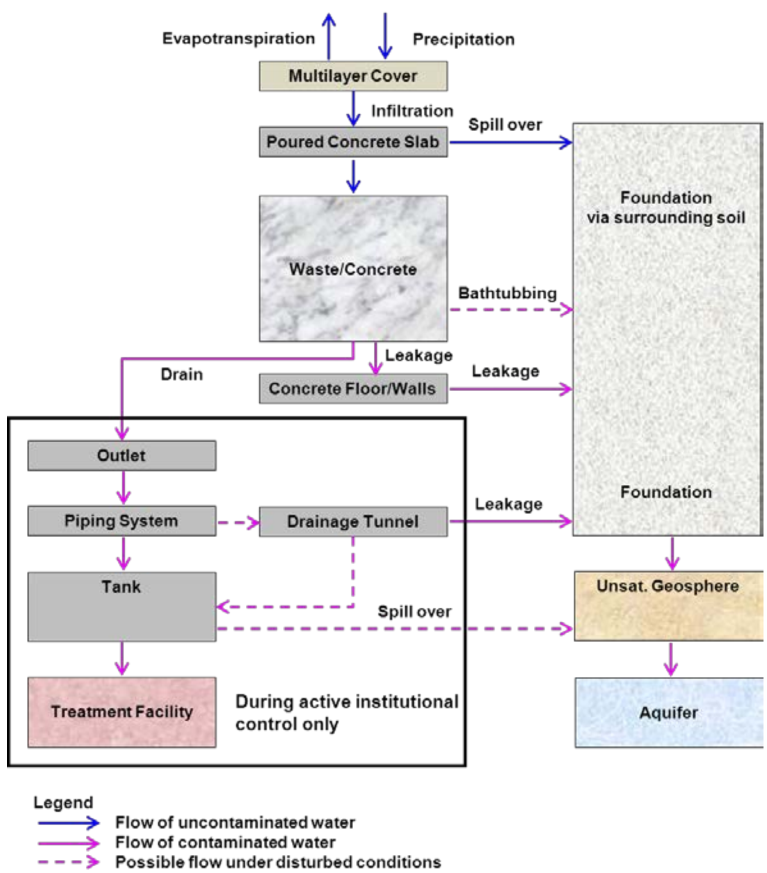

Fig. 2: Principal distribution of water fluxes for Normal Evolution Scenario.

Once the water reaches the bottom of the disposal cells, there are different possibilities: water may leak through the concrete floor or drain to the drainage outlet. For the Normal Evolution Scenario the first possibility has to be considered as the most probable one. The disposal cell barriers, the top concrete slab and the bottom concrete slab are all designed with the same conductivity properties and are supposed to underlie similar degradation processes. Consequently, the amount of water that is able to infiltrate through the top concrete slab should be able to leak downwards through the bottom concrete slab in the same period of time. In case that some infiltration will be led towards the outlet, the water will pass into the piping system. As long as the drainage system is maintained in proper working condition, it is supposed that the drainage water will be taken care of in a safe way. After the end of active institutional control the infiltration control system and the outlets will be closed and any water entering the disposal cells will percolate through the concrete floor.

Although the sorption capacity of the concrete will lead to retardation of radionuclide migration, percolation of water through the concrete floor will lead to an advective flux from the disposal cells into the unsaturated layers below. Apart from this advective transport, there will also be diffusive fluxes between the waste/concrete bodies inside the disposal cells and the bottom concrete slab on the one hand and the bottom concrete slab and the top layer of the unsaturated zone on the other hand.

Diffusive fluxes between the different unsaturated layers have also been implemented in the computer model but in regard to the total transported radionuclide mass, further transport down through the unsaturated zone and into the saturated zone is mainly advective. Only during the first few hundred years, diffusive fluxes can be in the same order of magnitude as advective fluxes or even larger. In general, the importance of diffusive fluxes decreases with increasing time and distance from the source, as both parameters lead to smoothing out concentration differences between the layers, which are essentially driving the diffusive fluxes.

Once it enters the aquifer, the contaminated water will become diluted. In significantly reduced concentrations, the radionuclides will migrate with the groundwater through the aquifer. Depending on the sorption capacity of the aquifer, a certain percentage of the radionuclides will be retarded.

To estimate the radiological hazard, for the normal evolution scenario, it is assumed that members of the critical group, a self-supporting community living at a small farm, will drink water from a well located at a certain distance from the repository. The water will also be used for watering cattle and irrigating agricultural products that are eaten by the members of the critical group. The distance chosen for the normal evolution scenario is 1000 m, which is considered the minimum distance towards an agreeable site for a respective settlement in direction of the groundwater flow.

Mathematical Models for the Normal Evolution Scenario

The computer code used for carrying out the long-term calculations is GoldSim Simulation Environment extended by the Radionuclide Transport Module. In spite of GoldSim’s ability to run probabilistic calculations, at the temporary stage of the ISAR, the calculations have been focused on deterministic calculations and sensitivity analysis to investigate the influence of specific parameters. Fig. 3 shows a simplified version of the GoldSim model for the NDF. The different repository compartments and sediment layers are represented by mixing cells.

For each time step during the calculation, the content of these cells: water, solid mass and radionuclides, is completely mixed and the radionuclide concentration in water is calculated based on the sorption capacity of the solids inside the cell. The links between the cells indicate the advective and diffusive fluxes that are calculated for each time step between the different model compartments. The model uses the radionuclide concentration at the end of the aquifer element to calculate the dose rate that would result from the usage of water from a well at that location under the conditions of the biosphere model.

The assumptions, equations and data for the biosphere model have been taken from the farm scenario developed for the same type of facility in IAEA TECDOC 1380 [3] and supplemented by data from well-established data bases where required. The main exposure pathways considered for members of the public in this scenario are ingestion, inhalation and direct irradiation. For the scenario purposes the diet of members of the critical group has been limited to water, green vegetables, root vegetables, grain, beef and milk products, which define the different ingestion pathways. It is supposed that irrigation with contaminated water is used for the growing of grain and vegetables. No irrigation is foreseen for cow pastures, but they are considered as having been used for crop production in the past and therefore as being also contaminated to a certain degree. Exposure due to direct irradiation is considered for occupancy on contaminated soil and exposure due to inhalation is considered for breathing air contaminated by dust from irrigated soil.

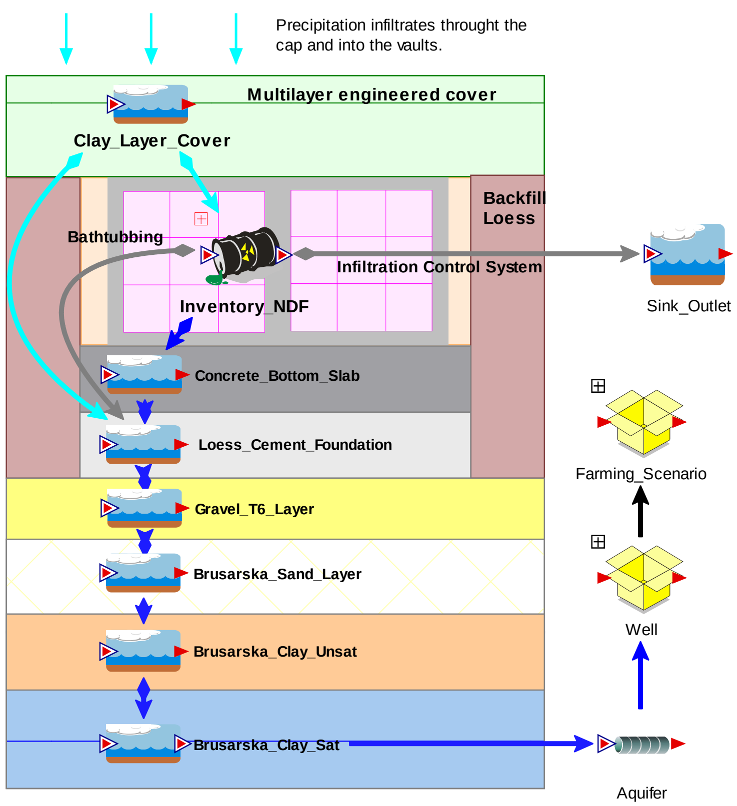

Fig. 3: Simplified GoldSim model for NDF Radiana.

RESULTS OF POST-CLOSURE SAFETY ASSESSMENT

Normal Evolution Scenario

The results for the total annual dose resulting from the farm scenario for the expected normal evolution of the repository are shown in Fig. 4. In addition to the curve for the total annual dose, the contributions by the most important radionuclides can be taken from this figure. The total dose curve (largely covered by curves for Tc-99 and C-14) shows the sum for all radionuclides considered in the calculations including those not displayed in the figure.

The curve of total annual dose shows a clear maximum of 0.028 mSv/yr at 2780 years after closure caused by C-14. The second highest contribution to the total annual dose is by I-129 which has a maximum at 830 yrs after repository closure with a peak value of 0.002 mSv/yr. All other contributions by individual radionuclides are below 1 µSv/yr.

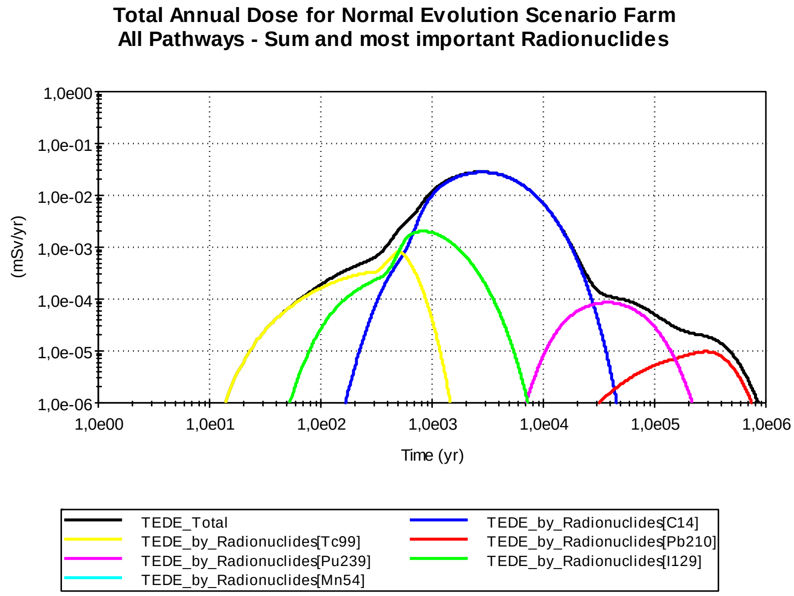

Fig. 4: Annual dose to members of the critical group, total and main contributing radionuclides.

As described above, the farm scenario combines different exposure paths for members of the critical group. Comparing the total annual dose curves for the different pathways against each other in Fig.5 shows clearly that there is one pathway that is carrying the major part of the total annual dose.

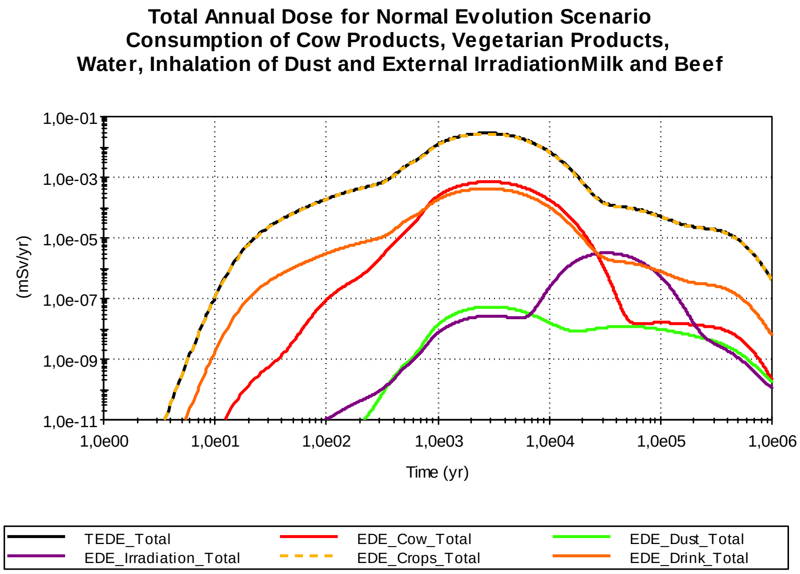

Fig.5: Exposure paths contributing to annual dose for Normal Evolution Farm Scenario.

The dose calculated for ingestion of crops amounts to 96% of the total dose for the time of maximum annual dose. All other pathways (including the ingestion of animal products, the drinking of contaminated water, the inhalation of dust and the direct irradiation from contaminated soil) contribute only marginally to the total dose rate.

In order to further analyze the main contribution to the estimated total annual dose for the farm scenario and the normal evolution of the repository, the different crop ingestion pathways were compared which again showed that one ingestion path is mainly responsible for the total dose received by the ingestion of vegetarian products: The ingestion of grain products, which contribute 79 % to the total dose rate from ingestion of vegetarian products. Accordingly, nearly 80 % of the total dose estimated from the farm scenario results from the ingestion of grain products.

A closer look at the calculation of this value reveals that nearly 99% of the grain contamination originates from the interception of irrigation water by the plant leaves and only little more than 1 % from the uptake of contaminated water by the grain roots. Consequently, the results for the Normal Evolution Scenario combined with the Farm Biosphere Scenario are dominated by the assumption in regard to the irrigation of grain and all parameters associated with this pathway.

Sensitivity Analysis

The sensitivity analysis of the long-term calculations was applied to all parameters, which were considered to have significant influence on the performance of the repository or known for having a significant margin of uncertainty. For the individual calculations only one parameter was varied while the remaining set of parameters was left unchanged. The relative importance of the individual parameters determined in this way is strongly related to the existing mathematical model and its associated data set and is likely to change with changing model assumptions or data set. For the Radiana model the relative importance of a parameter is bound to its influence on the release, migration and human consumption of C-14 as the major contributing radionuclide.

Most important parameters with strong influence on the overall result and associated large uncertainty are:

- Evolution of the infiltration rate into the disposal cells
- Retardation of radionuclides inside repository and along their release pathway
- Irrigation rates used during future agricultural production and uptake of C-14 by grain plants

Evolution of the infiltration rate results from a combination of future evolution and performance of barriers and environmental conditions. Uncertainties are considerable but the values chosen for the normal evolution scenario seem to be rather conservative already. For example, the complete loss of cover, which can be considered as extremely disturbed evolution, will lead to an increase of the maximum total annular dose of approximately 35 µSv/yr. This is about twice the total annular dose with technical barriers functioning according to design, but it nevertheless shows that not much credit has been taken from the performance of these barriers.
Retardation of radionuclide migration is governed by the Kd-values (partition coefficients) of the concrete as well as the Kd-values for the unsaturated layers and the aquifers. For a few radionuclides (not including C-14) the selected Kd-values were measured directly for natural material from the site but most data were taken from generic data sets. Generally, for generic Kd-values the bandwidth of uncertainty is a very large one and can be in the order of +/- 1-2 orders of magnitude or even more. Changing the Kd-values for the model materials by one order of magnitude has the largest impact on the peak total dose if applied to the concrete. In this case, the peak dose rate will be either multiplied by 5 or divided by 10 with decrease or increase of Kd-values, respectively. If the Kd-values for the unsaturated sediments are changed, a similar impact can be observed: the peak dose rate will be either multiplied by 1.6 or divided by 6. For the aquifer this effect is less pronounced with an increase by only 4 % and decrease by a factor of 1.4.

In regard to the biosphere model those parameters connected with grain production and consumption have a nearly linear influence on the maximum total annual dose. However, some of them like the annual consumption of grain or the expected yield of grain per m^2 have this large influence only because the calculated concentration of C-14 is such a large one. Those parameters that lead to this large concentration are the amount of irrigation and the share of irrigation expected to be intercepted by the grain leaves.

DISCUSSION OF POST-CLOSURE SAFETY RESULTS

On the one hand, the normal evolution scenario developed for the NDF at Radiana renders a peak annual dose of 28 µSv/yr, which is clearly below the regulatory limit of 100 µSv/yr. On the other hand, some of the parameters used for the mathematical model are known to have both large uncertainties and a large influence on the result. It would therefore be desirable to decrease the existing uncertainties by gaining further information on a set of parameters identified from the analysis of the Normal Evolution Scenario and the sensitivity analysis.

The sensitivity analysis also demonstrated that the assumptions in regard to the safety functions of the engineered barriers have only little influence on the result of the calculations. This may indicate that there is some excess conservatism built into the model.

The calculated retardation of radionuclides inside the repository and along the migration pathway has a large influence on the final results and a large uncertainty. Accordingly, better defined data on Kd-values, especially for sorption of C-14 onto concrete and onto the unsaturated sediments, could significantly reduce the existing uncertainties.

The uncertainty in regard to future irrigation rates cannot be reduced as this will depend on possible climate changes. It could be clarified though whether under today's climatic conditions the assumption of 300 mm/yr irrigation for grain as proposed by [3] for moderate climate is a reasonable one to get a more precise radiological impact for today's environmental conditions. However, the value for future times would still remain rather uncertain. To determine the degree of conservatism inherent in this part of the biosphere model, it would be more important to further investigate the migration of C-14 from irrigation water into grain products, which for the biosphere model is calculated mostly on the assumption that 30% of the irrigation will be intercepted by the leaves and accumulated in the grain.

To evaluate the general conservatism of the Normal Evolution Scenario, the most important "pessimistic" assumptions implemented in the model are listed below:

- Limited expectations in regard to permeability of clay and concrete barriers
- Infiltration after degradation of cover 200 % of today's infiltration at NDF site
- Immediate exposure of radionuclides to water upon failure of container
- No sorption to waste mass (representing about 30% of total waste/concrete mass in cells)
- Permanent and complete mixture of waste and infiltrating water

Considering the conditions listed above, in general it can be concluded that the source term model and that of the engineered facility are rather conservative ones. The biosphere model is considered as a rather conservative scenario to assess the potential radiological impact on members of the public but has also some uncertainties that might influence the results in either direction. In regard to the unsaturated zone and the geosphere, the question of conservatism is more difficult to answer. For these parts of the model, especially for the unsaturated zone, the Kd-values selected to calculate sorption to the sedimentary materials are decisive for radionuclide transport and have a large influence on the calculated annual doses. The Kd-values were mostly taken from generic data collections for similar media and represent best estimates. However, it is well known that this parameter has a broad bandwidth of variation in natural media like sand or clay. Consequently it has to be stated that the model for the underground pathway is not a conservative one but a best estimate model with considerable uncertainty associated with it.

SUMMARY AND CONCLUSIONS

In the framework of the project on the development of the technical design and the ISAR for the future NDF at Radiana, a draft version of the ISAR has been prepared. Its results render peak annual dose rates that comply with the Bulgarian regulatory requirements. Detailed analysis of the results shows that large uncertainties are inherent to the Normal Evolution Scenario model. Although several conservative assumptions have been implemented in the model, it seems desirable to reduce the existing uncertainties for the next stage of the safety assessment for this facility to increase confidence in the results of the long-term calculations. The most important parameters in this regard would be Kd-values for the sorption of C-14 onto concrete and onto the unsaturated sediments, and the assumptions and parameters concerning C-14 uptake of grain from irrigation. It should also be considered to re-evaluate the expected performance of the technical barriers or to reconsider their design values, especially the assigned permeabilities.

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