



Overview of the Lithuanian programme for disposal of RBMK-1500 spent nuclear fuel

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ABSTRACT

In Lithuania all the spent nuclear fuel (SNF) came from operation of the Ignalina nuclear power plant with two reactors of RBMK type (RBMK is a Russian acronym for ‘Channelized Large Power Reactor’ which is a water-cooled graphite-moderated reactor: RBMK-1500). Approximately 22,000 SNF assemblies are due for geological disposal in Lithuania. Currently it is envisaged that SNF will be stored in dry interim storage facilities (new and existing) for at least 50 y prior to possible deep geological disposal.

The decision on the final SNF management option (disposal in a national repository, disposal in regional repositories, etc.) has not yet been made but some investigations of the possibilities to dispose of the SNF in Lithuania have been initiated. With the support of Swedish experts, analysis of possible geological formations for SNF disposal was performed and the existence of potentially suitable formations agreed. The geological formations prioritized as prospective include the crystalline rocks in southern Lithuania and two clayey formations: the Lower Triassic clay formation and the Lower Cambrian Baltic Group clay formation, with priority given to the Lower Triassic clay formation.

This paper presents the main aspects of the research and other activities undertaken over the past decade in the field of SNF disposal: international cooperation; current status and plans for the Lithuanian national program; further investigations required; and competence developments.

KEYWORDS: RBMK-1500 spent nuclear fuel, Lithuania, geological disposal program.

Introduction

THERE is only one nuclear power plant (NPP) in Lithuania – the Ignalina nuclear power plant. It is situated in the northeast of the country, near the state borders with the Republics of Latvia and Belarus, on the bank of Lake Druksiai. Ignalina NPP has two RBMK-1500 reactor units. The final shutdown of the 1st reactor was on 31 December 2004 and the second reactor was shut down on 31 December 2009. A few years ago there was a

proposal to build a new nuclear power plant in Lithuania and in 2009 the environmental impact assessment report was prepared. After review by Lithuanian authorities it was concluded that the new Visaginas nuclear power plant could be built at the Ignalina NPP site; a final decision is still pending, however.

During operation of the Ignalina NPP, ~22,000 SNF assemblies (UO_2 fuel with 2.0, 2.4, 2.6 and 2.8% initial ^{235}U enrichment) from the two RBMK-1500 reactors were accumulated (Poskas *et al.*, 2012). It was decided to store these assemblies at an interim dry type of storage facility at the Ignalina NPP site for at least 50 years, prior to disposal. The existing SNF storage facility (constructed in 1999

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and completely full) contains ductile cast iron and heavy concrete dry storage containers. The remaining SNF is still stored in water pools at the Ignalina NPP and will be transferred to a new SNF dry storage facility. A new SNF storage facility is under construction to accommodate all of the SNF from the water pools. Approximately 200 containers will be stored in this new storage facility. According to the European Commission Directive on radioactive waste and spent fuel management (European Commission, 2011), storage of radioactive waste, including long-term storage, is an interim solution, but not an alternative to disposal. To this end, Member States are obliged to establish and implement national programs for management of spent fuel and/or radioactive waste from generation to disposal. Up to now, the decision on the final option for Lithuanian SNF management has not been made, but investigations of some possibilities have been initiated.

Initial activities

Activities related to SNF disposal started ~14 y ago. The strategy for Radioactive Waste Management was developed and approved by the Lithuanian Government in 2002. One of the tasks defined in the strategy was to prepare and implement a long-term research program on the analysis of possibilities to dispose of SNF and long-lived radioactive waste in Lithuania. Following implementation of the Strategy, the National research program for 2003–2007 was developed and approved by the Lithuanian Government (2002). Around this time, the Swedish Government established special support for funding of the decommissioning activities of the Ignalina NPP. The development of national competence in terms of SNF disposal was identified as one of the areas where support was requested. Following this, a multiyear cooperation project with Swedish International Project for Nuclear Safety (SIP) on competence development in the area of SNF disposal was initiated. In 2008, the ‘Strategy for Radioactive Waste Management’ was revised and subsequently the national research program for 2008–2012 was developed and approved by the Lithuanian Government (2008). With regard to EC Directive 2011/70/EURATOM, a new national program on management of spent nuclear fuel and radioactive waste (with content according to the Directive) is under preparation. Among the other activities, there are proposals to develop a plan of

implementation of a geological repository, to continue investigations, to initiate characterization of prospective regions and development of a repository concept.

Outcomes of the national research programs

Geological formations

Based on the investigations of Lithuanian geological structures, several formations were named as possible host rocks for a deep geological repository (crystalline rock, clayey formations, anhydrite and salt). During the 2002–2005 period, investigations of possible disposal of SNF in Lithuania were performed with the support of Swedish experts. The experts of the Lithuanian Geological Survey and the Institute of Geology and Geography together with Swedish experts analysed those formations identified, based on the available information (archived and published) (Kanopiene *et al.*, 2005). They concluded that there were some formations potentially suitable for SNF disposal (Fig. 1). Geological formations prioritized as prospective include the crystalline rocks in southern Lithuania and two clayey formations: the Lower Triassic clay formation and the Lower Cambrian Baltic Group clay formation, with priority given to the Lower Triassic clay formation (Kanopiene *et al.*, 2005). During the analysis of the geological formations and their distribution across the country, various factors were taken into consideration, e.g. the formation’s homogeneity, thickness, depth, distribution area, simplicity of tectonic structure, absence of aquifers between different geological formations, low neotectonic and seismic activity, proper isolation and the mechanical properties of the rocks.

With regards to the crystalline rock, it was defined that a 100 km² area could be found between the major fracture zones and with acceptable depth conditions. Reports of previous investigations show that the rock is unweathered and ‘monolithic’ with normal fracture content that, hence, fulfils the requirements both with respect to tightness and stability (Kanopiene *et al.*, 2005). Thus, crystalline rocks as well as clayey formations need further, more detailed study.

Repository concept in crystalline rocks

Implementing research on SNF disposal in Lithuania, the Lithuanian Energy Institute (LEI)

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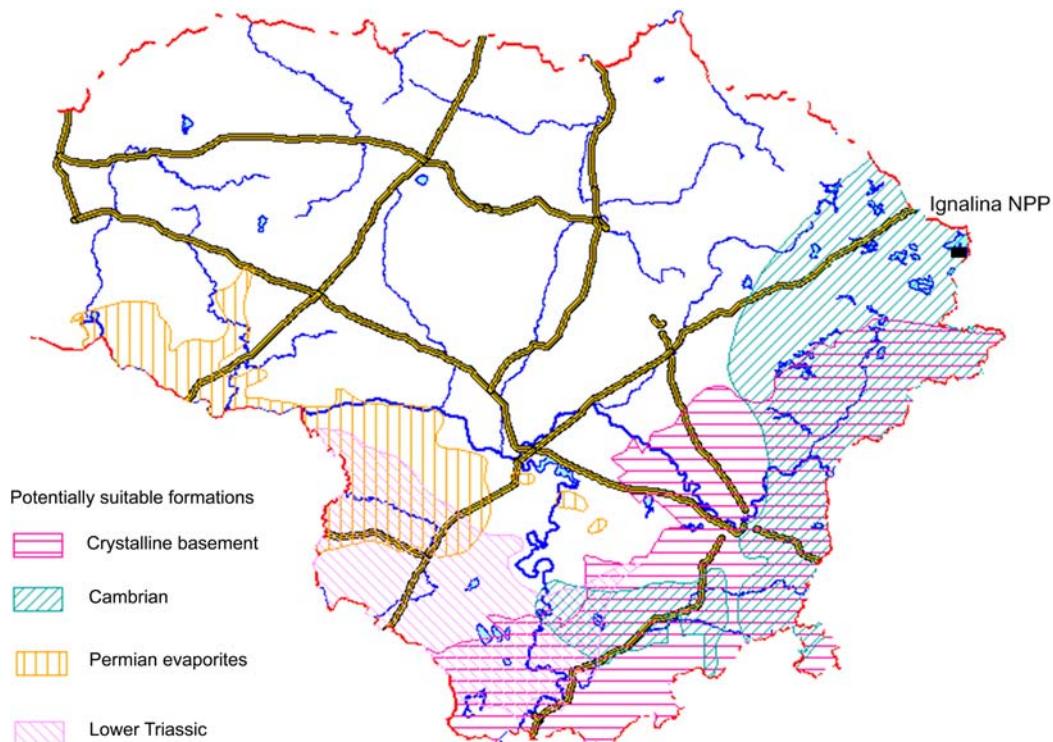


FIG. 1. Distribution of potentially suitable geological formations for SNF disposal in Lithuania (after Kanopiene *et al.*, 2005).

with the assistance of the Swedish experts proposed the concept of a deep geological repository in crystalline rock formations. It is based on a KBS-3 concept developed by SKB for disposal of SNF in Sweden. Both, vertical (KBS-3V) and horizontal (KBS-3H) canister emplacement options were considered. In the case of horizontal SNF emplacement, tunnels 1.85 m in diameter and 250 m long were assumed, the distance between the emplacement tunnels of 40 m and 1.2 m between the top/bottom of the canisters was estimated. In this case, the area of the proposed SNF repository in Lithuania would cover $\sim 0.4 \text{ km}^2$. Based on the KBS-3 concept, the copper canister with a cast iron insert was proposed for disposal of RBMK-1500 SNF. The wall thickness of the copper canister was 50 mm and the minimum wall thickness of the cast iron was 50 mm. Taking into account the results of criticality, dose-rate assessment and thermal calculations as well as the existing experience in canister shifting and emplacement technology, it was proposed to load 32 half-assemblies of RBMK-1500 SNF in one disposal canister. Based on

preliminary assessment, the reference canister would be 1050 mm in diameter and 4070 mm long (Fig. 2). For Lithuanian SNF disposal purposes, ~ 1400 such canisters would be required.

During the investigations a number of modelling studies on key aspects of SNF disposal were carried out by LEI. The main outcomes of these studies are presented below.

Criticality

Criticality safety analysis for the copper disposal canister with 2.8% ^{235}U RBMK-1500 SNF was performed using *SCALE* 4.3 computer code. The main conditions and assumptions accepted for the criticality calculations were: maximum loading of the canister, i.e. the insert in the canister contains 32 cylindrical holes each with a fuel half-assembly (18 fuel rods in each) inside; no credit for burnup. The fuel half-assemblies contain only fresh, undepleted fuel with 2.8% ^{235}U enrichment; and no structural damage in the fuel rods, half-assemblies, insert or canister body.

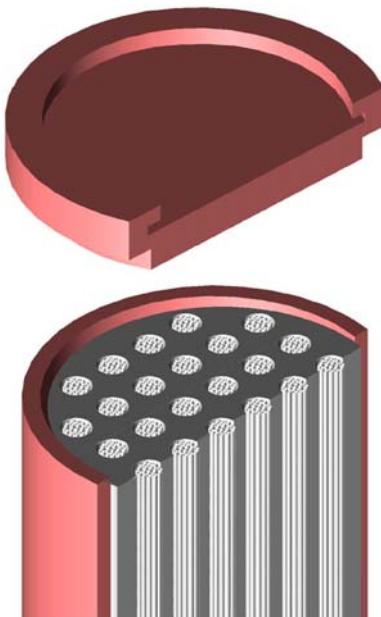


FIG. 2. The proposed canister for Lithuanian SNF disposal (reproduced from Poskas *et al.*, 2006).

Variation of the effective neutron multiplication factor k_{eff} (including 3 standard deviations) with water density for a copper disposal canister showed that k_{eff} values increased continuously when the water density was increasing and a maximum k_{eff} value of ~ 0.61 was reached when the water density was 1.0 g/cm^3 . The main requirement of the criticality safety was that effective neutron multiplication of the system containing fissile material must be < 0.95 . For a copper-disposal canister when long-term processes (corrosion, degradation, etc.) were not taken into account, k_{eff} values were less than the allowable value of 0.95 (Poskas *et al.*, 2006).

Dose rate

Dose-rate values are important, when, after interim dry storage, SNF would be emplaced in canisters and transferred to the repository. Calculated dose-rate levels indicated what measures should be introduced (e.g. remote handling, additional shielding) to meet radiation-safety requirements. The γ dose rate outside the canister was also important for radiolytic disintegration of water and for nitric-acid formation from entrapped air before saturation of the buffer. The canister design criteria require that

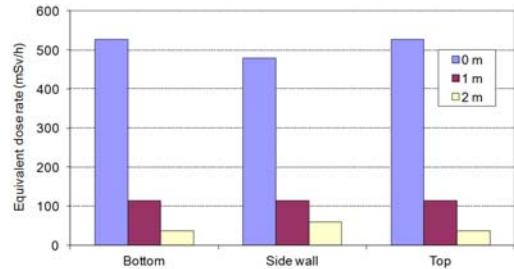


FIG. 3. The total equivalent dose-rate values on the copper canister surface and at distances of 1 and 2 m (reproduced from Poskas *et al.*, 2006)

the γ dose rate should not exceed 1 Gy/h (1 Sv/h if only β , γ radiation) in order to minimize the importance of the process (SKB, 1999). Sequences SAS2H and SAS4 from the *SCALE* 4.3 computer code were used for dose-rate assessment of the canister with RBMK-1500 SNF (Poskas *et al.*, 2006). The main assumptions for the modelling of the fuel assembly irradiation were as follows: the RBMK-1500 fuel assembly that consisted of 18 fuel rods was homogenized and described as an element of five concentric cylinders in the reactor's fuel channel; fuel enrichment = $2.8\% \ ^{235}\text{U}$, burn-up = 30 MWd/kgU , irradiation time = 3 y , cooling time = 50 y ; for dose-rate calculations, axial burn-up distribution of a fuel assembly was not taken into account.

Neutron and gamma radiation makes up the total equivalent dose rate and from the RBMK-1500 SNF canister stored for 50 y , the total equivalent dose rate is $\sim 500 \text{ mSv/h}$ (Fig. 3).

The results of dose-rate calculations show that the total equivalent dose rate was formed mainly by the γ radiation ($> 99.9\%$); neutrons only formed an insignificant part of the total dose rate. The estimated dose rate on the surface of the copper disposal canister with RBMK-1500 SNF was rather high compared to SNF storage casks but did not exceed the aforementioned limit of 1 Sv/h which is the maximum allowable dose-rate value according to the Swedish KBS-3 concept.

Temperature evolution in SNF tunnels in crystalline rocks

First of all, the temperature evolution in SNF tunnels was assessed using the *FLUENT* code (Poskas *et al.*, 2006). Additional analyses taking into account the coupling with hydrodynamic (TH

analysis) and hydrodynamic-mechanical processes (THM analysis) were performed using the modelling tool, *COMPASS* (Justinavicius *et al.*, 2014). The end-to-end distance between RBMK-1500 SNF disposal canisters for the KBS-3H concept was assumed to be 1.2 m (backfilled with compacted bentonite), the distance between the emplacement tunnels was assumed to be 40 m. The modelling results revealed the importance of coupled heat (T) and hydrodynamic (H) processes for peak temperature in the engineered barriers, whereas the impact of mechanical (M) processes evaluation was insignificant (Fig. 4). The peak temperature at the outer surface of the disposal canister ($\sim 92^\circ\text{C}$) did not exceed the permissible temperature of 100°C which is the limit to prevent mineralogical transformation of bentonite from swelling to non-swelling phases.

Radionuclide migration from the canister with an initial defect (near-field, far-field) in crystalline rocks

Up to now, research on radionuclide release and transport from the generic geological repositories for RBMK-type SNF has been limited. Preliminary studies on the radionuclide transport through the engineered and natural barriers of the conceptual repository for RBMK-1500 SNF were performed and presented by Brazauskaitė and Poskas (2006) and Poskas *et al.* (2007). The analysis was performed for the canister, the initial defect of which increased, and the continuous groundwater pathway formed $>200,000$ y after closure of the repository. The radionuclides ^{59}Ni , ^{129}I , ^{135}Cs and ^{226}Ra were identified as dominating the radioactivity of the near-field flux. More research on radionuclide transport from a geological repository for RBMK-type SNF is needed.

The research on radionuclide transport from a generic geological repository for the RBMK-1500 SNF of 2.8% ^{235}U initial enrichment (with Er absorber) and average burn-up of ~ 29 MWd/kgU was presented by Poskas *et al.* (2013). Radionuclide transport analysis was focused on the engineered barrier system (EBS) with a horizontal canister emplacement (KBS-3H) and performed taking into account possible differences in the data on the initial size of a canister defect, defect-enlargement time and radionuclide release start time. For numerical simulations, the computer code *AMBER* (UK) was used. The analysis of radionuclide transport peculiarities demonstrated

that release from the EBS was most intense after defect enlargement (Fig. 5).

Radionuclides with the largest radiological impact were identified based on the mass-transfer analysis complemented by the analysis of radio-toxicity flux. The results showed that, depending on the differences in the initial defect size, defect enlargement time and release start time, the peak flux from the EBS may vary by a factor of 2 (for ^{129}I) and 1.5 (for ^{226}Ra) for RBMK-1500 SNF (Poskas *et al.*, 2013).

The results of the analysis of the disposal behaviour of different SNF types under generic repository conditions with vertical canister emplacement and a one-canister defect scenario with two different corrosion rates were presented by Poskas *et al.* (2014). A comparison of peak fluxes from the near field for Lithuanian RBMK-1500 and Swedish boiling water reactor's SNF revealed differences that were not directly proportional to the differences in SNF inventory (Fig. 6).

LEI competence and cooperation

The above-mentioned activities related to safety assessment were mainly performed by the Lithuanian Energy Institute and valuable experience was gained and new competences developed over the period of ~ 15 years during these investigations. In summary it includes: knowledge of the practices and principles of geological disposal of radioactive waste; experience in technical and administrative aspects of radioactive-waste management projects; availability and experience in the application of computer code for radioactive-waste disposal modelling purposes: characterization of spent nuclear fuel and radioactive waste characteristics (*SCALE* and *MCNP/MCNPX* codes); the safety and environmental impact assessment of SNF and radioactive-waste treatment, storage and disposal facilities (*MICROSHIELD*, *MICROSKYSHINE*, *VISIPLAN*, *AMBER* and *GOLDSIM* codes); modelling of radionuclide transport through the engineered and geological barriers of a repository (*AMBER*, *GOLDSIM* and *COMSOL* codes); estimation of gas generation and migration in a geological repository (*PETRASIM (TOUGH2)* and *COMSOL* codes); and thermo-hydro-mechanical processes modelling in engineered barriers of a repository (*COMPASS* and *COMSOL* codes).

Note that the existing experience has been gained mainly from international cooperation. An effective

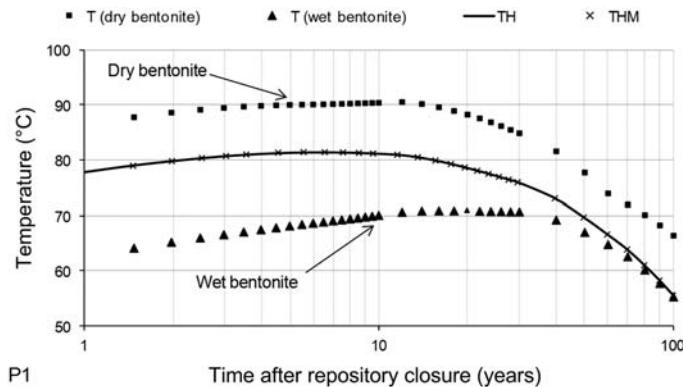


FIG. 4. Temperature profiles at the outer surface of the SNF canister resulting from T, TH and THM analyses (reproduced from figure 3, Justinavicius *et al.*, 2014 with kind permission from Springer Science+Business media).

start-up of competence development was a multi-year cooperation project with the Swedish International Project for Nuclear Safety (SIP) ('Competence development in the area of SNF disposal'), 2000–2005.

In order to ensure effective transfer of knowledge and practices existing in other countries, LEI participated in various research projects coordinated by the International Atomic Energy Agency (IAEA) ('The use of numerical models in support

of site characterization and performance assessment studies for geological repositories', 2005–2010 and 'Treatment Requirements for Irradiated RBMK-1500 Graphite to meet Disposal Requirements in Lithuania', 2010–2013) and took advantage of IAEA fellowships, training courses and workshops. In order to become a part of the common research community on nuclear issues in Europe, LEI has taken part in numerous EC-funded projects.

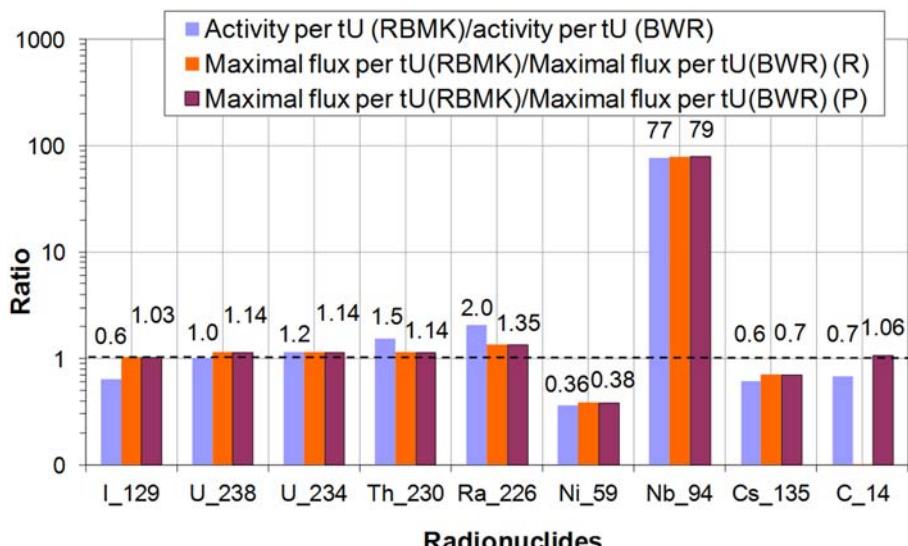


FIG. 5. Fractional flux of radionuclides diffused from the engineered barriers to the geosphere in the case of a canister with an initial defect (defect enlargement time – 10^4 y after closure of the repository; start of radionuclide release – 10^3 y after closure of the repository; reproduced from Poskas *et al.*, 2013)

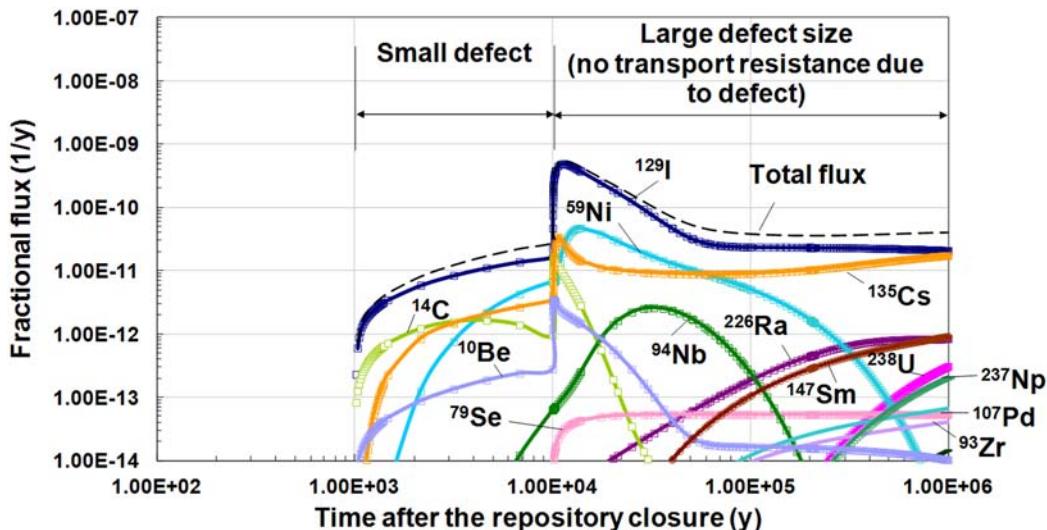


FIG. 6. Comparison of the ratio of the radionuclide inventory and maximal near-field flux for RBMK and BWR SNF per tU in case of: (a) reasonable, and (b) pessimistic canister defect parameters (log scale) (reproduced from Poskas *et al.*, 2014).

The EC 7th FP research project on ‘Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste (CARBOWASTE)’ was launched in 2008 for a 5 y period. LEI was involved in a large, 30-partner consortium addressing retrieval, characterization, treatment, reuse and disposal of irradiated graphite and other carbonaceous waste.

Together with partners in another research project ‘Fate Of Repository Gases, 2009–2013 (FORGE)’, LEI experts focused on understanding gas generation, its migration through engineered and natural barriers of a geological repository and consideration of these processes in quantitative assessment of repository performance.

Within the EC 7th FP project ‘Carbon-14 Source Term’ (CAST, 2013–2018), LEI researchers together with the experts from 32 other organizations seek to develop understanding of the potential release mechanisms of carbon-14 from radioactive waste materials under conditions relevant to waste packaging and disposal to underground geological disposal facilities. The project focuses on release of carbon-14 as dissolved and gaseous species from irradiated metals (steels, Zircaloys), irradiated graphite and from ion-exchange materials as dissolved and gaseous species.

Besides the research projects, LEI experts were involved in coordination and support action type

projects. Together with 14 other partners from New and Old Member States of the European Union, LEI contributed to the evaluation of skills and current participation of New Member States in the Euratom research programme and to the identification and implementation of effective and efficient solutions leading to more New Member States being involved in future Euratom Programmes (EC 7th FP project ‘New MS Linking for an Advanced Cohesion in Euratom Research (NEWLANCER)’ 2011–2013).

Being involved in the review of safety evaluation of a wide range of radioactive-waste related activities, LEI took part in EC 7th FP project ‘Sustainable network for independent technical expertise for radioactive waste disposal (SITEX)’ (2012–2014). The project was devoted to the establishment of conditions required for developing a sustainable network of technical safety experts who have their own skills and analytical tools, independently of the operators, and who are capable of conducting their own research programs in coordination with research activities performed by operators.

Currently, LEI experts are involved in the ongoing EC 7th FP project ‘Building a platform for enhanced societal research related to nuclear energy in Central and Eastern Europe (PLATENSO)’ (2013–2016). The objective of PLATENSO is to

enhance the capabilities of research institutes in Central and Eastern European countries to take part in EU research with respect to governance, social and societal aspects linked to nuclear energy. The project is being performed by 19 partners from 12 EU countries.

Current needs, international projects

According to IAEA terminology, the current Lithuanian SNF disposal program corresponds to an 'Initial site investigation and preliminary facility design' stage and the national competence to perform activities related to this stage is very important. Besides the competence developed and existing experience, further development and knowledge transfer/support are still required. This is important in order to be able to implement the principles of EC Directive 2011/70/EURATOM at national level and to move towards final disposal of SNF in Lithuania.

While defining the disposal concepts, it is necessary to have enough competence to highlight their advantages and disadvantages. It is important to be able to adapt a disposal concept to a country's need, i.e. in the case of a repository in crystalline rock with an overlying sedimentary rock system, how much credit should be given to the sedimentary rock cover? What safety function should be defined for engineered barriers, natural barriers, etc? Approaches for management of various activities related to development and implementation of a disposal facility, considering time and duration demands, etc. is very important and needs to be set up at an early stage of a repository-development program. Besides, the timing of various activities, commissioning and decommissioning of installations is the input to the cost assessment of the disposal process. The current needs and international cooperation areas also include the analysis of available disposal-cost assessment methodologies, updating of the structure to the level which allows direct comparison of the cost of different concepts and in different countries; justification of safety scenarios and modelling issues for different stages of disposal-program development; identification of priorities in R&D based on uncertainty analysis, etc.

For countries with less advanced geological disposal programs, it is very important to join in the projects with advanced countries in order to benefit from their experience, gain competence and move successfully towards safe nuclear-fuel disposal.

Knowledge transfer from more advanced programs helps to avoid duplication of research that has already been done. Cooperation and networking will reduce regional disparity in the European Union and will reinforce EU excellence in nuclear safety and radioactive-waste management.

Conclusions

Starting from the year 2000, the outcome from research and other activities undertaken in the field of SNF disposal in Lithuania resulted in: development of some competence in the field of SNF disposal; prioritization of potential geological formations for SNF disposal in Lithuania; proposal of a preliminary repository concept (design of the repository and canister); preliminary calculations of temperature distribution, criticality, dose rate from disposal canisters, modelling of radionuclide migration from the repository; and participation in international research and coordination projects.

For now the Lithuanian SNF disposal program is at the stage of initial site investigation and preliminary facility design. The main points in the near-future activities in the field of SNF disposal include planning of the implementation of geological repository, investigations and characterization of prospective regions, initiation of the development of a repository concept as well as an increase in competence through international cooperation and maintenance of the competence over the longer term.

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