Thermo-hydro-mechanical effects on host rock for a generic spent nuclear fuel repository

Želimir Veinović[1a]; Galla Uroić[2]; Dubravko Domitrović[1b]; Leon Kegel[3]

[1a] Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10000 Zagreb, 0000-0002-1572-2191

[1b] Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10000 Zagreb

[2] Eugena Kvaternika 13, 44320 Kutina

[3] ARAO Agency for Radwaste Management, Litostrojska cesta 58A, 1000 Ljubljana

Abstract

After the adoption of the National Program for the Implementation of the Strategy for the Management of Radioactive Waste Used Resources and Spent Nuclear Fuel, by the Government of the Republic of Croatia, the issue of radioactive waste management in Croatia became current. Slovene-Croatian co-ownership over the Krško nuclear power plant (KNPP) means that half of the operational and decommissioning waste, as well as spent nuclear fuel (SNF) belongs to Croatia. Until now, SNF has been kept in a pool at KNPP, and dry storage before disposal is also planned. A generic project of a SNF repository has been developed and has already undergone a second revision and review. The project idea involves site selection in both countries and the conceptual solution of the SKB-3V type in crystalline rock. This paper presents an estimate of the thermal-hydro-mechanical effects (THME) of the SNF repository in crystalline rock (granodiorite) of SKB-3V concept by developing a numerical model in the SIGMA/W, SEEP/W and TEMP/W software. Simulations have shown that it is possible to construct a SNF repository in the crystalline rocks of Croatia or Slovenia, that the generic repository project is well-designed and that a model of hydro-thermo-mechanical effects of spent nuclear fuel on the rock in Croatia/Slovenia can be produced, which proves the suitability of the rock mass for this purpose.

1. Introduction

After the decision of the Government of the Republic of Croatia (124th Session, 9.11.2018, **Official Gazette 100/18**) on the adoption of the National Program for the Implementation of the Strategy for the Management of Radioactive Waste, Disused Sources and Spent Nuclear Fuel (Program for the period until 2025 with a view to 2060) (**Government of the Republic of Croatia, 2018**) and the ratification of a joint generic project for the disposal of spent nuclear fuel by the Republic of Slovenia (RS) and the Republic of Croatia (RC), the problem of radioactive waste management in Croatia is becoming urgent. The Croatian program for the disposal of low and intermediate level radioactive waste has been reduced to one site (Trgovska Gora, Čerkezovac site) approved by the Government of the Republic of Croatia, but not yet confirmed as fully acceptable. On the other hand, the problem of disposal of spent fuel from the Krško Nuclear Power Plant has been postponed for about 30 years and dry storage of spent fuel elements is currently planned near the Krško Nuclear Power Plant (KNPP) until a potential disposal site is found and its functionality proven.

The specific problem of the co-ownership of the KNPP by the RS and the RC is related to both the purchase of electricity and the ownership of waste generated by the operation of the power plant. Half of low and intermediate level radioactive waste (LILW) and half of spent nuclear fuel (SNF) belong to Croatia and the other half to Slovenia. Slovenia has chosen a location for its part of LILW, while neither country has a solution for the permanent disposal of SNF.

At this point, all spent nuclear fuel and highly radioactive waste, all over the world, is stored within nuclear power plants or dry storage facilities. The only country with a building permit for a deep geological repository of spent nuclear fuel is Finland, which is unlikely to start landfilling for another 3 or more years. Sweden and France are close to obtaining building permits, but are far behind in terms of the Finnish program. Other countries of the world are at least 10 to 20 years away from building a repository of spent nuclear fuel and/or high-level radioactive waste (HLW).

Due to the specificity of these materials, SNF and HLW should be deposited in deep geological reposito-

Corresponding author: Želimir Veinović

zelimir.veinovic@rgn.hr

ries (**Veinović et al. 2012**), at depths of 400-1 000 m, in solid igneous or sedimentary rock, which will guarantee the safety of the repositories during the required period of at least 100 000 or 1 000 000 years, until the amount of ionizing radiation of all components of these materials (individual radionuclides) is reduced to that of uranium ore. There are different concepts for the disposal of SNF and HLW, depending on the type of rock and the country that developed them, but all include engineering barriers (canister and buffer materials) and certain types of underground spaces that are designed for long periods of exploitation. One of the most important factors that will condition the success of the disposal and disposal concept, apart from the lithostratigraphic and other geological characteristics of the rock at the site, are certainly the hydro-thermo-mechanical effects of spent nuclear fuel on the rock.

Although RC and RS do not yet have an SNF disposal site selected, it is necessary to know whether there is a possibility for such a disposal facility in Croatia or Slovenia and under what conditions. One of the logical potential solutions is a repository in granite or similar crystalline rocks (e.g. granodiorite).

The aim of this paper is to analyse the functionality of a part of a possible generic model of SNF landfill in Croatia or Slovenia, at the generic location. This paper, in addition to developing a qualitative model of potential rock behaviour and functionality of a selected SNF disposal concept, will demonstrate that Croatia has the capacity to develop projects and studies on the functionality and safety of the future SNF disposal site.

2. Deep geological repository of spent nuclear fuel

Disposal of HLW and SNF into deep geological repositories is currently considered the best way for management of these materials for several reasons (**Veinović et al., 2015**):

- The intended disposal depth (400-1 000 m) implies a long way for radionuclides to reach the surface, or the drinking groundwater, as well as the reduced possibility of human intrusion;
- A well-selected geological environment (low permeability of magmatic, sedimentary or metamorphic rocks) will mean a lower rate of radionuclide transport to the surface;
- Engineering barriers (canister and buffer material between rock and canister) represent an additional obstacle that will slow down the transport of radionuclides.

Considering a repository of HLW and SNF, i.e. the durability of the repository system, is designed for a period of 100 000 to 1 000 000 years (**Veinović et al., 2015**), the reasons given above for selecting a deep geological disposal site also favour the durability of a land-

fill. The expected decline in the activities of HLW and SNF to the level of uranium ore, which is considered an acceptable amount at the time of arrival of radionuclides from a repository, will be already after 10 000 years for HLW and after about 100 000 years for SNF. In both cases, repositories are designed to last a much longer period of time in order to increase the safety of the repository.

2.1. Selected concept

Although there are several concepts developed for the disposal of HLW and SNF in deep geological repositories, which differ to some extent, two principles, namely shallow vertical boreholes drilled from disposal tunnels and axial disposal within the disposal tunnels are technologically the least demanding (**Veinović et al., 2015**). **Figure 1** shows both concepts, developed by the Swedish nuclear fuel and waste management company - SKB.

Considering that the Slovenian/Croatian Reference Scenario for Geological Disposal Facility in Hard Rock (**ARAO & Fond NEK, 2019**) implies the application of the KBS-3V concept, and given that some of the other concepts are not applicable in Slovenia and Croatia (for example, depositing in deep vertical boreholes from tunnels, the so called "German concept", developed for salt domes, or the "French concept" of long horizontal boreholes developed for abundant layers of clay or claystone), the KBS-3V concept was used for the development of the numerical model in this paper.

The KBS-3V concept was developed for the disposal of SNF in Sweden, with the idea of reducing the damaged zone, the so called excavation-disturbed zone (EDZ) of rock material created by the application of the drilling and blasting method, implementing instead larger diameter drilling (**Baldwin et al., 2008**). Originally, the idea involved long-lived titanium or copper canisters, and later the concept was elaborated with the idea of using steel and copper canisters, accepted in Sweden, Finland and the United Kingdom, and simplified to make disposal tunnels at depths of 400 to 700 m. However, the number of disposal tunnels will depend on the amount of SNF canisters required (**Baldwin et al., 2008**).

The concept includes the disposal of SNF in short boreholes (usually 6-8 m deep) of medium to large diameter (0.6-1.5 m) drilled in the floor of the disposal tunnels. The idea is to use short-lived steel canisters (with several hundred to several thousand years of durability) or long-lived canisters with copper liner (durability up to about 10 000 years), which would be deposited in crystalline rock with bentonite as a filling/buffer material for open and free spaces (**Baldwin et al., 2008; Domitrovic et al., 2012**).

A longitudinal section through the tunnel is shown in **Figure 2** and a cross-section (through one of the disposal boreholes) in **Figure 3**. A cross-section of the disposal borehole with canister is shown **Figure 4**.
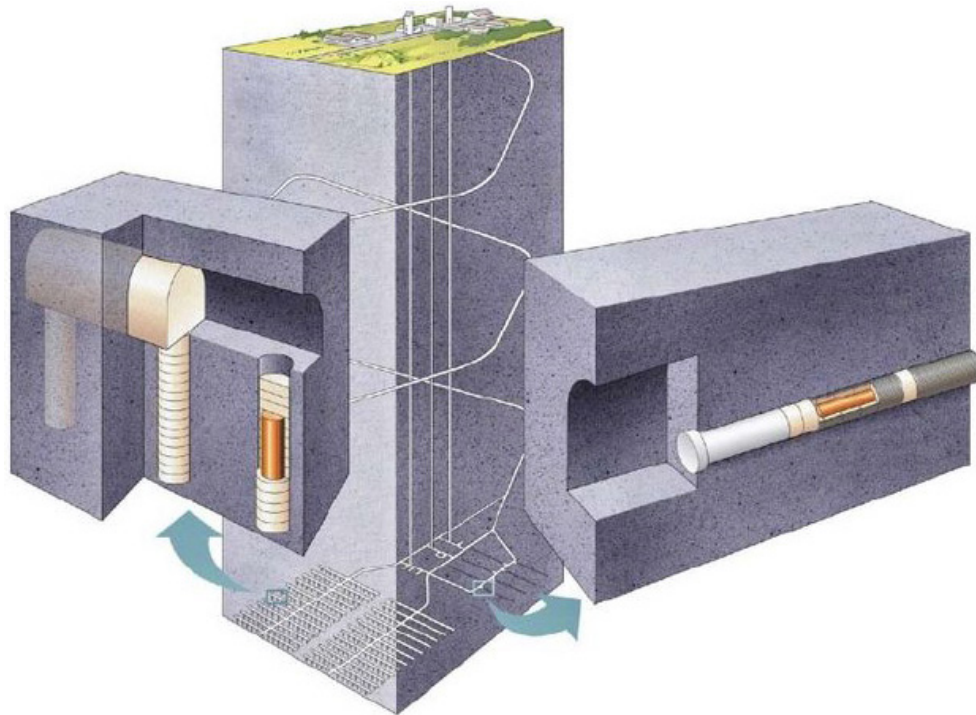
Figure 1: Swedish concepts for spent nuclear fuel disposal: KBS-3V (left) and KBS-3H (right)
(from: **Savage and Arthur, 2012**)
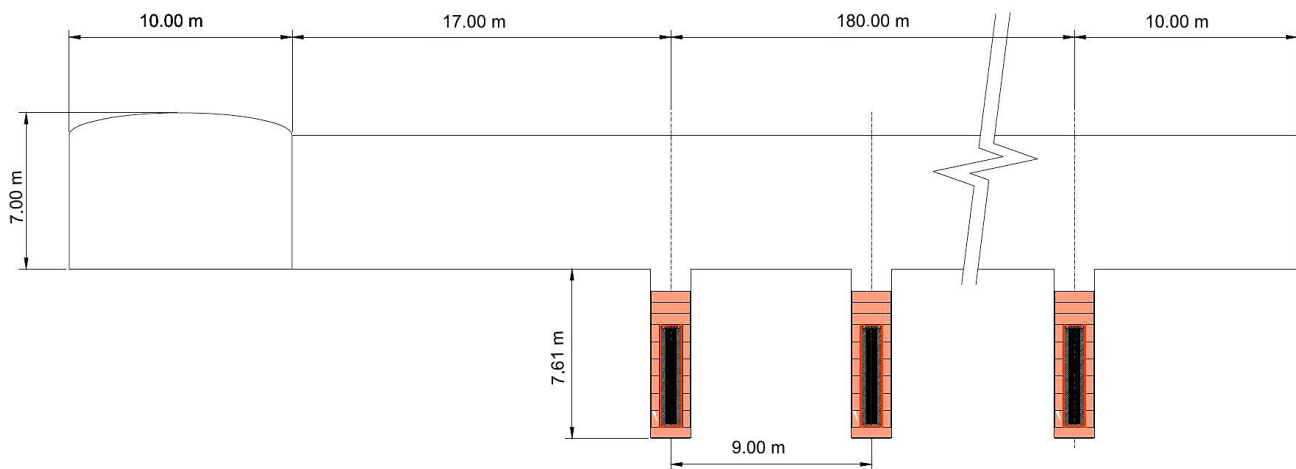
Figure 2: Longitudinal section through the disposal tunnel (from: **ARAO & Fond NEK, 2019**)

In most cases, it is assumed that the construction of underground spaces will include drilling and blasting (probably by the New Austrian Method), while disposal tunnels would be preferably drilled by a tunnel boring machine or, alternatively, by the drilling and blasting method (**Baldwin et al., 2008; Saanio et al., 2013; ARAO & Fond NEK, 2019**). The reason for this is the size of the EDZ in host rock, which would ultimately represent a pathway for seepage of groundwater, and thus for radionuclides (**Keto et al., 2012**). The drilling of short vertical boreholes for the emplacement of canisters will probably be carried out by the blind-hole drilling method (**Autio & Kirkkomäki, 1996**). EDZ is readily

omitted in numerical modelling of this type (THME modelling), most probably due to the complexity of the models and the duration of calculations (**Åkesson i dr., 2010; Chen et al., 2012; Kwon et al., 2013; Rutqvist et al., 2005; Toprak et al., 2013; Zhao et al., 2014**). However, the EDZ is one of the most important elements of disposal concept/technology. The inclusion of the EDZ into a numerical model is the most important improvement of existing models, because the EDZ is singled out as the most influential region of the model and a potential problem – a zone of faster groundwater flow and a potential propagation path for radionuclides, lower mechanical properties of the rock and a significant influ-
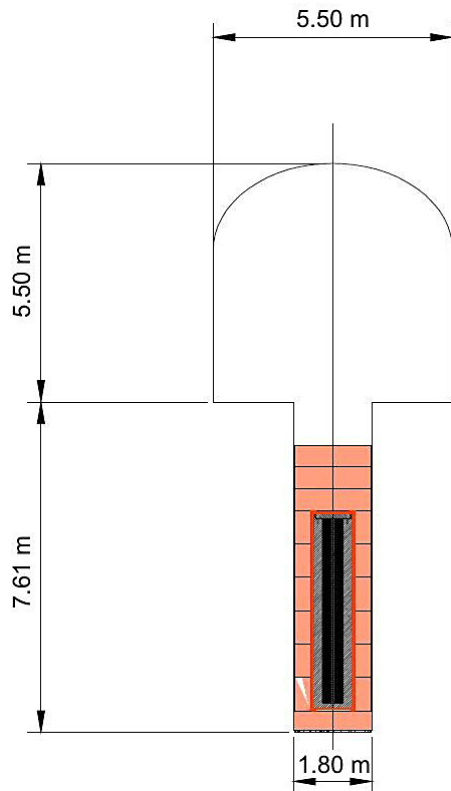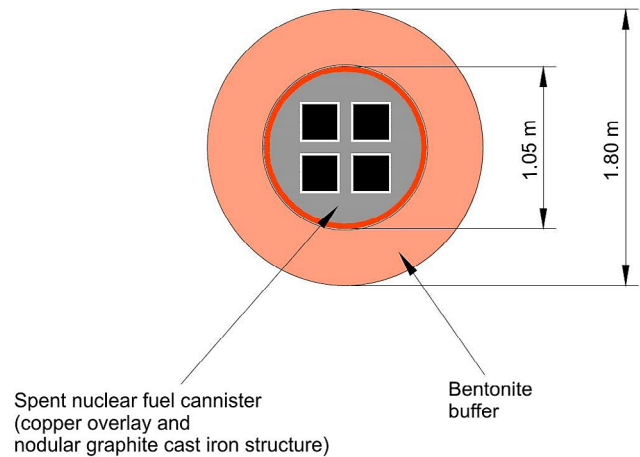
Figure 3: Cross-section of the disposal borehole with canister (from: **ARAO & Fond NEK, 2019**)

Figure 4: Cross-section through one of the disposal boreholes (from: **ARAO & Fond NEK, 2019**)

encer in heat transport. This significantly improves the numerical modelling of thermo-hydro-mechanical properties of the spent nuclear fuel repository and the determination of the qualitative characteristics and functionality of the repository. Proving that the model and the concept of the repository is within the required parameters, from the point of view of radionuclide retention, basically proves the functionality of the concept, which is one of the most important parts of the "safety-case" development and demonstrating the safety of the repository to stakeholders.

Disposal tunnels are originally designed to be approximately 250 m long with a spacing of about 40 m, which will depend on the selected host rock. The distance between short vertical boreholes is estimated at about 6 m and their depth at about 8 m (**Baldwin et al., 2008**). There are also minor modifications from program to program, so the Swedish program also involves levelling the bottom of the well with low pH concrete in a thickness of about 5-10 cm and a copper plate which is a few millimetres thick (**Baldwin et al., 2008**).

Supporting in underground spaces is to be minimized, since foreign material (concrete, steel, etc.) can reduce the required quality and durability of the facility, as it will eventually degrade and thus become a likely route for the transport of radionuclides through groundwater (**Saanio et al., 2013**).

Another factor to consider is the method of filling up disposal tunnels, as well as the closure of tunnel ends,

since the closure time of the entire landfill can last several decades. Namely, the concept of "retrievability" has been adopted as necessary in most countries, which means that canisters with SNF must be allowed to be retrieved from repositories if needed, e.g. in the case of advancement in SNF processing technologies. For this reason, the closure of the entire repository (transport and ventilation tunnels and shafts) is usually being prolonged in the timeline of repository projects. Since the filling and closing of disposal tunnels in different concepts usually results in the installation of bentonite or bentonite mixtures (bentonite/crushed rock or bentonite/sand, etc.), high pressures are expected when the bentonite swells due to its hydration (groundwater absorption).

2.2. Selected materials

Although the use of long-lived titanium or copper or short-lived steel canisters (**Baldwin et al., 2008**) is mentioned as an option, in most national programs (Sweden, Finland, United Kingdom, Slovenia, etc.) the adopted concept of canisters includes an internal massive nodular graphite cast iron structure, which will serve to stack spent fuel elements and give the canister mechanical strength, covered by a 50 mm thick copper overlay as a material with low corrosion potential (**NIREX, 2005; Raiko and Salo, 1996**).

The SNF canisters may vary in dimension as well as in cross-sectional shape of the internal structure depending on the type of reactor and fuel elements, as well as the chosen number of fuel elements. The SNF disposal canisters considered in this paper represent the first engineering barrier designed to retain radionuclides (withstand corrosion in deep geological disposal) over the period of 10 000 years (**Raiko and Salo, 1996**). These considered canisters can hold 4 assemblies per canister, which will give the total full canister mass of about 18 t (not more than 20). The dimensions of the canister are given in **Table 1**.

Table 1: The dimensions of a SNF disposal canister
(from: **ARAO & Fond NEK, 2019**)

DIMENSION	
Height [mm]	4610
Outer diameter [mm]	1050
Minimal thickness of copper [mm]	50

The life span of the canister is designed to be 10 000 years, with the condition that it must retain its integrity at least until the end of the high thermal emission period: 1 000 years (**NIREX, 2005**). The amount of heat generated by SNF is considerable and the canister must be designed in such a way that its degradation and loss of integrity do not occur due to an increase in temperature. Data on material activity, uranium content and thermal emission is given in **Table 2**.

Table 2: Typical SNF assemblies' parameters for a single
canister (from: **NIREX, 2005**)

Parameter	SNF assemblies in one canister
Gross mass of canister [kg]	17 900
Total activity content [TBq]	1.3×10^4
Heat output [W]	1 016
Mass of uranium [kg]	2 060
Fissile Content (U-233, U-235, Pu-239, Pu-241) [kg]	32

The total heat emission from the canister must not exceed the amount that would result in an accelerated decrease in the quality of the canister, its content, or the bentonite buffer, so the maximum allowed temperature on the outer wall of the canister is 100º C, at any time after disposal, and the maximum released heat output is 1 160 W (**NIREX, 2005**).

In most of the concepts for the disposal of SNF and HLW, bentonite clay is planned to be used as a filling material for tunnels after disposal and as a buffer (material filling the space between the reservoir and rock). Bentonite is characterized by high water absorption, es-

pecially in the case of sodium bentonite, with an expected permeability coefficient of about 1×10^{-12} m/s. Considering that it is stable and, in most cases, not overly sensitive to external factors found in a repository, it is regularly selected as the almost ideal fill material (**Juvankoski, 2010**).

In this paper, bentonite will be considered as:
- a buffer between the canister and the host rock (compacted bentonite in the form of rings and disks);
- a tunnel filling material (compacted bentonite blocks and bentonite pellets).

Given that bentonite is expected to remain stable and retain its properties, primarily low permeability, for up to a million years, except in the case of heating above 100ºC, the KBS-3V concept is designed in such a way that the temperature on the outer surface of the canisters should not be above 80ºC (**Baldwin et al., 2008**)

As the alternative to filling tunnels with bentonite blocks, if the rock material permits it, a mixture of crushed host rock and bentonite pellets may be used, and alternatively solely bentonite powder or pellets. The required parameters for bentonite are given in **Table 3**.

Geological disposal is based on the isolation of waste in the geosphere at locations that are expected to be stable over a long period of time. Repository concepts and potential host rocks vary from country to country, but host rock types typically include magmatic intrusive and extrusive rocks, sedimentary rocks (with a high content of clay minerals), and salt (salt domes). The choice of the host rock for the disposal largely depends on the available geological formations of appropriate thickness and condition (**IAEA, 2009**).

From an engineering point of view, except in extremely permeable and weak rocks (poor mechanical characteristics) and in areas of increased likelihood of earthquake occurrence, it is possible to find a host rock that, depending on the disposal concept used, could serve to build a repository. Some concepts (e.g., hydraulic cages) have been adapted for use in relatively "poor geological environments". It certainly benefits if the site is selected within monolithic rock with good geomechanical characteristics, in a quiet geological environment that has not been exposed to particularly signifi-

Table 3: Required bentonite parameters (from: **Keto et al., 2012; Juvankoski, 2010; Schafers et al., 2019**)

Parameter	Blocks	Pellets	Rings and discs
Dimensions [mm]	550 x 470 x 330	6.5 (diameter) 5-20 (length)	400 (height) 1 050 (inner diameter) 1 700 (outer diameter)
Mass [kg]	183-196	-	1 907 (disc) 1 151 (ring)
Bentonite content [%]	30-38	75-90	75
Dry density [kg/m³]	1 990-2 070	900-1 100 (emplaced pellets) 2 070 (single pellet)	2 100
Water content during emplacement [%]	17.5-37.5	8.5-9.5	≈ 16

Table 4: Simplified site selection criteria for a deep geological repository from the point of view of safety and technical feasibility (from: **SFOE, 2008**)

Criteria	Sub criteria
1. Properties of the host rock for disposal and effective containment zones	A. Spatial range B. The effect of hydraulic barriers C. Geochemical conditions D. Propagation routes (radionuclides)
2. Long-term stability	A. Site stability and host rock properties B. Erosion C. Repository-induced impacts D. Conflict of use
3. Reliability of geological surveys	A. Ease of rock characterization B. Exploratory of spatial conditions C. Predictability of change over long periods of time
4. Engineering suitability	A. Properties and conditions related to rock mechanics B. Underground access and drainage

cant morphological and other changes over a long period of time (at least in the last million years).

Criteria for selecting a site for disposal of SNF and/or HLW are numerous and complex and include a number of points that guarantee a site's compliance with geological, hydrogeological, hydrological and other characteristics required for the good performance of a repository. Simplified site selection criteria, largely related to host rock characteristics, are given in **Table 4**.

Considering the geology of the Republic of Croatia and the Republic of Slovenia, it is unlikely that the future repository will be constructed in clay, claystone, mudstone, salt or similar materials. The most probable rock material in which a repository would be built are eruptive rocks or, in the case of finding a quality rock mass, in metamorphic rocks. Considering that no official site selection research has been conducted so far for a SNF disposal site in Croatia or Slovenia and that the only scientific work dealing with this topic (**Borojevic Sostaric and Neubauer, 2012**) primarily considers locations with magmatic rocks in Croatia and the Reference Scenario for Geological Disposal Facility in Hard Rock (**ARAO & Fond NEK, 2019**) relates to a possible deposition in crystalline (magmatic) rock, for the purpose of designing the model for this paper, magmatic rock has been selected and the conceptual solution was adapted to this. The probable type of magmatic rock into which the SNF would be emplaced is granodiorite.

It is important to note the following: since the actual host rock for the disposal of SNF in Slovenia and Croatia has not yet been officially designated or confirmed, there is a possibility that a repository will finally be constructed in material other than granodiorite, and there is also the possibility of disposal of SNF outside these two countries in the event that any future repository (coun-

try) agrees to this solution and if the local repository proves to be a costly investment.

3. Numerical model of thermo-hydro-mechanical effects

Numerical modelling of thermal-hydro-mechanical effects (THME) is usually performed by software such as Abaqus (Åkesson et al., 2010), Code_Bright (**Åkesson et al., 2010; Toprak et al. 2012; Toprak et al., 2013**) and Tough-Flac 3D (Blanco-Martin et al., 2017; Rutquist, 2011) since they have several advantages. CODE-BRIGHT has the capability of 3D modelling and the introduction of dynamic changes to the system, as well as the simple ability to model with the input of functional changes of parameters over time. Since there was no possibility to work in these programs, and the GeoStudio software package was available at the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, the development of numerical models and simulations were carried out with GeoStudio.

GeoStudio is a software package that includes several modelling programs:

- SLOPE/W – for soil and rock slope analysis;
- SEEP/W – for analysis of groundwater flow in saturated and non-saturated conditions in a porous environment;
- SIGMA/W – for stress and deformation analysis of soil and structural materials;
- QUAKE/W – for the analysis of earthquake-induced liquefaction and dynamic load;
- TEMP/W – for the analysis of heat transfer and phase changes in a porous medium;
- CTRAN/W – for analysing the transport of liquids and gases in a porous environment;
- AIR/W – for analysing air circulation in porous media.

GeoStudio makes it possible to use the same model in several of its programs, as well as to combine effects and programs themselves, making it easier to simulate complicated conditions in a geological environment. One of the key problems is the ability to build only 2D models.

For the purpose of designing numerical models, materials and their characteristics, the concept of disposal and other parameters had to be defined. Thus, the following factors and parameters were considered and selected:

1. Disposal concept – the Swedish SKB-3V concept has been selected, where canisters are emplaced in short vertical boreholes made at the floor of the repository tunnels.
2. Fill/buffer Material – sodium bentonite was selected, with generic properties such as Wyoming bentonite.
3. Canister – as proposed in the Reference Scenario for Geological Disposal Facility in Hard Rock

Table 5: Parameters required for simulation in SIGMA/W (from: **ARAO & Fond NEK, 2019; Korkiala-Tanttu, 2009; Keto et al., 2012; Juvankoski, 2010; Nguyen et al., 2017; Jacinto and Ledesma, 2016**)

Material	Model used	Young's elasticity modulus [kPa]	Cohesion [kPa]	Weight density [kN/m³]	Poisson's coefficient
Granodiorite in situ	Elasto-plastic	40 000 000	10 000	27.00	0.23
Granodiorite disturbed		2 000 000	6 000	26.00	0.28
Bentonite	Linear elastic	10 000 000	20	20.59	0.30
Copper		1.17×10^8	-	87.57	0.36

Table 6: Boundary conditions for the calculation of stress and displacement in SIGMA/W (from: **ARAO & Fond NEK, 2019; Korkiala-Tanttu, 2009; Keto et al., 2012; Juvankoski, 2010**)

Boundary condition	Category	Type	Value
Flow	Hydraulic	unite flow	1×10^8 [m/s]
Fixed x	Displacement	x displacement	0 [m]
Fixed x/y	Displacement	x displacement	0 [m]
		y displacement	0 [m]
In situ stress conditions	Stress	x stress	0 [kPa]
		y stress	13 505 [kPa]

(**ARAO & Fond NEK, 2019**) with an outer copper liner and 4 spent fuel assemblies was selected.

4. Rock – a magmatic rock (granodiorite) with generic properties similar to those in Croatia and Slovenia was selected.

5. Simplifications – chosen under conditions that would not impair the quality of models and simulations, but to simplify their production:
   a. 2D models;
   b. absence of a support system, the assumption is that it is a high-quality rock of the first category;
   c. bentonite properties are identical for buffer and material for filling tunnels;
   d. profile of a repository tunnel with only four boreholes;
   e. time limit of simulations 25 years.

6. Excavation-disturbed zone (EDZ) – was considered in terms of tunnelling by drilling and blasting method.

7. Depth of construction – was assumed to be 500 m.

2.1. Simulation in SIGMA/W

Parameters selected to develop the model are given in **Table 5**. The parameters were selected according to the literature related to the selected concept and the proposed generic location (**ARAO & Fond NEK, 2019; Korkiala-Tanttu, 2009; Keto et al., 2012; Juvankoski, 2010**).

The boundary conditions to be specified for the calculation of stress and displacement states are given in **Table 6** and selected in accordance with the literature regarding the selected concept and proposed generic location (**ARAO & Fond NEK, 2019; Korkiala-Tanttu, 2009; Keto et al., 2012; Juvankoski, 2010**).

The basic model with finite element mesh was defined by stages. The following "regions" of material have been defined: intact rock, zone of disturbed rock mass around the tunnel (30 cm thick due to drilling and blasting), copper canister and bentonite buffer. The rock stress model is given in stages: state after tunnel excavation and borehole construction, condition after installation of canister and buffer material and condition after filling up the disposal tunnel and are shown in **Figure 5**.

As is to be expected, the model identified areas of critical stress as the ceiling of the disposal tunnel (callote) and the edges of the bottom of the tunnel. During
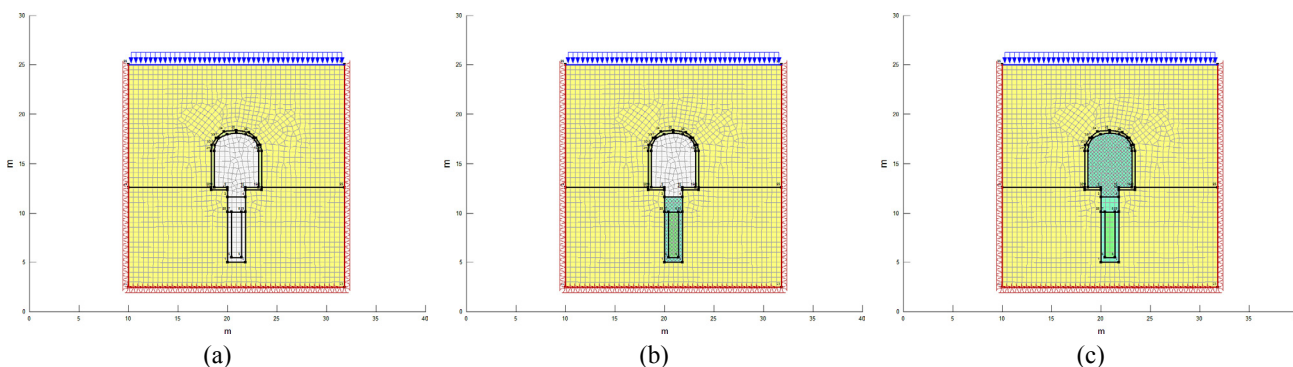

Figure 5: Basic model with finite element grid for calculation: (a) state after tunnel excavation and borehole construction, (b) state after installation of canister and buffer material; (c) state after filling up the disposal tunnel
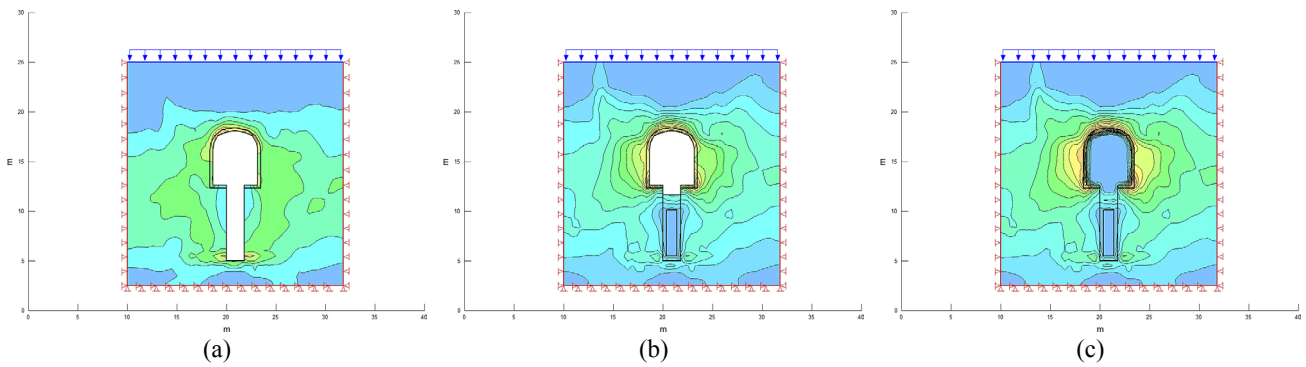
Figure 6: Model of rock stress for a cross-section through the disposal borehole, by phases: (a) state after tunnel excavation and borehole construction, (b) state after installation of canister and buffer material, (c) state after filling up the disposal tunnel. The applied version of the software does not allow the creation of a legend with colours and values but rather places number values at certain points (see **Figure 7**).

the excavation phase, critical stresses also occur at the bottom of the borehole. The resulting stresses, by phase, are shown in **Figure 6**. GeoStudio 2007 does not allow the insertion of a legend with colour-value data, which is the reason why the legend is not given in the figure. However, stresses did not exceed the shear or normal strength, and there was no failure of rock mass.

Maximal displacement was detected in the phase of filling of the disposal tunnel (latest phase in the model) and is shown in **Figure 7**.
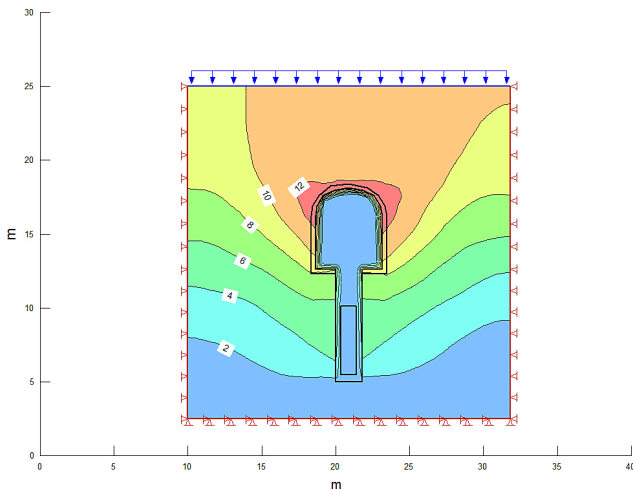
Figure 7: Model of the rock displacement for a cross-section, shown for the stage after filling the disposal tunnel (displacement in [mm])

The maximum displacement is 12 mm (tunnel calotte) which is within the safety parameters.
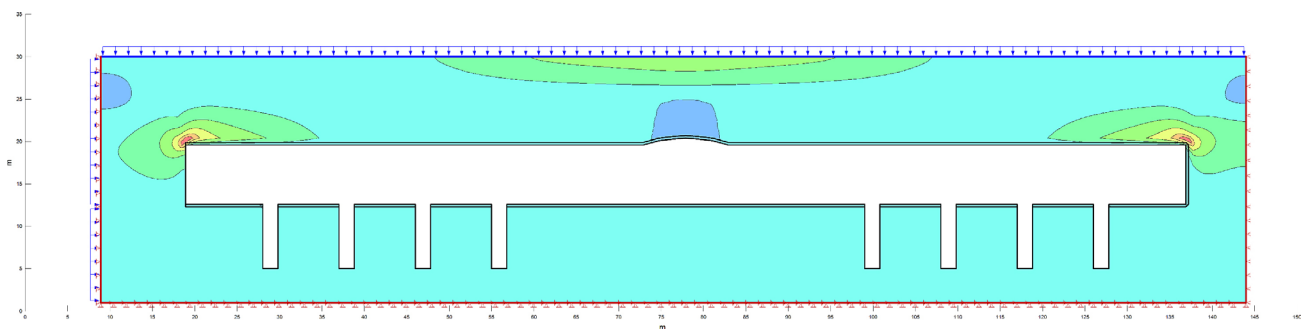
The resulting stress for the model made along the disposal tunnels is shown in **Figures 8-10** for three phases: excavation, installation of the canister and filling the disposal tunnel, respectively. Displacements for the same model and phases are shown in **Figures 11-13**.

2.2. Simulation in SEEP/W

According to the data from the existing documentation (**ARAO & Fond NEK, 2019**), the permeability of somewhat fractured magmatic rocks (granite, granodiorite) in Slovenia and Croatia is assumed to be in the range of $1x10^{-8}$-$1x10^{-12}$ m/s. Permeability of the EDZ is assumed to be in the range $1x10^{-6}$-$1x10^{-8}$ m/s (**Keto et al., 2012**). For the purpose of model development, values in this paper were selected: $1x10^{-8}$ m/s for intact rock mass, and $1x10^{-6}$ m/s for EDZ, which are more conservative values.

The simulation in the SEEP/W software shows that flow is mainly present in EDZ, since it is significantly more porous than the rest of the rock mass. Waterflow xy velocity magnitude and the main flow directions (streamlines) are shown in **Figure 14**.

The results show that the flow through the EDZ is dominant, since it is more permeable than the rest of the rock. The waterflow velocities are extremely small, so that, except in the case of stronger cracks that would provide substantial waterflow, it is not expected that a
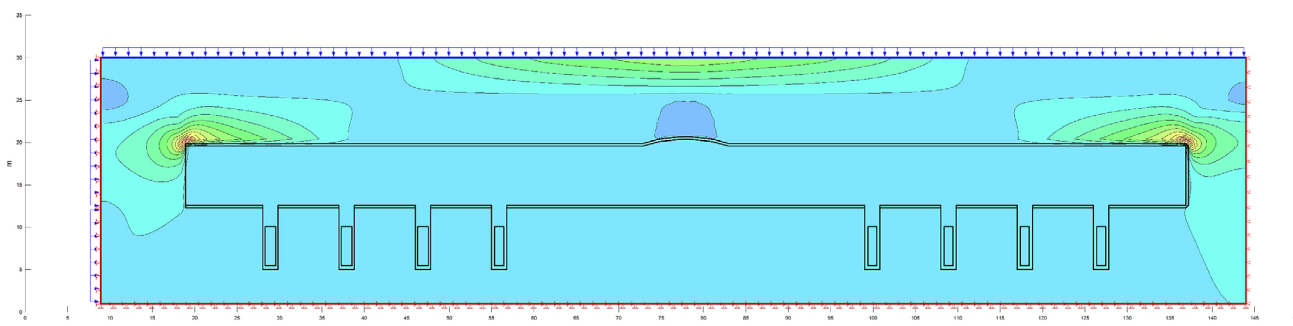

Figure 8: Resulting stress for the model made along the disposal tunnels during the phase of excavation and borehole drilling
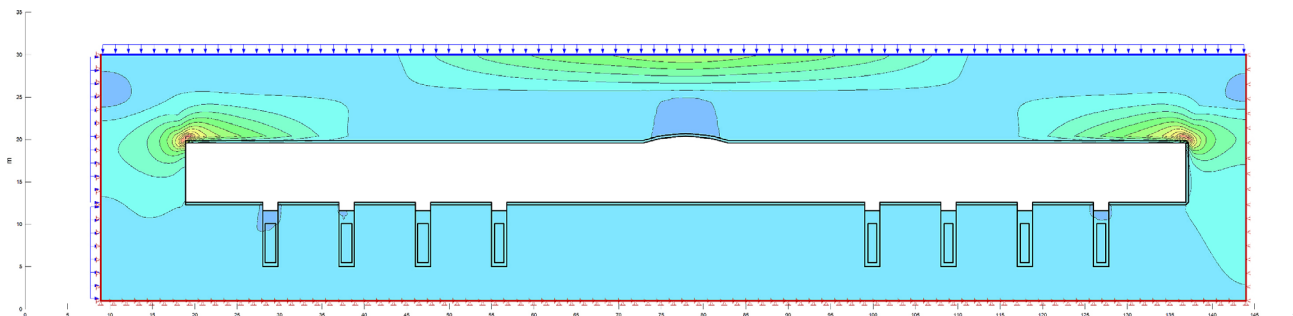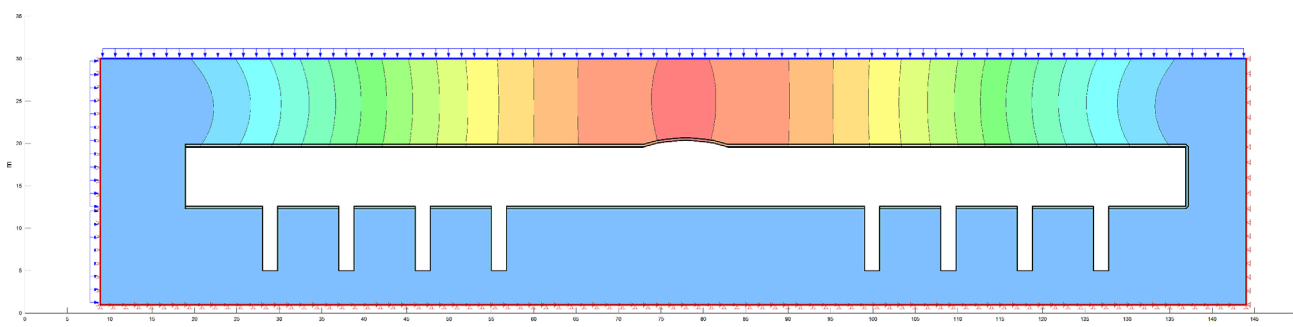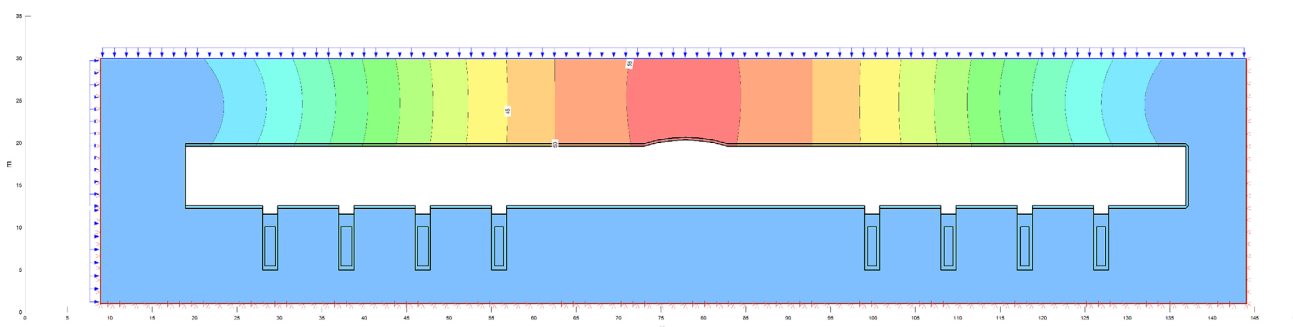
Figure 9: Resulting stress for the model made along the disposal tunnels during the phase after the installation of canisters and buffer material

Figure 10: Resulting stress for the model made along the disposal tunnels during the phase after filling up the disposal tunnel

Figure 12: Resulting displacements for the model made along the disposal tunnels during the phase after the installation of canisters and buffer material
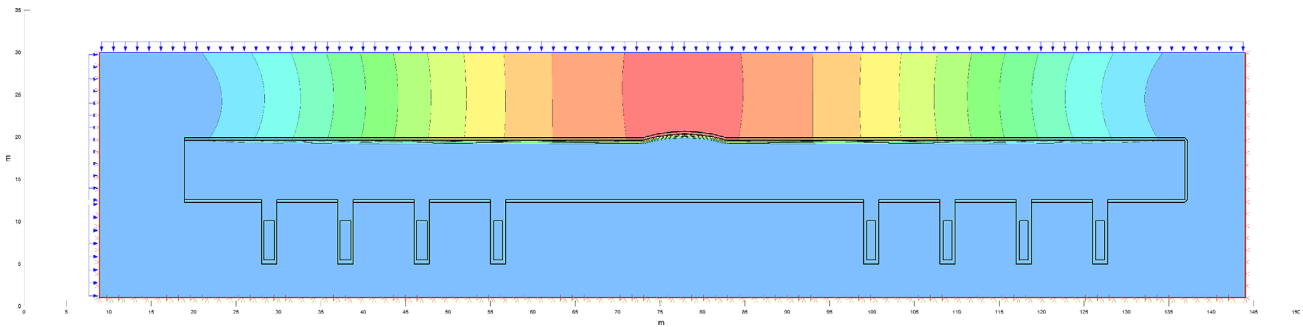

Figure 11: Resulting displacements for the model made along the disposal tunnels during the phase of excavation and borehole drilling

larger flow of water would occur in the underground repository.

The results for the model constructed along the disposal tunnel are similar to the cross-section model, but are of lower resolution, so they are not included in the paper.

2.3. Simulation in TEMP/W

TEMP/W is part of the GeoStudio software package that uses a finite element method to model thermal changes in soil due to environmental changes or anthropogenic impact (**GEO-SLOPE, 2014**). It is necessary to

Figure 13: Resulting displacements for the model made along the disposal tunnels during the phase after filling up the disposal tunnel
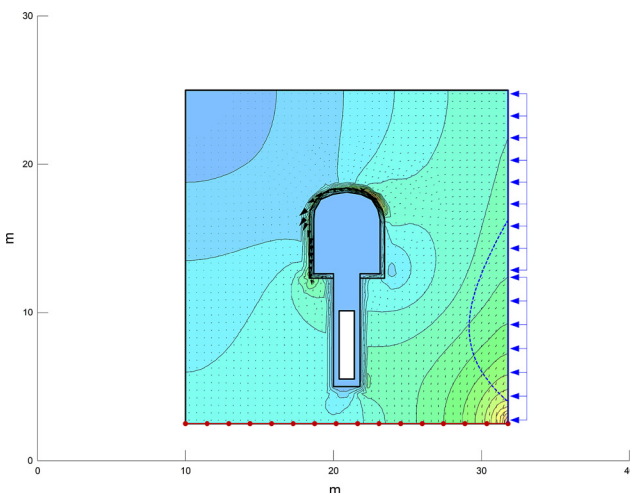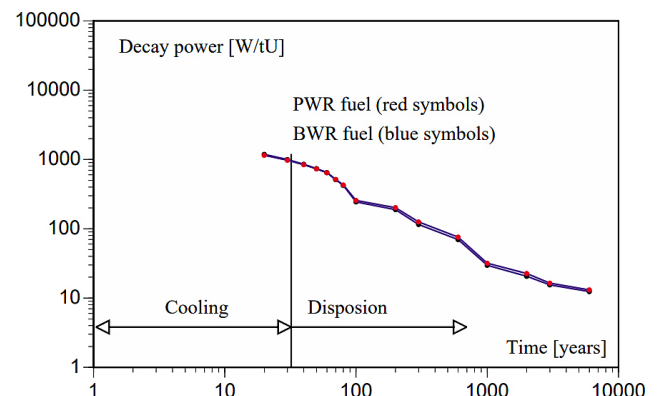

Figure 14: Waterflow xy velocity magnitude and the main flow directions for a cross-section through the disposal borehole

Figure 15: Change in thermal power over time for SNF from the Pressurized Water Reactor and Boiling water reactor (from: **Ikonen, 2003**).

point out that the initial state – the moment of canister installation, is problematic, since the water content (saturation) is the lowest, which means that the thermal conductivity is low, and temperatures are high. At higher temperatures, thermal conductivity has a higher value, increasing by about 0.1% per ºC (**Ikonen, 2003**). As well as the degree of saturation, the released energy (the thermal power of SNF assembly) changes over time, as shown in **Figure 15**.

Given the assumed depth of construction of the underground repository, according to the thermal gradient in the magmatic rocks of Croatia and Slovenia, the rock temperature (in situ) was estimated at 25ºC (**ARAO & Fond NEK, 2019**).

The simulation performed for the Finnish Olkiluoto repository (**Ikonen, 2003**), which served as an orientation model for the preparation of this paper, included data for conductivity and thermal capacity from laboratory studies conducted on cores taken from boreholes (**Kukkonen, 2000**). Estimates and measurements on Slovenian and Croatian rocks have provided data in the range 2.5-3.4 W/mK (**ARAO & Fond NEK, 2019**). It is important to note that the conductivity of the rock decreases slightly as a function of temperature. For the
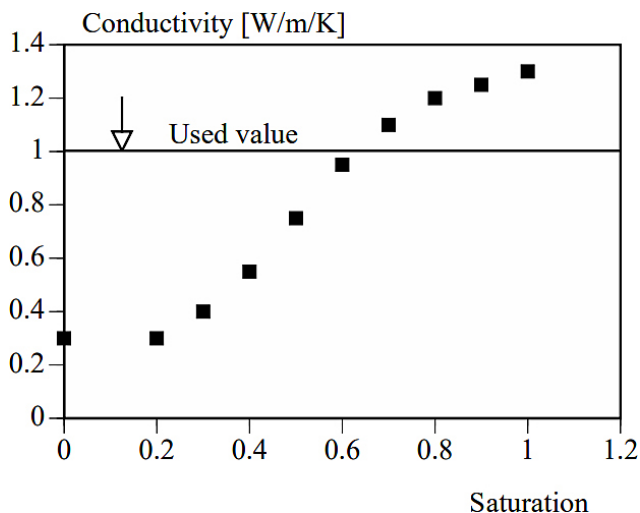
purpose of model development, a value of 3 W/mK was selected in this paper (according to: **ARAO & Fond NEK, 2019; Ikonen, 2003; Kukkonen, 2000**).

The mass thermal capacity of the rock also increases slightly as a function of temperature, and a value of 784 J/kgK was selected for model development (according to: **ARAO & Fond NEK, 2019; Ikonen, 2003; Kukkonen, 2000**). A value of 2 700 kg/m³ was chosen for the rock density, so the volumetric thermal capacity of the rock was assumed to be 2.15 MJ/m³K. The selected diffusivity value for the rock is $1.21x10^{-6}$ m²/s. The degree of rock saturation is a parameter that has been estimated according to existing research and a value of 0.5% (0.005 m³/m³) was selected for granodiorite (**ARAO & Fond NEK, 2019**).
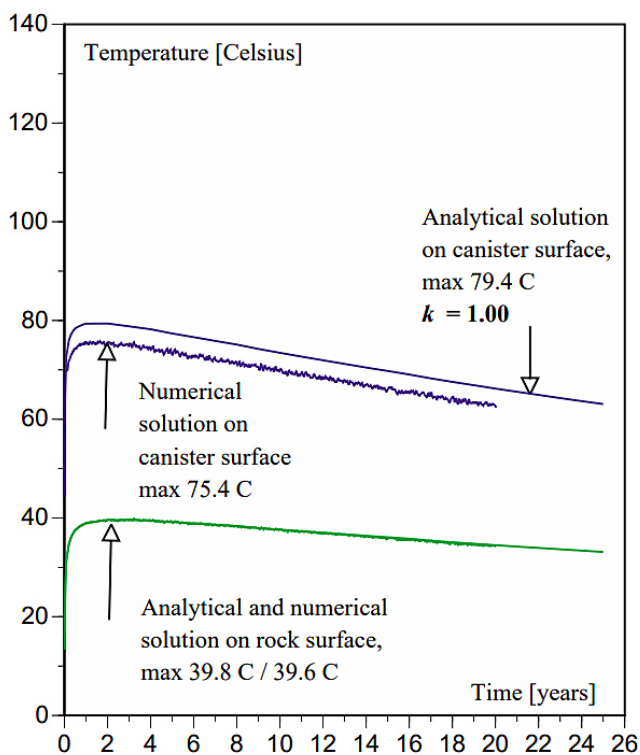
The conductivity value of the bentonite buffer will depend on the degree of saturation (see **Figure 16**), and a value of 1.0 W/mK was selected for model development.

The volumetric heat capacity for saturated bentonite with a total density of 2.0 – 2.1 t/m³ can be calculated at $3.10x10^6$-$3.40x10^6$ J/m³K (**Knutsson, 1983**) and $3.40x10^6$ J/m³K was selected as the more conservative estimate. The percentage of water in bentonite, according to **Table 3**, was selected at 0.16 m³/m³ (16%).

Figure 17 shows the relationship of temperature change on the surface of an individual canister and borehole walls over time. This relationship served to create a
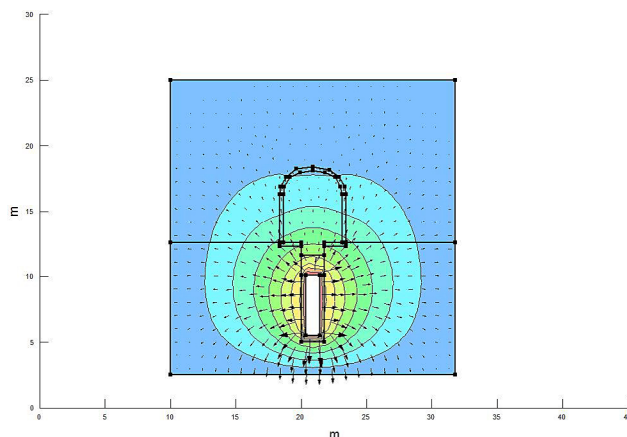
Figure 16: Thermal conductivity of bentonite as a function of a degree of saturation (from: **Ikonen, 2003** according to **Kukkonen, 2000**)

Figure 18: Heat propagation through the rock (temperatures) 25 years after installation of cannister containing SNF

of figures, here is the given model after 25 years since installation (see **Figure 18**).

Since the "GeoStudio 2007" does not have option of placing legends with colours representing temperatures with the resulting picture, changes of temperature over time for the critical profile (through the middle of the canister) are shown in **Figure 19**.

It is observed that the maximum of the temperatures (on the canister wall) follow a downward trend corresponding to the data in **Figure 17** (the relationship of temperature change on the surface of an individual canister and borehole wall over time), which was one of the initial conditions of the analysis.

Although it is to be expected that temperatures on the surface of the canister will decrease over time, due to the reduction of heat released from the SNF, one of the important parameters for selecting the speed and the beginning of disposal is the age of the SNF assemblies, i.e. the time they spent cooling in the pool near the power plant or in dry storage. Thus, the thermal impact on the bentonite buffer and host rock will be lower with less heat released from the fuel elements. For this reason, it is necessary to wait long enough for the fuel elements to cool to such an extent that the temperature on the wall of the canister is below 90°C. A critical element in the impact of heat is certainly bentonite, whose properties will change if exposed to temperatures of 100°C and above, while rock as such does not have a similar reaction to elevated temperatures, especially in locations with higher temperature gradients. Potential parent rocks in Slovenia and Croatia have an expected host rock temperature of 25°C at a depth of about 500 m, while, for example, temperatures of older rock masses in Sweden and Finland have about ten degrees lower temperatures at the same depths, which means that the system will experience more significant changes in the event of disposal of HLW or SNF.

For the longitudinal model, along the disposal tunnels (left and right relative to the central transportation tun-

Figure 17: Temperature history on a single canister surface and on the rock wall (from: **Ikonen, 2003**)

function of changing the temperature over time for the numeric model.

According to the selected parameters and with the boundary condition – the reservoir is a heat source, and a basic model for analysis was developed in SIGMA. Identical "regions" of material were defined as for the other simulations: intact rock, zone of EDZ around the tunnel (30 cm thick), copper cannister and bentonite fill. Simulations of heat propagation through the rock were performed for time periods of 1, 2, 5, 10, 15 and 25 years after cannister installation. To avoid the multiplication
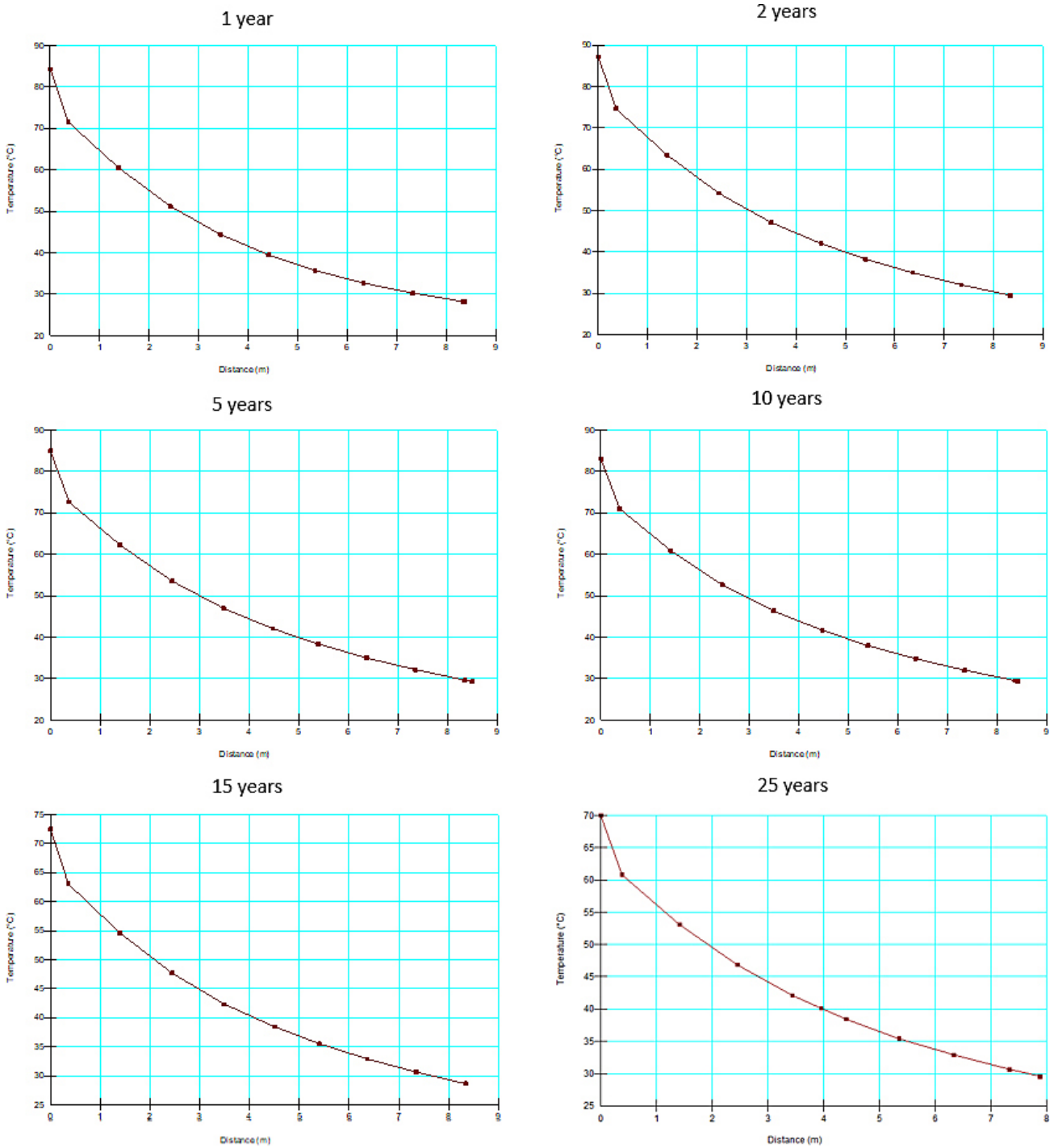
Figure 19: Changes of temperature over time for the critical profile (through the middle of the canister)

nel), a separate analysis was made to show the impact of several adjacent canisters heating the rock at the same time. **Figure 20** represents the result of a numerical analysis of the temperature distribution 25 years after installation. Changes of temperature over time for the critical profile (through the middle of the canisters) are shown at **Figure 21**.

It is important to conclude that maximum temperatures do NOT rise to the maximum permissible by concept design (90-100°C), which means that the solution

geometry and material selection meet the required concept requirements (in accordance with: **Ikonen, 2003**).

4. Discussion

One result that must be discussed is the change of the temperature with time. Since the released energy – thermal power of SNF assembly changes over time, as shown on **Figure 15**, so will the temperature of the buffer and the host rock. One of the observed phenomena is
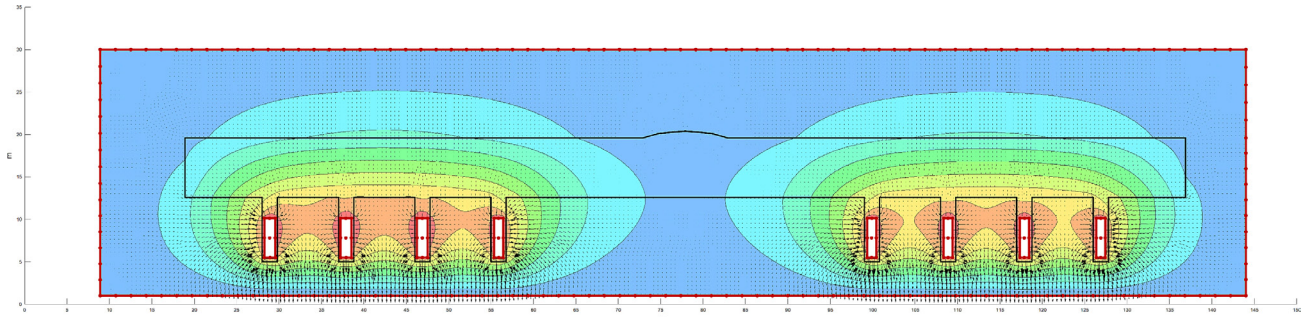
Figure 20: Heat propagation through the rock (temperatures) 25 years after the installation of canisters containing SNF
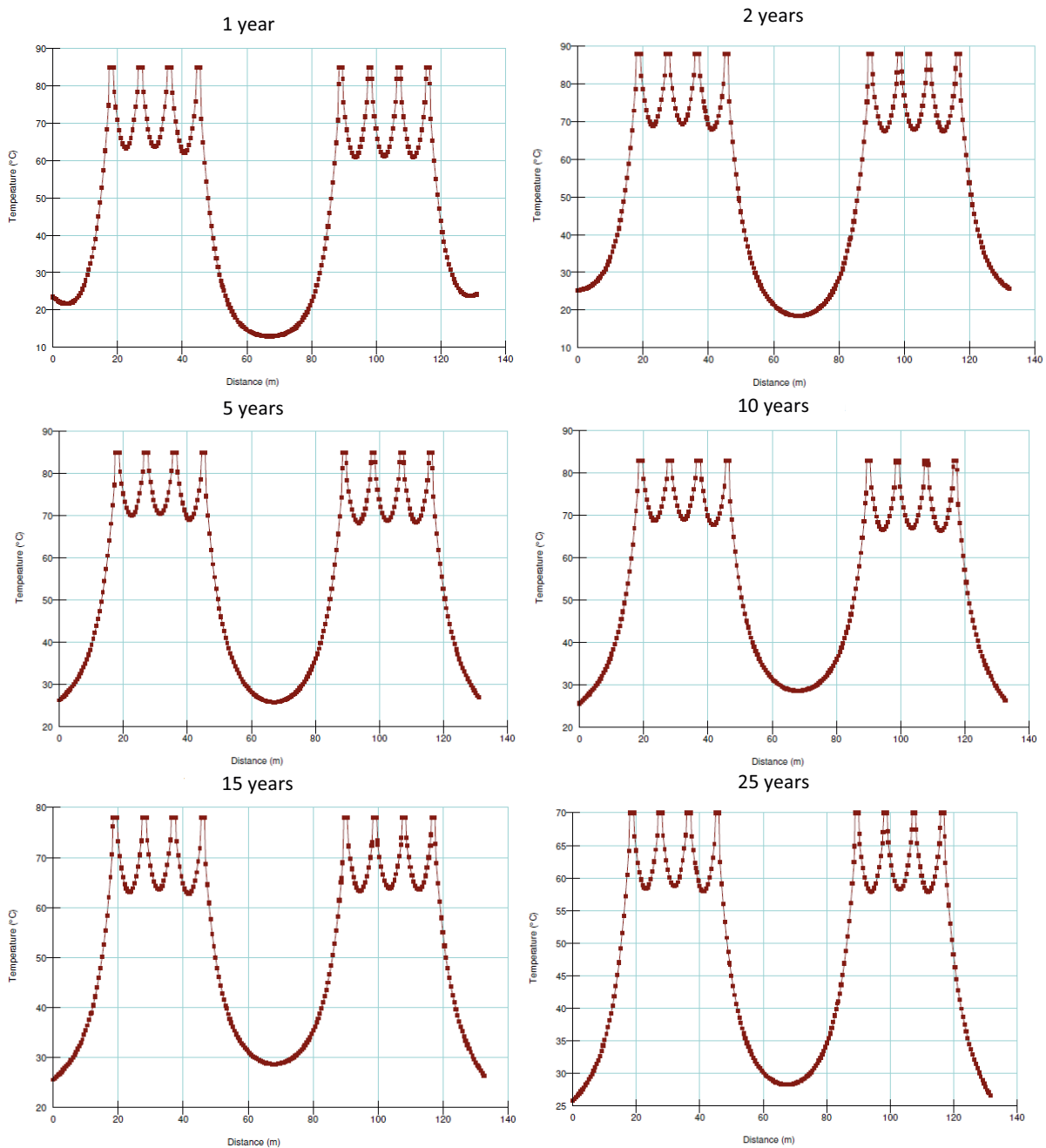
Figure 21: Changes of temperature over time for the critical profile (through the middle of the canister) along the disposal tunnel
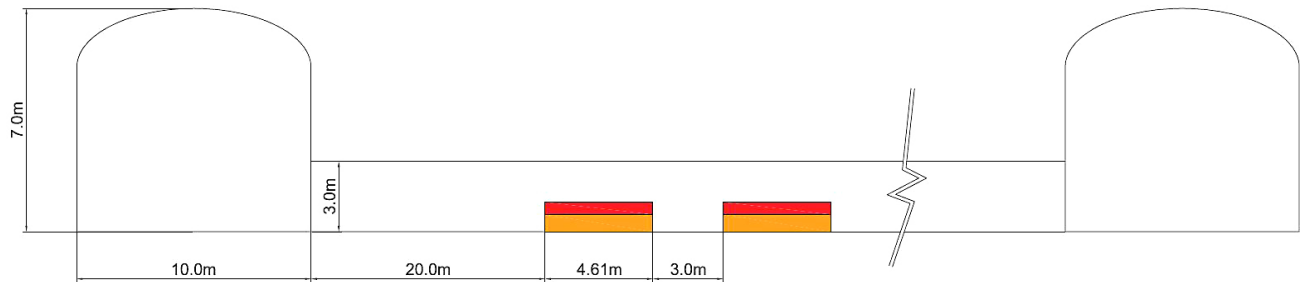
Figure 22: Disposal Concept in-tunnel (axial), either with short or long-lived canister and buffer material, developed by NAGRA and OPG (from: **NAGRA, 2009 & 2002, Baldwin et al., 2008**)

a gradual increase of the temperature after a couple of years and then a lowering of the temperature, gradually, as the SNF cools down. Therefore, the results of the peak temperatures on charts shown in **Figures 19 and 21** do agree with values shown in **Figure 17**, and the model is correct. The reason why the temperatures exceed maximal temperatures shown in **Figure 17** is due to a conservative approach and the selection of higher thermal power at the moment of disposal in order to prove that even in that instance, the temperature of the bentonite buffer will not reach 100ºC, the boiling point of water. The minimal temperatures in **Figures 19 and 21** are lower than 25ºC on some charts, the temperature expected in granodiorite in Croatia/Slovenia at a depth of 500 m. The reason for this are imperfections of the software, since 25ºC was included in the model as a boundary condition.

Although this type of numerical modelling would be preferable if performed in 3D, two-dimensional simulations are sufficient, at least at this stage of work (THME modelling for generic repository model). The GeoStudio software package 2D simulations somewhat limit the application and accuracy, given the three-dimensional positioning of warm bodies (canisters with SNF). In view of this, in the future it would be advisable to use another numerical tool (e.g. CODE BRIGHT) for modelling of the site-specific repository.

One of possible paths for future research is a comparison of the selected KBS-3V concept with another, e.g. KBS-3H or the Swiss so-called "Concept 3" – in-tunnel (axial) with a short-lived canister and buffer (**NAGRA, 2009 & 2002**) or the Canadian so-called "Concept 4" – in-tunnel (axial) with long-lived canister and buffer, shown in **Figure 22**, developed by Ontario Power Generation (OPG) (**Baldwin et al., 2008**).

One of the main issues and improvements of the THME model presented in this paper was the introduction of a damaged zone, the so-called excavation-disturbed zone (EDZ) of rock material created by the application of the drilling and blasting method for the construction of underground spaces. EDZ is usually not considered in THME simulations due to the simplification of a problem in order to facilitate numerical modelling (**Åkesson i dr., 2010; Chen et al., 2012; Kwon et al., 2013; Rutqvist et al., 2005; Toprak et al., 2012;**

Toprak et al., 2013; Zhao et al., 2014). However, EDZ is one of the most significant parts of the model, since it represents a preferable pathway for underground water and radionuclide transport. Also, it significantly affects the stability of the underground spaces' stability and displacement of material, and somewhat the propagation of heat from the SNF canister.

5. Conclusions

This paper investigates the thermal-hydro-mechanical (THME) effects of spent nuclear fuel (SNF) disposal in a deep geological repository in crystalline (magmatic) rock, granodiorite. The parameters of potential host rocks in Croatia/Slovenia were used for numerical analysis as well as geometry taken from a specific design solution.

The selected SNF disposal concept KBS-3V is applicable to the selected host rock, and the parameters of rock excavation (geometry of underground spaces) were well selected. The assumption of the occurrence of the highest stresses in the tunnel calotte, within the safety factors, is proven. There was no collapse of material during the simulations, and the displacements were within the expected range (even without a support system).

The materials used as a buffer (sodium bentonite) meet the required conditions – low permeability and the required thermal conductivity. It has been demonstrated that the model (with a given canister spacing) does not reach the maximum temperature allowed by the concept design (90-100ºC), therefore heating of the rock will not produce side effects e.g. overheating of bentonite and the evaporation of water.

It has been confirmed that groundwater flow rate will not have a negative impact on engineering barriers and that the damaged zone serves as a route for faster water flow, the so-called "hydraulic cage".

For further research several improvements are planned:
- A comparison of the KBS-3V concept with at least one another SNF disposal concept;
- An introduction of the more complex models in 3D (containing more detailed geometry and parameters);
- Using parameters from rock samples tested in laboratory or in-situ;

- Comparative testing of several different solution geometries (different spacing between disposal boreholes, different types of bentonite, different forms of filling underground spaces, different humidity of bentonite, etc.).

Acknowledgment

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SAŽETAK

Termohidromehanički efekti na stijeni dubokoga geološkog odlagališta iskorištenoga nuklearnog goriva

Donošenjem Nacionalnoga programa provedbe Strategije zbrinjavanja radioaktivnoga otpada, iskorištenih izvora i istrošenoga nuklearnog goriva Vlade Republike Hrvatske pitanje upravljanja radioaktivnim otpadom u Hrvatskoj postaje aktualno. Suvlasništvo nad Nuklearnom elektranom Krško (NEK) znači da polovina pogonskoga i dekomisijskoga otpada te istrošenoga nuklearnog goriva (ING) pripada Hrvatskoj. Za sada se ING čuva u bazenu NEK-a, a predviđeno je i suho skladištenje do trenutka odlaganja. Generički projekt odlagališta ING-a već je prošao drugu reviziju i recenziju. Projektna ideja uključuje traženje lokacije na teritoriju obiju država te konceptualno rješenje tipa SKB-3V u kristaliničnoj stijeni. U radu je dana procjena termohidromehaničkih efekata (THME) odlagališta ING-a u kristaliničnoj stijeni (granodiorit) SKB-3V koncepta izradom numeričkoga modela u programima SIGMA/W, SEEP/W i TEMP/W. Simulacije su pokazale kako je moguće izgraditi odlagalište ING-a u kristaliničnim stijenama Hrvatske ili Slovenije, da je generički projekt dubokoga geološkog odlagališta dobro osmišljen i da je model termohidromehaničkih efekata ING-a na stijeni u Hrvatskoj/Sloveniji izvediv, što dokazuje podobnost stijenske mase za ovu svrhu.

Ključne riječi:
termohidromehanički efekti, odlagalište, iskorišteno nuklearno gorivo, kristalinična stijena

Authors contribution

Želimir Veinović (Assistant Professor, radioactive waste management, spent nuclear fuel disposal, waste management, soil mechanics, geotechnics, earthquake engineering, ionizing radiation protection, numerical analysis) provided data on the host rock and engineering barriers and developed numerical models of the deep geological repository. **Galla Uroić** (mag.ing.min., geotechnics, radioactive waste management, spent nuclear fuel disposal, NORM and residues management, ionizing radiation protection, numerical analysis) developed numerical models and carried out a numerical analysis of the deep geological repository. **Dubravko Domitrović** (Assistant Professor, radioactive waste management, spent nuclear fuel disposal, soil mechanics, soil dynamics, numerical analysis) developed numerical models of the deep geological repository. **Leon Kegel** (Bsc. Meteorology, Head of the ARAO Planning and Development Section, provided data for a generic project of a deep geological disposal facility concerning a disposal concept and host rock parameters, decommissioning and radioactive waste and is a spent nuclear fuel management expert.