Paper 105

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Proceedings of the Eighth International Conference
on Engineering Computational Technology,
B.H.V. Topping, (Editor),
Civil-Comp Press, Stirlingshire, Scotland

The Prototype Repository Test: Thermal Model Verification

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Abstract

The disposal of spent nuclear fuel and other nuclear waste is one of the main contentions concerning the nuclear power industry. The design and construction of the deep geological spent nuclear fuel repository is a very sophisticated process, which includes many types of particular analyses. One of the important partial studies of a nuclear waste repository can be called thermal dimensioning, a basic simulation of thermal conditions depending on the structure and size of the repository. The important parameters for repository layout are the thermal properties of the host rock and barrier, heat generated by the nuclear waste, number of disposal boreholes and their spacing. The design of the repository is determined by thermal criteria, which place limits on the maximum temperature that can be allowed in the barrier surrounding the boreholes. One of the most important procedures in modelling is verification and validation of the model. It is very difficult to validate the model of the deep geological spent nuclear fuel repository, because it is difficult to build the physical model of the repository.

The unique opportunity for model verification and validation is the prototype repository experiment. This is the physical model of a small part of the repository. We can use the experimental achieved data for comparison with the computed data. The main goal of this paper is a comparison between the results achieved in the prototype repository experiment and the results obtained using the model. The temperatures are compared at sample points where the sensors in the experiment are placed. The accuracy of the model and its capabality to predict the behaviour of the real design of the deep geological spent nuclear fuel repository is shown. The main temperature profiles in the vicinity of the boreholes are shown in the paper.

Keywords: thermal simulation, spent nuclear fuel, prototype repository, finite element method.

1 Introduction

Even the fast development of the new technologies always some amount of high radioactive wastes remaines from nucler power plants or from different industries which will be necessary to isolate from biosphere for thousands years. The mix of technological and nature barriers is supposed for the safe deposition of those radioactive wastes. As the most promising nature barrier for the condition of the Czech Republic shows to be the massive rock of granite which fulfils requirements on the long term stability, homogenity, minumum flow of groundwater, suitable physical and chemical characteristics of the rock, [1].

In spite of the simulations of thermal processes are almost a routine in many technical problems, it is not the case for the spent nuclear fuel repository. It requires special approaches. There are several thousands canisters in the repository and we need both to represent detailed local field in the vicinity of canister in the scale of centimetres (important for chemical and degradation processes in the bentonite) and to include the heat interaction of all the canisters in the repository (we cannot simply give boundary conditions for single canister). We solved and compared the heat conduction for the single canister case (3D and axisymmetric) and for the periodic structure of the canisters in [2] and influence of boundary conditions on the spatial temperature distribution in the periodic model in [3].

The mathematical models of the thermal dimensioning must be evaluated with the physical experiments. One of the most complex experiments relating to the deep geological spent nuclear fuel repository was realised in Sweden, in the SKB Aspo Hard Rock Laboratory (HRL) [4]. So called Prototype Repository simulates a part of a KBS-3 nuclear waste repository. The aim of the Prototype Repository is to demonstrate the integrated function of the repository components and to provide a full-scale reference for comparison with models and assumptions.

2 The Prototype Repository

The Prototype Repository is designed, constructed and tested, to the extent possible, to simulate the real deep repository system regarding preparations, machinery for installation and deposition, geometry, materials, and rock environment. The experiment is located at 450 m depth in the Aspo HRL. The Prototype Repository drift, 65 m long and 5 m in diameter, was excavated using a Tunnel Boring Machine (TBM). Six vertical deposition holes, 8.37 m deep and 1.75 m in diameter, were bored in the tunnel. The Prototype Repository consists of two sections. The installation of the first Section of Prototype Repository was made during summer and autumn 2001 and Section 2 was installed in spring and summer 2003.

Section 1 consists of four full-scale deposition holes, copper canisters equipped with electrical heaters, bentonite blocks and a deposition tunnel backfilled with a mixture of bentonite and crushed rock and ends with a concrete plug as shown in Fig. 1.

The inner part of Section 1 was wet, and in order to handle the water inflow a draining system (a sump inside hole 1 where water was drained from) was installed.

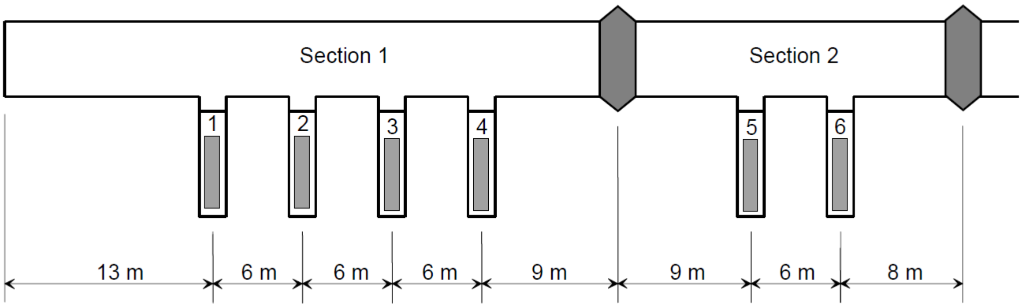

Figure 1: Schematic view of the Prototype Repository, from [5].

Section 2 consists of two full-scale deposition holes with a backfilled tunnel section and ends also with a concrete plug. To simulate the thermal behavior of the nuclear waste, heaters are installed in the canisters. The bentonite buffer in deposition holes 1, 3, 5 and 6, the backfill and the surrounding rock are instrumented with gauges for measuring temperature, water pressure, total pressure, relative humidity, resistivity and canister displacement.

The instruments are connected to data collection systems by cables protected by tubes, which are led through the rock in watertight lead throughs. Instrumentation is used to monitor processes and properties in the canister, buffer material, backfill, and the near-field rock. The evolution will be followed for more than 10 years in Section 1 and approximately 5 years in Section 2, depending on the physical development of the test [5].

Some results of the Prototype Repository experiment (for comparison with the results of the model), temperature in sample points approx. at mid height of the canister and 2 m from the canister center are shown in Fig 2. There are depicted the temperatures in the vicinity of the boreholes 1 - 6 in the figure.

3 The Model of the Prototype Repository Experiment

The model representing the Prototype Repository Experiment for comparison the model results and the experiment is presented here. The model represents a structure of boreholes in a tunnel of the Prototype repository. It is a good model for local temperature analysis in the vicinity of the canisters, see [2]. Schematic view of the Prototype Repository is shown in Fig. 1. The dimensions of the Prototype Repository are specified in Table 1. Material properties are based on the data from [5], [6]. The material properties are specified in the Table 2. The concrete plugs are neglected in the model, due to its negligible dimensions, we do not need the material properties of the concrete plug.

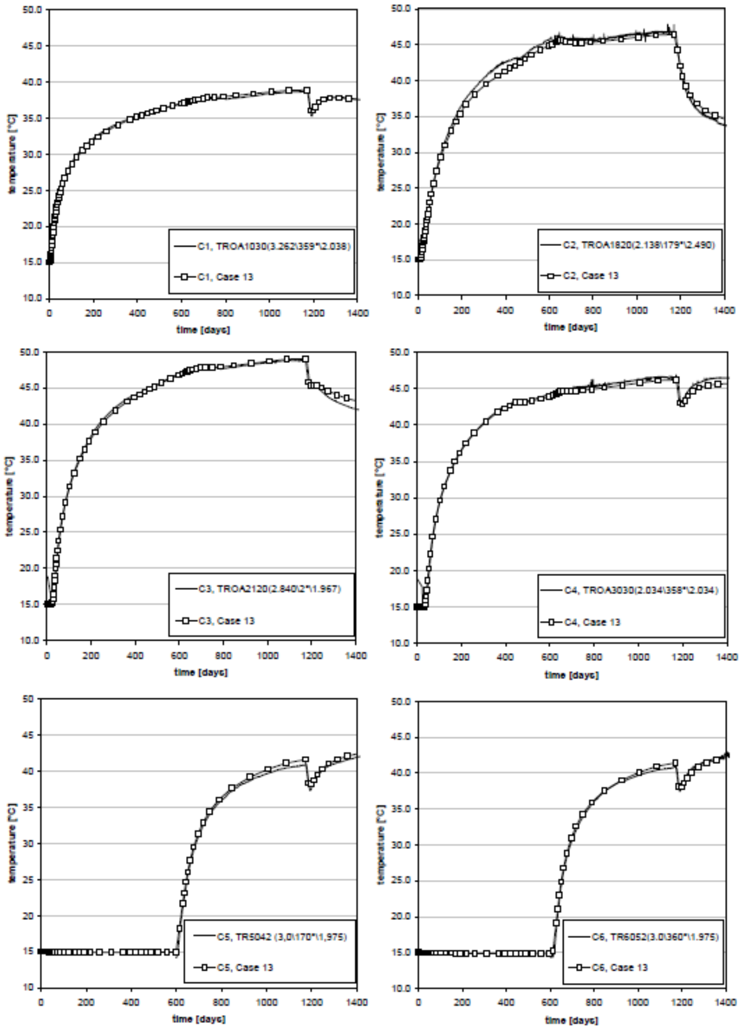

Figure 2: Temperature in sample points approx. at mid height of the canister and 2 m from the canister center, [5].

The model represents the tunnel with deposition holes (Prototype Repository) with surrounding granite massiff. The dimensions of the granite "box" surrounding the Prototype Repository are approx. 170 x 120 x 60 m. The detail of the mesh of the model with boreholes, tunnel etc. is shown in Fig. 3.

We solve the problem with ANSYS software package. It includes two different environments - ANSYS "native" and ANSYS Workbench, see [7]. Ansys Workbench is relatively new product characterized by user friendly graphical user interface. But it doesn't includes all ANSYS features accesible in batch mode or in old "native" interface. But the Workbench is a sufficient tool for our first simple case study. All tasks are performed in ANSYS Workbench (geometry creation in Design Modeler, finite element mesh creation, setting of the boundary and initial conditions, executing the solver, result processing). More sofisticated procedure of ANSYS usage was shown

Dimension	Value	Dimension	Value
Deposition hole depth	approx. 8 m	Bentonite thickness above the canister	1.5 m
Deposition hole diameter	1.75 m	Total tunnel length	63 m
Canister height	approx. 5 m	Length of Section 1.	40 m
Canister diameter	1.05 m	Length of Section 2.	23 m
Bentonite thickness bellow the canister	0.5 m	Tunnel diameter	5 m

Table 1: Dimensions of the repository components in the model.

	Density $[kg/m^3]$	Heat conductivity $[W/m/K]$	Heat capacity $[kJ/kg/K]$
Granite	2700	2.7	850
Bentonite	2000	1	2500
Steel	7800	460	45
Tunnel backfill	2800	1.5	880

Table 2: Material properties used in the model

in [3].

As shown in [3], type of choosed boundary conditions (prescribed temperatures, zero heat flow, infinite elements - ANSYS) does not have an effect on the maximal temperatures in this type of model. Temperature distribution in the immediate vicinity of the borehole is similar in all analyzed cases of the boundary conditions. Initial conditions, temperature before the start of the experiment, is 15 deg C. The disposed canisters in boreholes produce residual heat due to nuclear decay of radioactive products (SNF/HLW). This heat power is substituted by heaters with specified heating power, see [5]. The heating power used in the model is the same like in the experiment. Heating power in the experiment is specified in the table in Fig. 4. This condition is realized as a Neumann's boundary condition - heat flow on the surface of bentonite blocks neighbouring with the canisters. Initial heating power of all canisters was 1800 W.

4 Results

Let us focus on the temperature in time in the boreholes vicinity especially. There are depicted temperature profiles in the centre of the height of the first container, 2 meters from the axis of the container in the Fig. 5. There are depicted the temperatures left

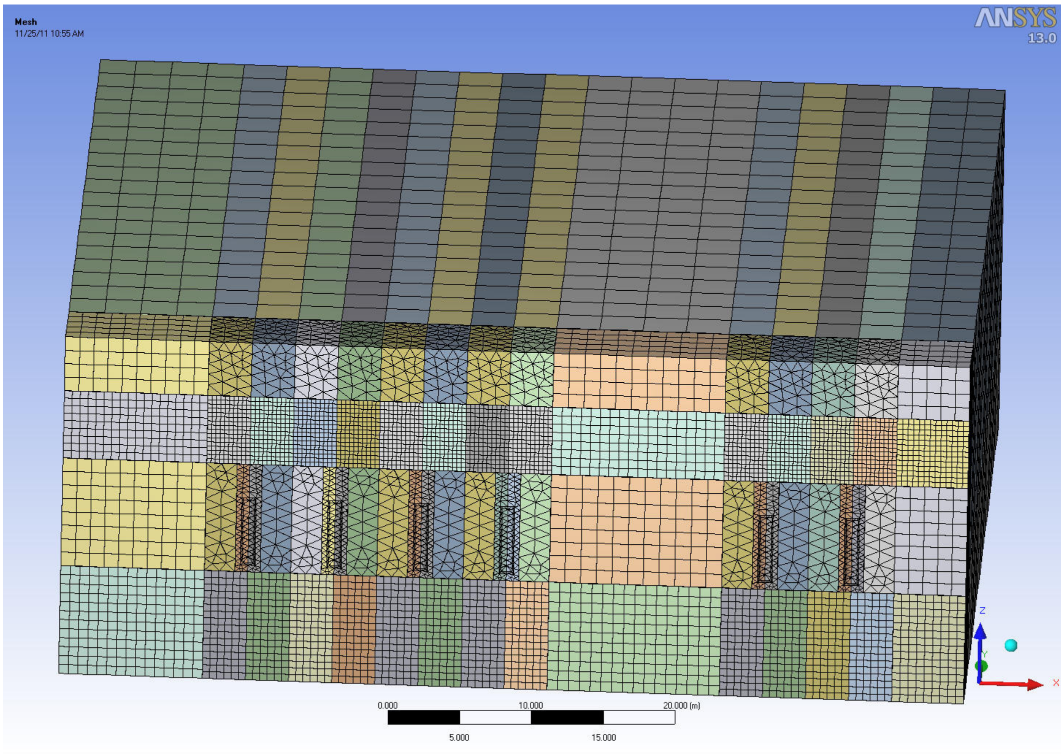

Figure 3: The detail of the finite element mesh of the Prototype Repository model

side and right side from the borehole in the figure. We do not have an information about the sensors placing in the PRototype Repository Experiment. We assume two extreme cases - left side and right side from the axis of the borehole. We can conclude, that the computed temperatures are similar to the experimental achieved results. The experimental results are between the computed results. The difference is about 8 percents. The uncertainity is caused by the placing of the sensor in the experiment. There is apparent the switching off the power to all canisters between December 6-15th, 2004. Decreasing and increasing of the temperature. The magnitude of this jump is apparent in computed and experimental results.

Further results for comparison can be temperatures dependent on the distance from the borehole's axis in specified time. This type of result for the first borehole and the date of November 15, 2004 is depicted in Fig. 6. The largest magnitude of the difference between experiment and computed results are in the vicinity of the borehole. The difference about 4 percents (experiment vs. model results) can be caused by the different material properties used in the model.

Activity	Date
Start backfilling	3/9 2001
Start heating canister 1	17/9 2001
Start heating canister 2	24/9 2001
Start heating canister 3	11/10 2001
Start heating canister 4	22/10 2001
Finish backfilling	20/11 2001
Plug casting	14/12 2001
Decreased power (-20 W)	17/9 2002
Decreased power (-40 W)	5/9 2003
Decreased power (-30 W)	8/9 2004
The drainage of tunnel was closed	1/10 2004
The power to all canisters was switched off	2/12 2004
The drainage of the tunnel was opened	6/12 2004
The power to the canisters was switched on	15/12 2004
Decreased power (-30 W)	2/12 2005
A packer installed in the rock was broken	18/5 2006
Decreased power (-30 W)	21/12 2006
Decreased power (-30 W)	11/12 2007
Decreased power (-30 W)	29/1 2009

Tab. 2 Klíčové události a data experimentu v sekci 1.

Activity	Date
Start backfilling	29/4 2003
Start heating canister 5	8/5 2003
Start heating canister 6	23/5 2003
Finished backfilling	25/6 2003
Plug casting	11/9 2003
Decreased power (-30 W)	8/9 2004
The power to all canisters was switched off	2/12 2004
The drainage of the tunnel was opened	6/12 2004
The power to the canisters was switched on	15/12 2004
The power to canister 6 was switched off	6/9 2005
The power to canister 6 was switched on	2/11 2005
Decreased power (-30 W)	2/12 2005
Decreased power (-30 W)	21/12 2006
Decreased power (-30 W)	11/12 2007
The power to canister 6 was decreased with about 200 W due to problems with the heaters	8/4 2008
The power to canister 6 was decreased with about 300 W due to problems with the heaters	5/6 2008
Decreased power to canister 5 (-30 W)	29/1 2009

Figure 4: Key dates for heating power of the canisters, [5].

5 Conclusion

The finite element models focus on the thermal dimensioning of the deep geological spent nuclear fuel repository to solve the crucial problems for the repository construction. The comparison with the experimental results provides the opportunity for model verification and validation. The prototype repository experiment is an excellent opportunity for evaluation of our results.

The next step is to use the model for prediction of temperature conditions in the planned concepts of the deep geological spent nuclear fuel repository. The expected concepts are similar to the prototype repository, we can expect the similar differences between acheived temperatures in the real repository and its model.

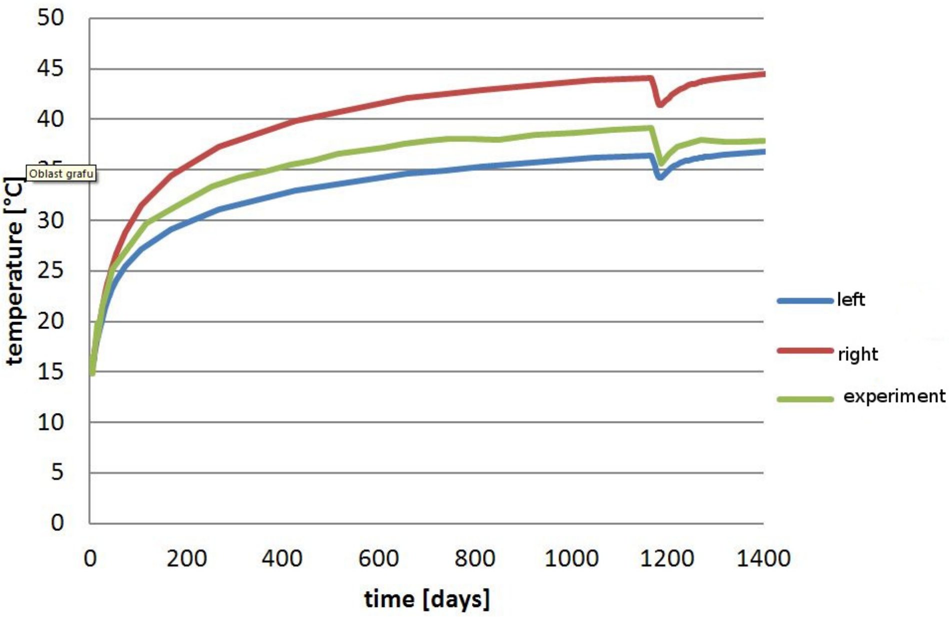

Figure 5: Temperature profiles, left side (blue), right side (red), experiment (green) - first borehole.

Acknowledgements

This project is realized under the state subsidy of the Czech Republic within the research and development project FR-TI/362 ”Research of properties of material for safe disposal of radioactive waste and development of procedures for their assessment supported by Ministry of Industry and Trade of the Czech Republic.

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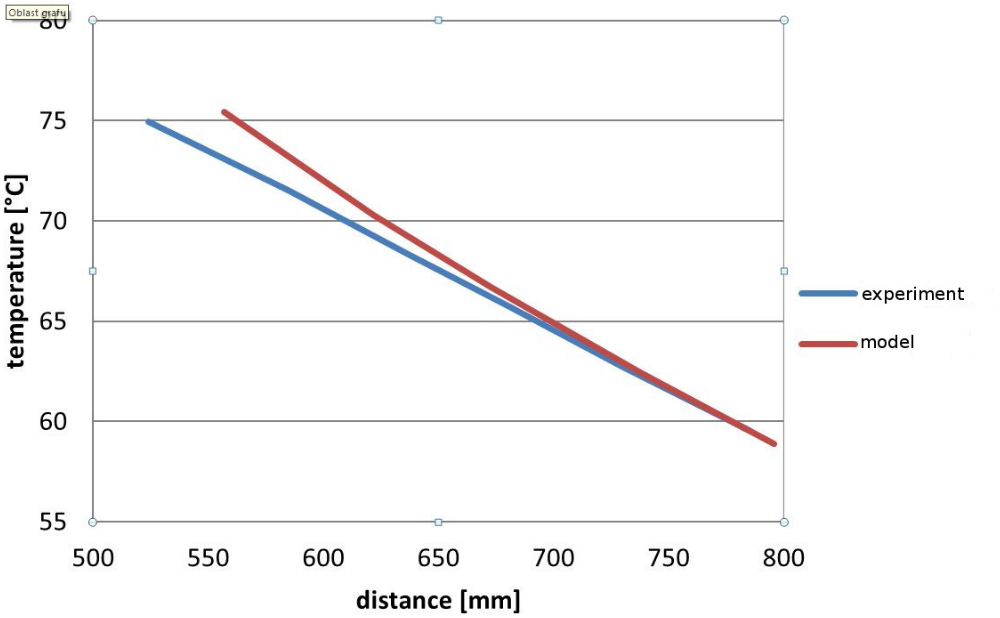

Figure 6: Temperature profiles in the vicinity of the first borehole, November 15, 2004.

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