DUKOVANY RADIOACTIVE WASTE REPOSITORY

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Abstract

Siting, safety assessment and design of Dukovany radioactive waste disposal facility in Czech Republic are described. The site was chosen after performed area survey. The safety assessment is based on the evaluation of critical scenarios including groundwater transport, intrusion and habitation after institutional control. Waste acceptance criteria are set on the basis of the safety assessment taking into account dose limits, the conditions of operations, the waste inventory, the characteristics of natural and engineered barriers and the planned duration of institutional controls. Repository capacity of 55 000 m^3 is based on 112 disposal vaults. Since 1994, 5 disposal vaults have been filled and closed.

INTRODUCTION

The Czech concept of waste management from nuclear power plant (NPP) operations has been gradually developed and implemented. It consists of solidification of radioactive concentrates by bituminization, volume reduction of solid wastes by compacting and disposal of conditioned wastes in surface concrete vaults.

Disposal of radioactive wastes after appropriate conditioning is generally considered to be an acceptable method of providing the necessary protection for human health and the environment. The most important activities related to waste disposal are the selection of the appropriate disposal site with its natural confinement characteristics for the waste under consideration, the conditioning of the wastes and construction of engineered barriers so that the wastes are adequately isolated from man and the environment and operational risks are reduced.

The objective of waste disposal is:

- to ensure operational safety of personnel in keeping with the dose limits established by national regulations for radiation protection,
- to confine radionuclides within the repository site for the period of time they represent an unacceptable risk and
- that the radiological impact of released radionuclides conforms to criteria lestablished national regulations for radiation protection.

Waste confinement by the disposal system should remain effective until the radionuclides have decayed to acceptable levels to enter the environment. With sufficient natural and man-made barriers, the release of radionuclides can be delayed and limited, its transport through geosphere and biosphere retarded and its concentration sufficiently diluted to assure that the impact will remain in prescribed levels.

The activities initiated or carried for the assessment of the radiological impacts from low level radioactive waste disposal to protect human health and the environment in the Czech Republic are described in the sections which follow.

PRESENT WASTE INVENTORY

The most significant source of radioactive waste in the Czech Republic is from operation of the nuclear power plant in Dukovany which consists of 4 units of VVER 440 (water cooled water moderated power reactor => PWR) of 440 MWe each. In addition one nuclear power plant in Temelin with 2 units WWER 1000 is under construction.

The operational radioactive waste generation rate for the 4 operating units are given below:

- evaporator bottom concentrates 440 m^3/yr
- spent ion exchanger resins 24 m^3/yr
- solid waste 145 m^3/yr

The most significant volume of the generated are evaporator concentrates. In the design of the NPP it was assumed that up to 1% of fuel element cladding may fail (1-4). However, the activity of the generated waste is 2 orders of magnitude below the initially assumed values (3,4). The predominating radionuclides in waste which have been in storage long term are : Co-60, Cs-134 and Cs-137 with concentrations in the range of 10 - 100 kBq/l. The transuranic radionuclides Pu-238, Pu-239 and Am-241 have been found to be below 1 Bq/l. The concentrations of long-lived beta radionuclides C-14, Sr-90 and Tc-99 are up to 8 kBq/l.

SITE SELECTION

Initial site selection studies started in the late seventies. There were 2 legal documents ensuring by the force of law that authorized release limits from a repository would be below levels reasonably achievable, taking into account social, economic conditions and requirements for environmental protection.

The original Czech Regulation on Protection against Ionizing Radiation formulated the basic principles of radiation protection based on the International Commission on Radiological Protectin (ICRP) and International Atomic Energy Agency (IAEA) recommendations of that time. General requirements on construction, equipment and operation of working places with sources of radiation were set.

The original Decree of the Czechoslovak Atomic Energy Commission on General Criteria for Siting of Nuclear Facilities with Regard to Nuclear Safety determined the general criteria for ensuring safety in siting of nuclear facilities including their environmental impacts.

Several promising sites were identified according to the above mentioned criteria. After area surveys were performed, the site near the Dukovany NPP was chosen.

A hydrogeological characterization of the radioactive waste disposal site was performed. Data were collected on chemical and physical properties of the groundwater, groundwater regime, water-bearing characteristic of hydrogeologic unit, water use and climatological data. The fluctuations of ground water level were studied, particularly in relation to precipitation. As a result, a ground water table map was obtained. The site survey also involved data on land use, population distribution, and locations of national parks, surface and groundwater resources, vegetation as well as on background radiation and environmental contamination.

The base of the site is formed by a granulite body with a low fissure permeability and a hydraulic conductivity in the range of 1.E-6 to 1.E-7 m/s. The aquifer thickness is about 10 m. The hydraulic conductivity of the aquifer and the upper unsaturated sandy clay layer vary in the range of 3.E-6 to 5.E-8 m/s. The mean annual rainfall is 0.567 m (1,2).

Field tests as well as laboratory studies were performed to obtain realistic values of soil retardation factors for the radionuclides. Laboratory tests were performed using geological materials obtained from boreholes drilled at the site. Both, static as well as dynamic techniques were used to determine the distribution coefficients (Kd's) and the retardation factors.

Samples of various soil layers taken from test boreholes gave Kd-values for Cs, Sr, Co, Ni and I in the range 2.E+2 - 3.E+4, 2.E+1 - 5.E+2, 3.E+2 - 2.E+3, 2.E+2-2.E+3 and 0 - 1 ml/g respectively. For other radionuclides in question, the Kd's were taken from the literature.
The Kd's were used to estimate the radionuclide delay in geological media taking into account its limitations associated with their empirical character. Studies were performed to obtain Kd values in various experimental conditions related to contact time, pH, competitive ion concentrations (H^+, Na^+, K^+, Ca^{2+}, Cl^-, HCO_3^-, SO_4^{2-}, EDTA) and the solid-liquid ratio (5,7).

SAFETY ASSESSMENT

Safety assessment is a procedure for evaluating the performance of a disposal system, its radiological impact on man and the environment. It is an iterative process requiring a wide variety of information to describe the behavior of the disposal system and to provide reasonable assurance of compliance with safety and regulatory requirements.

The assessment of waste confinement first requires an identification of the various mechanisms, rates and pathways by which radionuclides could leave a repository, migrate through barriers to enter the human environment and cause exposure to man. Once these features, events and processes are identified, an estimate of the radiation dose can be made based on normal and potential accidental conditions at the repository. Since complete and specific data for such analyses are unlikely to be available, the first approach is to perform safety analyses by assuming values for the various parameters that are conservative but yet as realistic as practical. The evaluated radiation dose by such analysis is then compared with limits established by the national authorities and the ICRP and the IAEA.

Such assessments are performed by using scenarios describing possible future conditions, events and processes to be considered and the use of mathematical models to describe the system being assessed. It is therefore important that the range of scenarios considered is sufficiently broad. Some aspects of the safety assessment will derive directly from the site authorization for waste disposal, others will derive from operational and post-closure safety cases.
Mathematical models of the disposal system were tested by performing calculations of the radionuclide migration from the repository by groundwater to man taking into account the site specific parameters. A methodology was developed to define the source term with the use of experimentally determined parameters and as a result the radionuclide concentration at the populated areas could be calculated.

Source term

The source term includes the effects of chemical and physical processes which can occur during the migration including radioactive decay, homogeneous reactions in liquid phase and heterogeneous reactions between solid and liquid phase. The reactions may include hydrolysis, precipitation, ion exchange, diffusion, dissolution and adsorption. Source terms for the scenarios have been corrected and newly derived from actual waste volumes, containment barrier data evaluation and assumed radionuclide content. Originally, the radionuclides of greatest interest were Co-60, Sr-90, Cs-137 (1,5). Later on, Pu-239, Am-241, C-14, Ni-59, Ni-63, Nb-94, Tc-99 and I-129 were also considered (2,7,10).

The safety assessment assumes that drums used for waste packaging would last for approximately 50-100 years. After this period the resulting waste form was assumed to be attacked on its surface to produce a degraded waste which if contacted by water would increase the release of radionuclides by an order of magnitude.

The release scenario for normal operation allows the penetration of the cover by water into the disposal cell, damaging of the waste drum, leaching of a portion of the radionuclides and penetration through the concrete wall of a vault to the environment.

Groundwater migration

A detailed description of all potentially possible processes is very complicated. Therefore it has been necessary to accept some simplification in the system description to enable the modelling (e.g. water is incompressible). For some models it also was assumed also that the aquifer was porous, homogeneous, isotropic and the water velocity is constant. For chemical reactions between solid and liquid phase, a simple linear model was used assuming that ion exchange with a linear adsorption isotherm is the controlling mechanism and that equilibrium will be reached.

The physical and chemical phenomena considered in the model for migration of radionuclides in groundwater are:

- convection
- longitudinal and transversal dispersions
- sorption of radionuclides in aquifer
- radioactive decay

According to modelling experiences it can be concluded that basic mechanisms which apply to realistic site characteristics can be simulated with simplifying assumptions. Analytical models are preferable for uncertainty analysis and preliminary investigations of transport phenomena using conservative data even when some field data are lacking. However, they are applicable, if the aquifer can be assumed to be porous, homogeneous, and isotropic and the water velocity is constant. Numerical models posses the ability to treat more complicated systems with heterogeneous aquifers.

Exposure Pathways

Radionuclides released into groundwater can reach surface water bodies. The resulting activity in the water phase causes human exposure due to consumption of drinking water and agricultural products contaminated by irrigation practices.

The safety assessment of the Dukovany repository was based on 3 critical scenarios:

- Groundwater transport to the nearest water supply

- Intrusion after end of institutional control (300 years after closure), for example as a result of construction works or exploratory borehole drilling

- Human habitation on the site after end of institutional control (300 years after closure)

The last two scenarios are significant after closure of the repository and are described further in the sections which follow.

Based on these scenarios it was assumed that the significant contribution to the individual doses are:

- Consumption of drinking water
- Consumption of vegetables irrigated with contaminated water
- External irradiation to contaminated soil
- Inhalation of resuspended particles of contaminated soil

The discharge of groundwater to the biosphere is usually a long-term process. Therefore, a simple dosimetric model based on the concentration factor methods was used. Radionuclides are assumed to reach equilibrium in environmental materials and transfer coefficients are steady state concentration ratios between coupled compartments of the environment.

The associated radiological impact will occur after the institutional control of the site and no further disposal takes place. Studies related to human intrusion were performed. Two scenarios were found to be the most pessimistic cases of a large number of possible scenarios that result in a direct alteration of the normal evolution of the site.

The first scenario is related to the construction of a house at the site and the other with the inhabitation of a house placed in the same site including the consumption of drinking water and vegetables grown on the repository material diluted with fertile soil distributed in the vicinity of the house.

The pathways considered were for the construction scenario:

- Inhalation of resuspended soil during the excavation work
- External irradiation from direct exposure to the repository material

For residential scenario, the considered pathways were:

- External irradiation from direct exposure to the contaminated soil
- Consumption of vegetables grown on contaminated soil
- Inhalation of resuspended dust containing radionuclides

Compartment models based on the scenarios described above were formulated to estimate committed effective equivalent dose due to different exposure pathways.
Concentrations of radionuclides in various foodstuffs were calculated using recommended values

for model parameters. The next step included calculation of activity intake by man and the resulting dose. The values of activity-dose conversion factors were taken from ICRP recommendations.

MODELING AND TESTING

Model Testing

A mathematical model and corresponding computer code are verified when it is shown that the code behaves as intended and that the equation are correctly encoded and solved.

Code verification has been performed by checking step-by-step the logic of the models or checking line-by-line the code listing if available. Then the calculated results are compared with results obtained from analytical solutions of equations or by using another available code.

Important parts of the model used have been additionally tested within two international validation studies, BIOMOVS (Biospheric Model Validation Study), examining models for biosphere transport and within NSARS (Near Surface Radioactive Waste Disposal Safety Assesssment Reliability Study), testing models for ground water migration (6,8.9). The approach used consisted of comparing model predictions among participants for specific test scenarios without experimental data being available. It was concluded that the models used yielded acceptable results.

A mathematical model and corresponding computer code are validated when it is shown that they provide a good representation of the processes in the real system. Validation is carried out by comparison of calculations with field observation and experimental measurements. Its is clear that not all the models used can be fully validated because of the long periods and lack of experimental or field observation data. Therefore, submodels were tested and calibrated case by case.

The calculated ground water levels have been compared with the observed levels with good results. Important parts of the model used for transfer of radionuclides through food chains additionally have been tested within the BIOMOVS international validation study. The approach used consisted of comparing of model predictions against independent data sets derived from measurements after the Chernobyl accident. It was concluded that the models used yielded acceptable results as well.

Sensitivity analysis

In a sensitivity analysis the influence of changing parameters on the predicted behaviour of the system is evaluated. The main purpose is to identify parameters, which effect the system behavior strongly or else to a negligible extent. The presented sensitivity analysis results were obtained from the simplified version of the transport equation, the evaluated case being presented by the individual dose from a single release of a contaminant from a unit source volume and under one-dimensional dispersion condition. Primary attention was paid to variations in the values chosen for leach rate, ground water velocity, retardation factor (sorption capability), hydrodynamic dispersion and length of flow-path.

The amount of leached radionuclides depends not only on leaching rate but also on the surface-volume ratio. From various results obtained by different studies it may be stated that the product quality, presence of water and the contact time of waste with leaching media mainly govern the leaching rate. In comparison, the surface-volume ratio is insignificant.

Peak concentrations in all cases decrease with decreasing ground water velocity, this decrease being least for the long-lived poorly sorbed radionuclides C-14, Tc-99 and I-129. For strongly sorbed radionuclides as Pu-239, Cs-137 and Co-60, the peak concentration varies in the range of several orders of magnitude for ground water velocity ranging from 1.E-4 down to 1.E-7 m/s.

The calculations showed that there is only a minor role played by dispersion at higher ground water velocities. At the lower velocities the more significant effects are for strongly sorbed radionuclides. This leads to a conclusion that the values of peak concentration at higher ground water velocities are in general governed by advection whereas dispersion does not play an important role. On the contrary, at lower rates of ground water flow the effect of dispersion is much more significant.

The general effect of increasing sorption is to decrease the peak concentration and to delay the time at which it occurs. However, this conclusion may not be valid if the radionuclide half-life is considerably longer than the travel time for a given distance.

WASTE ACCEPTANCE CRITERIA

Radioactive wastes are of different physical and chemical forms and contain variable amounts of radionuclides with different half-lives, activities and radiotoxicities as well as various amounts of non-radioactive materials. Some of these materials are in the form in which they originate. Therefore they have to be conditioned to make them suitable for disposal, particularly those with high specific activity, liquid content, leachability, unacceptable content of toxic or combustible material or mechanical and thermal stability.

The waste acceptance criteria for radioactive waste disposal define the characteristics of disposed radioactive wastes, namely the content of radionuclides, the structural stability, leachability, the possible generation of gases, microbial degradation, the content of corrosive, explosive and pyrophoric materials, free liquids and complexing agents, the corrosion resistance, surface dose rate and surface contamination of packages. The waste acceptance criteria are derived from the safety analysis of the possible environmental impacts of the radioactive waste disposal system.

Waste acceptance requirements were suggested by the operator on the basis of the safety assessment taking into account dose limits, the conditions of operations, the waste inventory, the characteristics of natural and engineered barriers and the planned duration of institutional controls (2,10).

Radiological Criteria

Quantitative radiological criteria for waste acceptance can be derived from radiological protection objectives by using safety assessment procedures. The basic radiological limitations on the acceptability of radioactive wastes are the limits on the concentration of radionuclides in the waste and the total activity that may be disposed in a given repository.

Limits on the concentration for long-lived radionuclides in the waste ensure that the site may be returned to unrestricted use after a specific number of years. They are controlled by human intrusion scenarios. Limits on the concentration for short-lived radionuclides in the waste ensure the safe transport and handling of radionuclides. They relate to "normal or operational" scenarios and are not site-specific.

Limits on the total activity are mostly site specific; they are not independent but form part of a system involving criteria described further.

Non-Radiological Criteria

Other criteria deal mainly with the capability of the waste package to prevent or delay radionuclides from reaching the biosphere in amounts resulting in the exceeding of dose limits. They are in the form of performance standards.

To minimize radiation dose and the release of radionuclides during handling, transport, storage and disposal, the main predisposal operations are generally immobilization and packaging.

It may be sometimes necessary to transform waste into a form suitable for transport, handling and disposal. The operation includes waste conversion into less soluble form, reduction of complexing agents, combustible or explosive materials or to avoid degradation of wastes and to minimize the volume of wastes. It should be added here, that the site and the engineered barriers of the repository also contribute to this objective.

The waste packaging must, with the waste form itself, provide enough shielding to protect workers and the public and be robust enough to contain the waste in any conceivable accident as well as during normal handling and transport to prevent spread of the activity. Further requirements for disposal include:

- Liquid waste must be solidified
- Solid waste must not contain free standing liquids
- Waste must not be of an explosive nature and must not have an explosive reaction to water
- Waste must not be pyrophoric or flammable
- Waste must not generate or contain toxic gases, vapors, fumes
- Waste containing hazardous, biological, pathogenic or infectious material must be treated and conditioned to reduce the potential hazard from non-radioactive materials

However, the basic limitations on the acceptability of radioactive wastes are the specific activities and the total activity that may be disposed in the repository.

Waste acceptance criteria for the repository in Dukovany have been set as radionuclide activities related to drum, vault and repository. Mobile activity includes surface contamination of the waste package, leachable activity and non-standard waste activity.
Model calculations for the nearest water supply have proven that non zero concentration may be expected only for very long lived radionuclides with low retention in the aquifer. i.e. C-14, Tc-99, I-129.

REPOSITORY DESIGN

Repository facilities must be designed in such a way that the personnel and the public are adequately protected at all times from radiological hazards during normal operation as well as in accident situations. Requirements on a repository design, construction, operation and closure were specified in the Czech Regulation on Ensuring of Nuclear Safety in Radioactive Waste Management.

The multi-barrier approach relies on the performance of the engineered structures of the repository and the waste package itself and on processes in the geosphere and biosphere, all of which act to retard radionuclides to decay and to reduce their concentration.

These barriers include:

a) Geological formation in which repository is sited assuring protection from water and retardation of radionuclides along the possible pathways to biosphere and where future natural and man-made disruptive events are unlikely

b) Physico-chemical form of the waste assuring low release rate

c) Waste package

d) Engineered barriers keeping the possibility of infiltration of water to a minimum and its rapid removal

The condition a) has been achieved by the site selection.
The first man-made barrier is a fixing medium. After preliminary safety assessment it was decided to fix the waste by bituminization or vitrification. Such a solidified waste is characterized by a low leachability and low specific area due to the high mass content of the waste in the final product.

Solidified waste is disposed in steel barrels of 200 L volume. These barrels are considered to be a transport and handling package and are not considered as an isolation barrier due to their easy corrosion.

Radioactive wastes are placed into reinforced concrete disposal vaults (70 cm wall thickness) with an underdrain system and surface water system. Their main role is to prevent water from reaching waste packages. This is achieved by the vault design and by a drainage system. Dimensions of vaults are 17.3x5.3x5.4 m. The vaults are enveloped by a 30cm thick of modified asphalt concrete mix. The service life of the engineered barrier represented by these materials is assumed to be more than 300years. The capacity of one vault is 1200 drums (200 l each). The total volume of all 112 vaults is 55000 m^3 which corresponds to about 130 000 drums. The bottom of a vault is sloped to enable the precipitation water to be pump out of vault if necessary (1,24).
When the vault is filled with waste, it is closed by a concrete panel 0.5 m thick and covered by a layer of impermeable plastic to make it waterproof. At a later time, grout application is foreseen to improve the stability and retention ability of the system. A final cover will be placed on it made of a layer of clay, geotextile and layers of draining materials to close the repository.

FINAL REMARKS

The repository site was chosen after performed area survey. The safety assessment is based on the evaluation of critical scenarios including groundwater transport, intrusion and habitation after institutional control. Waste acceptance criteria are set on the basis of the safety assessment taking into account dose limits, the conditions of operations, the waste inventory, the characteristics of natural and engineered barriers and the planned duration of institutional controls. Repository capacity of 55 000 m^3 is based on 112 disposal vaults.

Since the beginning of operation in 1994 5 vaults have been filled and closed. Data obtained from radiological monitoring remain in the same range as in the preliminary surveys. Good relations have been established with the local population. It is expected that the repository will have sufficient capacity to serve both Czech NPP's for their whole service life until the year 2020.

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