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RADIONUCLIDE AND HEAT TRANSPORT FROM HYPOTHETICAL SNF CANISTER IN CRYSTALLINE BASEMENT, CASE OF SOUTH-EASTERN LITHUANIA

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Abstract. The Strategy on Radioactive Waste Management of Lithuania (Radioaktyviųjų… 2008) envisages evaluating the possibilities of disposal of spent nuclear fuel and long-lived radioactive waste from operation and decommissioning of Ignalina NPP in a deep geological repository. The crystalline basement and sedimentary cover of south-eastern Lithuania was selected for the current model case studies due to availability of geological and hydrogeological data from previous explorations. Groundwater flow, radionuclide (iodine-129 as mobile and long-lived one) transport and heat transfer, modelling using computer code FEFLOW was performed. The model domain of south-eastern Lithuania comprises Proterozoic-Archaean aquifer with overlaying aquifers system of sedimentary cover. The upward groundwater flow through defected canister located in tectonically damaged zone was conservatively generated. The main results of calculations are following: in case of upward groundwater flow, the maximum activity concentration of ^{129}I in groundwater of the tectonic fracture zone above defected canister will not exceed 10^{-4} Bq/l; the maximum temperature in the tectonic fracture will obtain about 30-35°C and will not impact on the radionuclide transport. Location of model domain in south-eastern Lithuania does not mean any reference to the site for deep geological repository. The results show that doses obtained by human via drinking water should be below the dose constraint (0.2 mSv /year).

Keywords: spent nuclear fuel, geological repository, crystalline basement, groundwater, finite elements model.

1. Introduction

More than 21 000 nuclear fuel assemblies were consumed during operation of the Ignalina NPP (INPP). The accumulated spent fuel (SNF) contains approx. 2 400 tons of uranium. Since the May of 1999, the SNF, after being stored in the water ponds inside the NPP buildings, has been removed from there, loaded into CASTOR RBMK-1500 or CONSTOR RBMK-1500 canisters and transported to an interim storage facility in the industrial area of the INPP, the SNF can be safety stored in these canisters for 50 years. Due to high content of long-lived nuclides, the spent fuel must be stored in deep geological disposal (Deep repository… 1998; IAEA Deep…1985).

There is an international consensus that high level and long-lived radioactive waste, first of all SNF, is best disposed of in deep geological repositories using a system of engineered and natural barriers (The scientific… 1995). Modern technology enables assessing the old deep geological formations as the most obvious candidate environments.

Several alternatives related to safe management and disposing of the SNF are being internationally analyzed for the future: constructing of deep geological repositories for SNF and other long-lived radioactive wastes in each SNF-generating country, a multinational repository constructed by joint efforts of several countries and a possibility of extending the storage period for up to 100 and more years.

The overview of the geological structure and composition of the sedimentary cover and crystalline basement of Lithuania was carried out by Lithuanian and Swedish experts starting the feasibility studies aimed to assess the whole geological environment in Lithuania (Suitability… 2005). Clayey formations, rock salt and anhydrite formations, and the crystalline basement rocks were identified for the future considerations. Since most information regarding deep geological formations in Lithuania is available on crystalline basement of south-eastern Lithuania, this host formation with overlaying 200–300 m thickness sedimentary cover was selected for the model case studies (Concept… 2005; Generic safety… 2005; Suitability… 2005).

Initially the reactors RBMK-1500 used 2% ^{235}U enriched nuclear fuel. Later, the fuel enrichment was increased up to 2.8%. The initial studies of radionuclide transport from the SNF canister has already been performed (Brazauskaitė, Poškas 2005, 2006, 2007, 2008; Jakimavičiūtė-Maselienė *et al.* 2006a, 2006b). These publications describe the SNF disposal system concept, container properties, engineering barriers, the radionuclide transport and retardation processes in the near-field and far-field regions of SNF disposal system. The effective dose has been predicted as well. Long-lived non-sorbed ^{129}I radionuclide (half-life $1.57 \cdot 10^7$ years) was identified as the most critical for safety of the disposal system. The heat generation from the SNF including evaluation of the maximum temperature on canisters surface and temperature distribution in bentonite, has been evaluated too (Sirvydas, Poškas 2009).

The aim of this study is to assess the heat transfer from SNF cask and consequently an impact of elevated temperature on radionuclide transport within groundwater if SNF cask would be disposed of in tectonically disturbed zone of crystalline basement. Model case is substantiated by more detailed and complicated site specific consideration in this study compared to previous ones.

2. Methods

Iodine-129 is a key nuclide defining safety of the disposal system. It is selected for the current study. The inventory of ^{129}I assumed for modelling case is $2.3 \cdot 10^9$ Bq per canister (the same as for Swedish BWR fuel). An estimated ^{129}I release rate through engineered barriers to far-field region was taken from a model case study (Generic safety… 2005; Brazauskaitė, Poškas 2007) as input function for 3D modelling of radionuclide transport in far-field aquifer-aquitard system.

Groundwater flow, radionuclide (iodine-129 as mobile and long-lived one) transport and heat transfer modelling using computer code FEFLOW was performed for model domain (approximately 0.8 km length, 0.6 km width and 0.52 km thick far-field block) which is located in south-eastern Lithuania. Source term for radionuclide transport was derived from canister defect scenario and initial conditions for heat generation from the canister were set as evaluated by LEI experts (Generic safety… 2005; Brazauskaitė, Poškas 2007; Sirvydas, Poškas 2009).

Model domain considered in this study is densely dissected by tectonic fault zones. It is conservatively taken that the canister is located in the two perpendicular tectonic faults of crystalline basement. The groundwater washes the canister after what it discharges into the upper aquifers. For enhancement of hydrodynamic effect it is taken that a productive three-well system is installed 363 m from the canister in the two perpendicular tectonic faults. The first productive well is installed in the Ordovician-Cambrian aquifer (290 m deep). The second well is installed in the Cretaceous aquifer (180 m deep) and the third well – in the Quaternary aquifer (100 m deep). The pumping rate of each well system is 1000 m^3/day.

The radionuclide transport from a repository toward the far-field region with aquifers can only start when the canister containing the SNF is defected, radionuclides dissolve in the water and are transported away from the container through the surrounding engineered barriers. In this study, the time for the mentioned processes is assumed 200 000 years after SNF closure (Generic safety… 2005; Brazauskaitė, Poškas 2007).

Radionuclide and heat transfer mechanisms of major importance to be taken into account are: advection in saturated zone, molecular diffusion, hydrodynamic dispersion, retardation by interactions with the solid phase and heat transfer by conduction and convection (De Marsily *et al.* 2002; Geiger 1965; Krishnamoorthy, Nair 1994; Mallants 2006; Mikšys 2004; Nakshabandi, Kohnke 1965; Suitability… 2005). There are many types of possible solid-liquid interactions but the most common is adsorption, particularly in the case of small particles (silt, clay, etc.) (Baker 1998; Lucero 1998; Vilks *et al.* 1998).

Temperature is an important parameter changing hydrogeological, mechanical and chemical conditions. Therefore the heat transport impact on the radionuclide migration was evaluated (Generic safety… 2005).

Hydrogeological framework of the southern Lithuanian region was outlined basing on the information summarized in recent geoscientific generalizations (Dundulis *et al.* 2004; Mikšys 2004; Suitability… 2005; Juodkazis 1989).

Quaternary deposits (glacial till, silt and various sands) in the area of model domain occur at the land surface. Total thickness of these deposits varies from 80 to 143 m (average thickness is 119 m). There is shallow unconfined groundwater aquifer and several semi-confined aquifers. Piezometric level and hydraulic properties of Quaternary aquifers are different and depend on the complexity of the geological structure. For modelling purpose, all Quaternary aquifers are considered as unified aquifer system (Suitability… 2005).

The Cretaceous aquifer consists of chalk, silt and sand. The top of the aquifer dips from the altitude of 61 m a.s.l. to the 10 m b.s.l. The thickness of the aquifer varies from 30 to 105 m. The hydraulic head of the aquifer varies between the altitudes of 150 and 155 m a.s.l.

The Permian aquifer consists of fractured limestone and sandstone. The top of the aquifer occurs from a depth of 141 m to a depth of 244 m. It dips to the west and southwest. The hydraulic head occurs between the altitudes of 160 and 210 m a.s.l.

The Silurian – Upper and Middle Ordovician aquifer system occurs over the studied area except the southernmost edge. It consists of limestone and clay. The top of the aquifer occurs at the depth of 204 m to 277 m. It dips to the west and northwest. The hydraulic head occurs at an altitude 150 m a.s.l.

The Lower Ordovician – Cambrian aquifer system consists of limestone, clayey limestone and sandstone. Altitude of the aquifer top is varying from –150 m to –210 m a.s.l. It dips to the west. The hydraulic head varies between the altitudes of 80 and 150 m a.s.l.

The Lower Cambrian aquitard occurs in the northern and north-eastern part of the area. It consists of argillite, sandstone and clay. Depth of the layer varies from 259 to 287 m. Altitudes of occurrence are between –140 m in the southern and –210 m a.s.l. in the north-western part of the area.

The Cambrian – Vendian aquifer system consists of sandstone and argillite. The thickness in study area is 100 m. The aquifer has a strong hydraulic connection with the underlying Protherozoic–Archaean aquifer. Therefore, the hydraulic heads of these two systems are similar. It is about 20 m a.s.l. in the south-western part and more than 110 m a.s.l. in the northeast (Suitability… 2005).

The Proterozoic–Archaean aquifer occurs over the studied area. It consists of fractured crystalline rocks and occurs at the depth from 300 m to more than 600 m. The crystalline rocks were exposed to denudation and weathering for different time intervals under various climate conditions. Commonly, the upper part of the basement is weathered. The composition of the weathered crust varies significantly, that is related to the composition of the basement rocks and physical-chemical exogenic conditions. Groundwater is accumulated in weathering and tectonic fractures. Hydraulic transmissivity of the aquifer could reach 50 m^2/d, and specific yield could be between 0.25 and 0.35 l/s (Suitability… 2005).

The site-specific and generic parameters are given in Tables 1 and 2.

Location of this model domain in the particular area of the territory of Lithuania is only demonstrative, showing what environmental impact would happen if deep geological repository was constructed in similar far-field conditions.

The numerical model used in this study is based on three-dimensional finite-element code FEFLOW 5.0, which allows modelling groundwater flow, contaminant transport and heat transfer in layered three-dimensional system taking into account fracture phenomenon. It is based on the physical conservation principles for mass, chemical species, linear momentum and energy in a transient and three-dimensional numerical analysis (Diersch 2002). Mathematical formulations of numerical analysis for present model domain are described in (Jakimavičiūtė-Maselienė *et al.* 2006a, 2006b).

Once calibrated, the model was used to predict radionuclide transport within groundwater and heat transfer in host formation and potential effect to environment. The influence of the heat transfer on the radionuclide transport was evaluated as well. The numerical model constructed in such a way as to imitate more intensive radionuclide transport to aquifers than it could be possible in realistic case. Therefore the defected canister is installed in the top part of the crystalline basement in the crossing point of two perpendicular single fractures though following the conceptual design it should be at a depth of 100 m from the top of crystalline basement. Another single fracture is located 300 m from repository in the flow direction.

Table 1. Heat transfer parameters selected for different zones (numbers in the bracket) of modelling domain in the southern part of Lithuania (Mallants 2006; Nakshabandi, Kohnke 1965; Vallander, Eurenius 1991; Žvykas 1989; Motuza, Marfin 1980)

No.	Geological formation	Lithological description (prevailing)	Temperature, °C	Heat capacity, 10^6 J/m^3/K	Heat conductivity, J/m/s/K
1	Quaternary	Loam (1, 3), sand (2)	7.4	2.42 (1, 3), 2.35 (2)	1.78 (1, 3), 1.80 (2)
2		Sand (1), loam (2, 3),	7.6	2.35 (1), 2.42 (2, 3)	1.80 (1. 3), 1.78 (2)
3		Silt (1), sand (2), loam (3)	7.8	2.43 (1), 2.42 (2, 3)	1.78 (1, 3), 1.80 (2)
4		Loam (1–3)	8.0	2.42 (1–3)	1.78 (1–3)
5		Sand (1, 2), loam (3)	8.2	2.35 (1, 2), 2.42 (3)	1.80 (1, 3), 1.78 (2)
6	Cretaceous	Chalk (1, 3), silt (2)	8.4	3.15 (1, 3), 2.43 (2)	2.00 (1, 3), 1.78 (2)
7		Chalk (1), silt (2), fine- grained sand (3)	8.6	3.15 (1), 2.43 (2), 2.35 (3)	2.00 (1, 2), 1.80 (3)
8			8.8		
9		Medium-grained sand (1, 2), fine-grained sand (3)	9.0	2.35 (1–3)	1.80 (1–3)
10		Medium-grained sand (1, 2), chalk (3)	9.2	2.35 (1, 2), 3.15 (3)	1.80 (1, 2), 2.00 (3)
11	Permian	Limestone (1, 3), clayey limestone (2)	9.4	3.90 (1–3)	2.00 (1–3)
12		Sandstone (1), clayey limestone (2), limestone (3)	9.6	2.63 (1), 3.90 (2, 3)	2.30 (1), 2.00 (2, 3)
13	Silurian–Ordovician	Limestone (1, 2), clay (3)	9.8	3.90 (1, 2), 3.27 (3)	2.00 (1, 2), 1.47 (3)
14		Limestone (1–3)	10.0	3.90 (1–3)	2.00 (1–3)
15	Ordovician–Cambrian	Sandstone (1), clayey limestone (2), limestone (3)	10.2	2.63 (1), 3.90 (2, 3)	2.30 (1), 2.00 (2, 3)
16			10.4		
17	Cambrian	Argillite (1), sandstone (2, 3)	10.6	3.21 (1), 2.63 (2, 3)	1.47 (1), 2.30 (2, 3)
18		Argillite (1), sandstone (2), clay (3)	10.8	3.21 (1), 2.63 (2), 3.27 (3)	1.47 (1, 3), 2.30 (3)
19	Cambrian–Vendian	Sandstone (1, 3), argillite (2)	11.0	2.63 (1, 3), 3.21 (2)	2.30 (1, 3), 1.47 (2)
20			11.2		
21			11.4		
22			11.6		
23			11.8		
24	Proterozoic–Archaean	Milonite (1), sandstone (2), gravellite (3)	12.0	1.90 (1, 3), 2.63 (2)	2.30 (1–3)
25		Epidozite (1), breccia (2), granite-gneisses (3)	12.2	2.32 (1), 2.00 (2), 2.12 (3)	2.30 (1, 2), 3.00 (3)
26			12.4		
27		Epidozite (1), plagiogneisses (2), granite-gneisses (3)	12.6	2.32 (1), 2.11 (2), 2.12 (3)	
28		Granite-gneisses (1, 3) plagiogneisses (2)	12.8	2.12 (1, 3), 2.11 (2)	2.00 (1, 3), 2.30 (2)
29			13.0		

Table 2. Parameters of the three single fractures, which represent tectonic fault zone (Adam *et al.* 1985; Nakshabandi, Kohnke 1965)

Parameters	Crystalline rocks (slices 24–29)	Sandstone (slices 19–23)
Thickness, m	1.0	1.0
Hydraulic conductivity, 10^{-4} m/s	60.0	5.0
Porosity	0.3	0.26
Longitudinal dispersivity, m	0.01	5.0
Transverse dispersivity, m	0.001	0.5
Henry sorption for ^{129}I	2.0	1.8
Rock density, kg/m^3	2000	1800
Heat capacity, 10^6 J/m^3/K	1.6	1.8
Heat conductivity, J/m/s/K	2.3	2.3

The heat transport from SNF to near-field was calculated for preliminary inventory of the radioactive waste (Generic safety… 2005; Sirvydas, Poškas 2009). The temperature may have a negative impact on the canister. The heat can accelerate the defect of the SNF canister and accelerate the radionuclide transport in to the far-field.

The geometrical discretization (Fig. 1) of model domain and used parameters values are presented in detail in (Jakimavičiūtė-Maselienė *et al.* 2006a,. 2006b) and briefly summarized in Table 1. The discretization of model domain in terms of boundary conditions is shown in Fig. 1 and Tables 3–4. The boundary conditions for radionuclide transport are evaluated in (Jakimavičiūtė-Maselienė *et al.* 2006a,. 2006b).

For numerical model, the created layers are adjusted to geometry of lithological bodies. In the model three zones with different parameter values were selected. For brief illustration of groundwater flow modelling features, a modelled hydraulic head distribution in 27th modelling layer, which corresponds to pumped Ordovician–Cambrian aquifer, is given (Fig. 2).

Model calibration as practiced in this study is a process by which the structure and parameters of a numerical model are progressively changed in an iterative manner to obtain an acceptable match between observed or expected and computed hydraulic heads and departing as little as possible from the original conceptual model. In addition to fitting hydraulic heads, calibration was based on the following criteria: computed water levels should always stand below the topographic surface; estimated hydraulic conductivity should be consistent with conductivity derived from available hydrogeological data; spatial patterns of parameters should be consistent with available geological information. A model of direct experimental data for substantiation of radionuclide transport is impossible because tracer experiments with long-living mobile radionuclide (^{129}I) are hardly validated, and the process of large-scale radionuclide transport is very long-lasting.

Parameters of relevance under far-field flow conditions routinely include hydraulic conductivity, areal recharge, dispersivity parameters and hydraulic heads specified along boundaries. Areal recharge was assumed to be uniform throughout the study area ($1.4 \cdot 10^{-4}$ m/d).

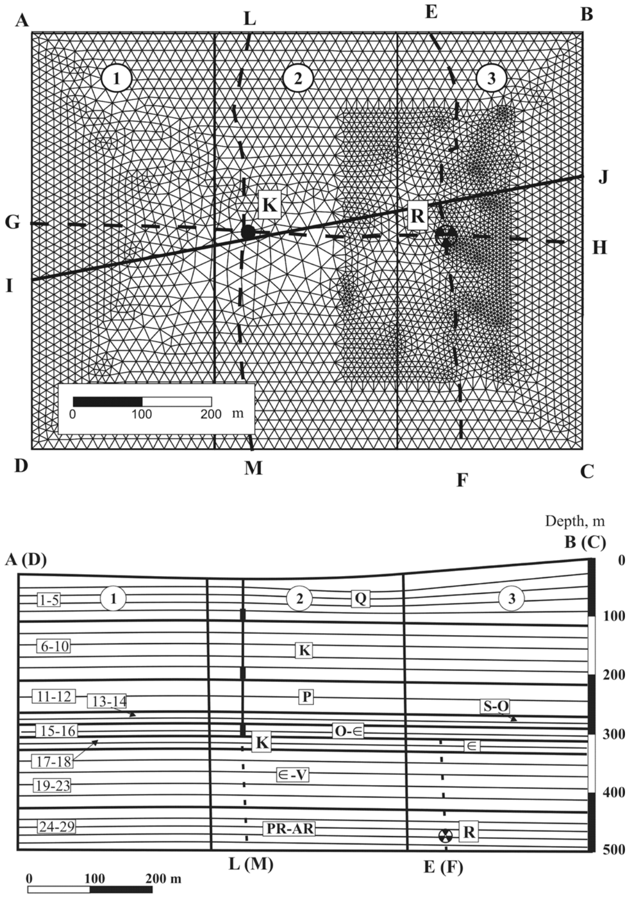

Fig. 1. Finite-element grid used for the model domain of southeastern Lithuania: I – plan view, II – cross-section IJ (Jakimavičiūtė-Maselienė *et al.* 2006a, 2006b): 1–3 – zones with different parameter values, AD and BC impervious boundaries, AB and CD – pervious boundaries, EF, GH and LM – perpendicular single fractures, IJ – line of modeled cross-section, R – location of repository, K – pumping wells system installed in Quaternary, Cretaceous and Cambrian-Vendian aquifers

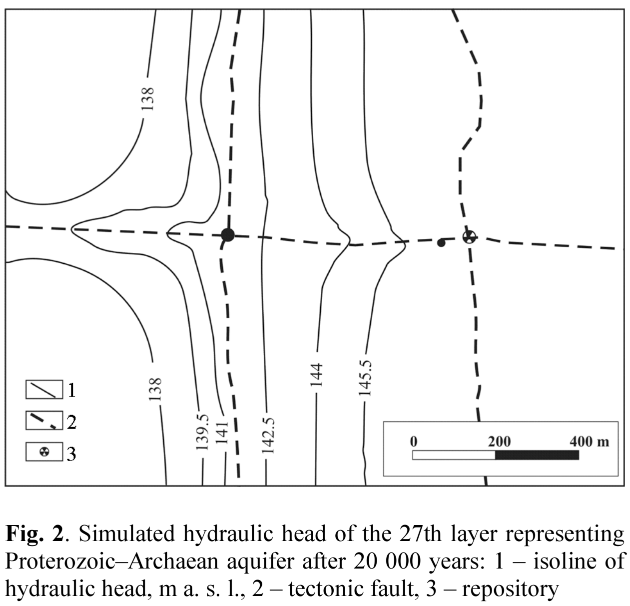

Fig. 2. Simulated hydraulic head of the 27th layer representing Proterozoic–Archaean aquifer after 20 000 years: 1 – isoline of hydraulic head, m a. s. l., 2 – tectonic fault, 3 – repository

Table 3. Flow boundary conditions for the model domain of southern Lithuania after model calibration (see Fig. 1)

Section or point (slice)	Type	Value	Comment
A-B (1–30)	–	–	unspecified (impervious) for all 30 slices
B-C (1–30)	Dirichlet (1st kind)	h_1 = 155 m; h_2 = 154.8 m; h_3 = 154.6 m; h_4 = 154.4 m; h_5 = 155.2 m; h_6 = 154 m; h_7 = 153.8 m; h_8 = 153.6 m; h_9 = 153.4 m; h_{10} = 153.2 m; h_{11} = 153 m; h_{12} = 152.5 m; h_{13} = 152 m; h_{14} = 151.5 m; h_{15} = 151 m; h_{16} = 150.5 m; h_{17} = 150 m; h_{18} = 149.5 m; h_{19} = 149 m; h_{20} = 148.8 m; h_{21} = 148.6 m; h_{22} = 148.4 m; h_{23} = 148.2 m; h_{24} = 148 m; h_{25} = 147.6 m; h_{26} = 147.2 m; h_{27} = 146.8 m; h_{28} = 146.4 m; h_{29} = 146 m; h_{30} = 145.5 m	pervious boundary (influx)
C-D (1–30)	–	–	unspecified (impervious) for all 30 slices
D-A (1–30)	Dirichlet (1st kind)	h_1 = 130 m; h_2 = 130.2 m; h_3 = 130.4 m; h_4 = 130.6 m; h_5 = 130.8 m; h_6 = 131 m; h_7 = 131.2 m; h_8 = 131.4 m; h_9 = 131.6 m; h_{10} = 131.8 m; h_{11} = 132 m; h_{12} = 132.5 m; h_{13} = 133 m; h_{14} = 133.5 m; h_{15} = 134 m; h_{16} = 134.5 m; h_{17} = 135 m; h_{18} = 135.5 m; h_{19} = 136 m; h_{20} = 136.2 m; h_{21} = 136.4 m; h_{22} = 136.6 m; h_{23} = 136.8 m; h_{24} = 137 m; h_{25} = 137.4 m; h_{26} = 137.8 m; h_{27} = 138.2 m; h_{28} = 138.6 m; h_{29} = 139 m; h_{30} = 139.5 m	pervious boundary (outflow)
E-F (19–30)	Dirichlet (1st kind)	h_{19-30} = 147 m	pervious boundary (influx into fractures representing tectonic fault zone)
L-M (5–30)	Dirichlet (1st kind)	h_{5-30} = 142 m	pervious boundary (influx into fractures representing tectonic fault zone)
K (5, 9, 16)	(4th kind)	$Q_{\rho\,1}^{w}$ = 1000 m³/d; $Q_{\rho\,2}^{w}$ = 1000 m³/d; $Q_{\rho\,3}^{w}$ = 1000 m³/d;	pumping rate of single well

Table 4. Boundary conditions for heat transfer for the convective form (Generic safety… 2005)

Point (layer)	Type	Value		Comment
		years	°C	
R (27)	Dirichlet (1st kind); Time-varying function $T(x_i,t)=T_1^R(t)$	<1	32	Release from repository (defected canister) to receiving triangular cell with area of 19.4 m²
		1–10	34	
		10–20	35	
		20–30	40	
		40–50	47	
		50–70	48	
		70–100	47	
		100–500	43	
		500–1000	38	
		1000–10000	36	
		10000–20000	34	
		20000–100000	15	
		>100000	12.6	

3. Results and discussions

Computer software FEFLOW enables spatial and temporal analysis of modelling results in many ways. The ^{129}I transport within groundwater for basic model has already been discussed (Jakimavičiūtė-Maselienė *et al.* 2006a, 2006b). The results of basic model showed that contamination plume of ^{129}I does not reach further than 700 m from the defected canister location. The highest predicted value of activity in the zone of longitudinal single fracture is of the order 10^{-4} Bq/*l*. Contamination plume of 10^{-4} Bq/*l* reaches the observation point near the defected canister (90 m), whereas the groundwater containing ^{129}I with activity concentration of 10^{-4}–10^{-7} Bq/*l* discharges out of the longitudinal fracture outside the model boundaries in the flow direction (Jakimavičiūtė-Maselienė *et al.* 2006b).

The calculation results of this work showed that contamination plume of ^{129}I is not influenced by newly formed single fracture, which is located in the flow direction. The peak activity concentration of ^{129}I in groundwater is expected to be approx. 0.0009 Bq/*l* in the observation well after 200 000 years after SNF closure.

As has been mentioned above the radionuclide transport from the canister of SNF considering Lithuanian conditions has been intensively studying by numeric methods for last decade. All studies are based on internationally recognized safety assessment methodologies which are described in (Brazauskaitė, Poškas 2006). The safety assessment of RBMK-1500 SNF has been performed using SKB methodology. The radionuclide release from the near-field of SNF disposal system has been analyzed in (Brazauskaitė, Poškas 2007). The canister defect scenario was developed for the identified safety relevant radionuclides. For radionuclide transport assessment the computer code COMPULINK7 (Sweden) was used. The results of analysis showed that most of safety-relevant radionuclides of the RBMK-1500 SNF are effectively retarded in the near-field region. The first dominated radionuclide in near-field is ^{59}Ni. After 50 000 after SNF closure years will dominate ^{129}I. Sensitivity analysis for the parameters that have a direct influence on the radionuclide releases were also performed (Brazauskaitė, Poškas 2007).

Modelling of the potential radionuclide release from the SNF canister and potential human exposure are discussed in (Brazauskaitė, Poškas 2008). In this paper, the main processes (groundwater flow, sorption, dispersion, etc.) that determine and influence radionuclide release in the far-field are described. Preliminary results of modeling the radionuclide release from the near field of the repository of the RBMK-1500 SNF are presented using computer code CHAN3D. The results showed that radionuclide transport from the far-field and near-filed regions are similar. The higher hydraulic conductivity values in the area around the container did not change (^{129}I) or impact slightly (^{226}Ra) the predominant radionuclides activity. The predicted effective doses do not exceed the dose constraint (0.2 mSv/year) over million years after SNF closure. In the beginning, the effective dose would be caused by non-sorbed radionuclide ^{129}I, and after 300 000 years after SNF closure the main dose contributing radionuclide is expected to be ^{226}Ra.

Modelling of ^{129}I transport in the tectonically fractured rocks of crystalline basement is described in (Jakimavičiūtė-Maselienė *et al.* 2006a, 2006b). Predicted activity concentration of ^{129}I in groundwater of the Ordovician–Cambrian aquifer at 363 m distance from repository in groundwater flow direction is of the order 10^{-3} Bq/*l* and will not exceed the existing dose restrictions. This aquifer is important for water supply.

The heat from the SNF canister distributes in the two perpendicular fractures in the groundwater flow direction. The peak temperature is expected after 50 years after repository closure and will reach 50 °C close to SNF canister. The temperature field variation in the monolithic crystalline rocks will be in range of background temperature values for the Proterozoic–Archaean rocks (12–13 °C) (Fig. 3).

The modelled temperature variation in the reference repository of the RBMK-1500 SNF are presented in (Sirvydas, Poškas 2009). For the time-dependent temperature evolution computer code FLUENT 6.1 was used. The

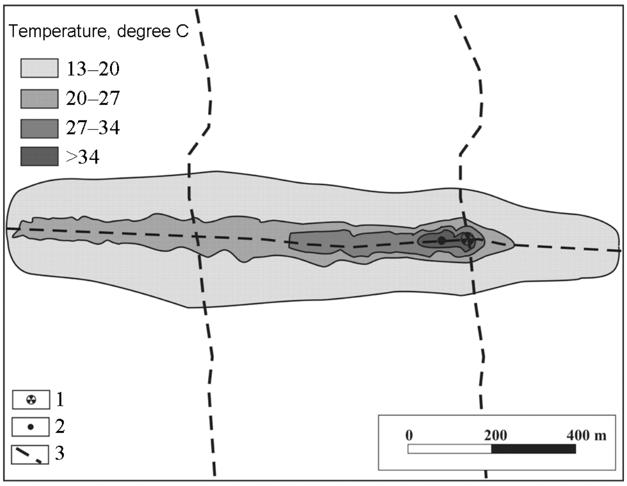

Fig. 3. Predicted heat plume in Preoterozoic-Archaean aquifer after 50 years: 1 – repository, 2 – observation point, 3 – tectonic fault

modelling was performed for different distances between the canisters and for different bentonite moisture content. The results of temperature modelling in the SNF emplacement tunnels illustrate the significance of bentonite thermal conductivity at the canister surface, bentonite backfill and host rock. The modelling has shown that it is necessary to separate the canisters by a 3 m distance so that their surface temperature should not exceed the permissible level of 100 °C.

Since the hydraulic conductivity is one of the key parameters that determine both the radionuclide transport within groundwater and heat transfer in host formation, the variability of simulation results depending on hydraulic conductivity change has been presented in this study. The hydraulic conductivity values used for parameter variability analysis are shown in Table 5.

Table 5. Hydraulic conductivity values of the three single fractures used for parameter variability analysis

Hydraulic conductivity, 10^{-4} m/s	Crystalline rocks	Sandstone
Basic value	60	5
Low value	30	2.5
	6	0.5
High values	120	10
	600	50

The activity concentration of ^{129}I in the groundwater will reach maximum value after approx. 190 000 years. The ^{129}I peak activity concentration will not exceed 0.0009 Bq/*l* (Fig. 4). Variation of the hydraulic conductivity of the host rock influences insignificantly on the ^{129}I peak activity in the groundwater at the observation point. The ^{129}I activity concentration corresponding to the dose limit of 1 mSv/year for drinking water pathway is 15.2 Bq/*l* (HN 73:2001). A current background activity concentration value of the globally distributed ^{129}I in the riverine water is approx. 10^{-6} Bq/*l*.

However, distribution of the temperature field in the tectonic fault strongly depends on hydraulic conductivity variation. The peak temperature 90 m away from SNF defected canister is predicted 50–65 years after SNF disposal system closure and temperature varies from 20.8 °C to 44 °C (Fig. 4).

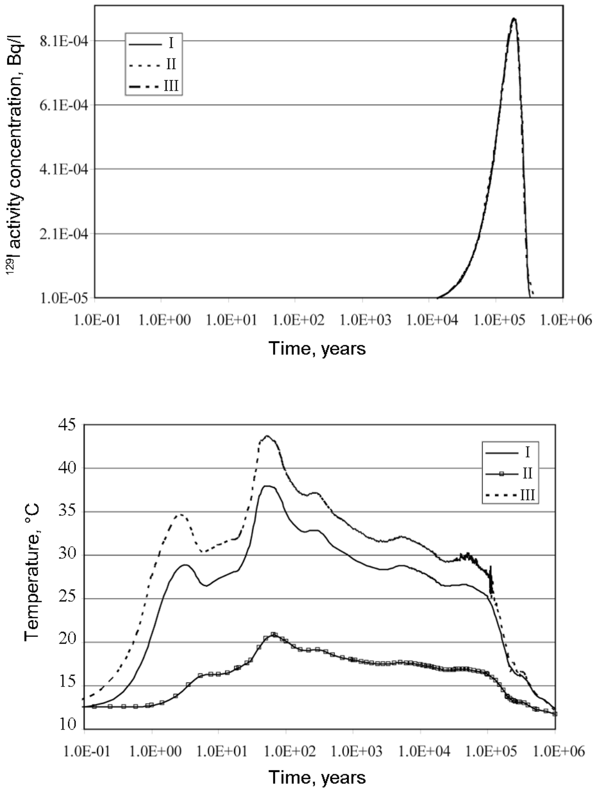

Fig. 4. Variability of ^{129}I activity concentration (I) and temperature (II) in the observation point of Preoterozoic-Archaean aquifer: I – normal hydraulic conductivity; II – normal hydraulic conductivity value decreased by one order of magnitude; III – normal hydraulic conductivity value increased by one order of magnitude (Table 5)

The numerical model for particular model domain attributed to SNF disposal system should be improved in the future and more scenarios of long-term evolution for repository-surrounded media should be worked out.

4. Conclusions

Long-lived non-sorbed radionuclide ^{129}I is a very important radionuclide defining safety of the SNF disposal. Numerical modelling shows that intensity of ^{129}I transport in the tectonically fractured rocks is only slightly dependant on the hydraulic permeability of the host rock. Migration of ^{129}I from the repository is mainly controlled by features of the engineering barriers (the canister).

Conservative modelling of ^{129}I transport from the SNF repository reveals that doses to humans would not exceed the existing dose restrictions, even taking into account the heat influence.

Basing on radiation protection requirements it would in principle be possible to dispose of SNF and other long-lived high-level radioactive wastes in the geological repository built in the fractured crystalline basement.

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RADIONUKLIDŲ IR ŠILUMOS SKLAIDA IŠ HIPOTETINIO *PBK* KONTEINERIO KRISTALINIO PAMATO UOLIENOSE (PIETRYČIŲ LIETUVOS PAVYZDYS)

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S a n t r a u k a

Radioaktyviųjų atliekų tvarkymo strategija numato galimybę panaudotą branduolinį kurą ir kitas ilgaamžes radioaktyviąsias atliekas, susidariusias eksploatuojant Ignalinos AE ir susidarysiančias ją demontuojant, galutinai patalpinti giliai geologinėse formacijose. Dėl didelio geologinės bei hidrogeologinės informacijos kiekio šiame darbe nagrinėti tik Pietryčių Lietuvos kristalinis pamatas bei jį dengiantys nuosėdinių uolienų sluoksniai. Radionuklidų bei šilumos sklaidai kristalinio pamato uolienose vertinti naudota kompiuterinė programa *FEFLOW* 5.0. Pasirinkta konteinerio defekto scenarijus, taikant skaičiavimus, atliktus LEI ekspertų. Modelis apima archėjaus ir proterozojaus vandeningąjį sluoksnį bei nuosėdinėje dangoje slūgsančius vandeninguosius kompleksus. Modeliuotas požeminio vandens srautas, kylantis per tektoniškai pažeistą zoną, kurioje palaidotas *PBK* konteineris. Iš pagrindinių modeliavimo rezultatų nustatyta, kad ilgaamžio ir mažai sorbuojamo radionuklido ^{129}I sklaidos intensyvumas mažai priklauso nuo geologinės aplinkos savybių, o šilumos sklaida neturi įtakos radionuklidų sklaidai. Žmogaus gaunama dozė, skaičiavimų duomenimis, nesieks ribinės vertės (0,2 mSv/metai).

Reikšminiai žodžiai: panaudotas branduolinis kuras, geologinis atliekynas, kristalinis pamatas, požeminis vanduo, baigtiniai elementai.

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