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Investigation on Suitability of Argillaceous Rocks of Vindhyan Supergroup as Host Rock for Deep Geological Repository using Thermal Analysis

T. K. Pal[1,*], R. K. Bajpai[1], A. Acharya[1], R. S. Bhatia[1] and D. Datta[2]
[1]Technology Development Division
[2]Radiological Physics and Advisory Division
BARC, Mumbai-400085, India
[*]Email: tkpal@barc.gov.in

Abstract

Argillaceous rocks are being considered as a potential host rock for deep geological repository (DGR) for hosting vitrified high level radioactive waste canisters by many countries worldwide. Numerical simulation of thermal evolution in the repository environment is an important study for the long term safety performance assessment of a DGR. In this study, thermal dissipation in the near field area of a conceptual repository in Ganurgarh shales from Bhander Group of Vindhyan Super Group, which is the thickest sedimentary succession of India, has been simulated using commercial software FLAC3D, which solves the governing heat diffusion equation using explicit and implicit finite difference methods. Model parameters like thermal conductivity, specific heat, density of the shales are generated in the laboratory. From the analysis of time dependent temperature profile it is observed that maximum temperature of 70.5ºC is attained at canister surface after 22 years of heating for a heat loadings of 500 W/overpack. Since the maximum temperature is well below the permissible limit of temperature (100ºC), the heat load of the source is increased to 700 W/overpack and in this case the simulated value of maximum temperature is 93ºC. Maximum temperatures at other locations within the near field region are also within the permissible limit.

Keywords: *Argillaceous rock, Vindhyan Supergroup, deep geological repository, host rock, thermal analysis*

Introduction

There is an international consensus that disposal of highly-active and/or long-lived radioactive waste generated during the various stages of nuclear fuel cycle in DGR is the most practical option available for long-term isolation of these radioactive materials from the biosphere. In India, vitrified products of high level radioactive waste in the form of canisters/ overpacks are being stored in engineered storage facilities and after a cooling period of about 30 years they are supposed to be disposed of in a suitable geological formation so called DGR at a depth of about 500-700m below the ground surface (Narayan et al., 2007). Countries across the world are working on various type of host rock, such as granite, basalt, argillite, tuff, etc., for assessing their suitability for DGR (Bajpai, 2004). Each rock type has its advantages and disadvantages when considered from the point of constructional, operational and post closure radiological safety aspects required for a DGR facility. In India, the choice of host rock is restricted largely to granite formations due to their very vast occurrence throughout the country and adequate thermo, mechanical and hydrological characteristics (Mathur et al., 1996). Countries like France, Belgium, Switzerland are actively involved in assessing suitability of argillaceous/clay type rock formations for DGR (Kickmaier et al., 1997, Jacques et al., 2014). Though the strength of argillaceous rock is not as good as that of granite rock, low water permeability and high sorption capacity due to presence of clay minerals are two desirable features of this rock type make that it as a potential host rock for DGR. Since India also has a good coverage of sedimentary rock type, work on various argillaceous/clay type rock formation is taken up for assessing it's suitability for hosting DGR (Bajpai, 2018). Claystones, mudstones, marls and shales, which belong to argillaceous rock types, have been identified as potential host rock for DGR. The sedimentary succession of the Vindhyan Supergroup is one of the thickest sedimentary successions in the world. In this study, the Ganurgarh shales from Bhander Group are considered as host rock formation for a conceptual repository. Very good thermal conductivity of this rock is a favorable characteristic for smooth dissipation of heat. Numerical simulation of dissipation of heat generated by waste filled canisters emplaced in DGR is an important study for the long term safety performance assessment of a DGR specially because design constrain posed by maximum allowable temperature of 100°C throughout the evolution of the facility to avoid water vaporization and resultant pressure build up which may eventually lead to release of radioactivity and its enhanced migration into geo-sphere. In order to achieve better radiological safety of a DGR by containing and isolating the radionuclides from the surface environment for a very long period, a multi-barrier design concept, where the disposed canisters are surrounded by clay barriers in disposal pit, is adopted worldwide (Narayan et al., 2007). Various authors have carried out numerical simulation of thermal conduction in such disposal mode (Goel et al., 2003, Zhao et al., 2014, Maheshwar et al., 2015a,b, Pal et al., 2016, 2019). Since the host rock considered in

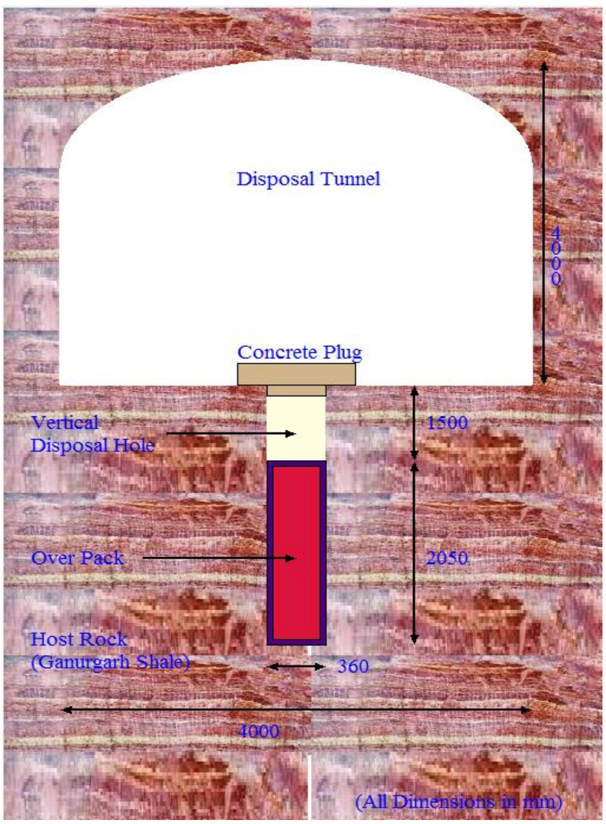

Fig 1. Schematic view of vertical disposal pit in shale rock

this study is argillaceous type, the thermal properties of the clay barrier such as thermal conductivity, specific heat are taken same as that of the host rock. So, the model geometry considered in this study, as schematically shown in Fig 1, does not consider clay barrier as a separate engineered barrier. The objective of the study is to see whether excluding the clay barrier, which has lower thermal conductivity than the host rock, heat loading of the source can be increased for the same design parameter, such as spacing between two disposal pits and two disposal tunnels while keeping the maximum temperature at any location of the of DGR within allowable temperature limit (100°C). Accordingly, the thermal heat source in this study is increased from the standard value for Indian scenario (500 W/overpack) to 700 W/overpack.

The simulation study is carried out using commercial software FLAC3D (Fast Lagrangian Analysis of Continua) which solves the governing heat diffusion equation using explicit and implicit finite difference methods. The rest of the paper is organized as follows.

Mathematical Model and Numerical Framework

In general, heat transport through porous media occurs through conduction and convection processes. However, in low water permeable porous media, such as argillaceous rocks, convection can be neglected (Hokmark et al., 2003, Mathur et al., 1998). The general 3-Dimensional heat conduction equation in a homogeneous and isotropic medium is written as

$$\frac{\partial T(x,y,z,t)}{\partial t} = D\left(\frac{\partial^2 T(x,y,z,t)}{\partial x^2} + \frac{\partial^2 T(x,y,z,t)}{\partial y^2} + \frac{\partial^2 T(x,y,z,t)}{\partial z^2}\right) \dots .(1)$$

where T(x,y,z,t) is the temperature at a location (x,y,z) at time (t), $D = \frac{k}{\rho C}$ is thermal diffusion coefficient, k is thermal conductivity, ρ is material density and C represents specific heat of the material.

Ganurgarh rock samples were collected as per IS-9179–1979 (1979) in the form of rough blocks and marked to represent their position and orientation with respect to the parent rock mass. The samples were collected from upper Bhander Group of Vindhyan Super Group from the town Damoh in the Sagar Division of north-eastern Madhya Pradesh. Geologically, two types of rocks, Rewa and Upper Bhander groups of Vindhyan Super Group, are present in Damoh. There are thick successions of greyish-brownish coloured Ganurgarh shales with overlaid sandstones. Intense weathering in these shales has lead them covert into clays. Shale samples were collected in medium to large lumps and cylindrical samples were prepared in accordance with the orientation and position of parent rock mass (Verma et al., 2016). The thermal properties k, C and physical property ρ of rock were measured at the laboratory. The experimentally measured thermal and physical properties of Ganurgarh shales used in this study are given in Table 1 (Verma et al., 2016). Temperature dependent values of the parameters are not considered in our model.

Table 1: Thermal and physical properties of the Ganugarh shales

Property	Value
Thermal conductivity (W/m/K)	3.36
Specific heat (W/Kg/K)	850.0
Density(Kg/m^3)	2431.25

The radioactive waste disposal system considered in this study comprises a 2.05m long and 0.36m diameter overpack, containing heat emitting waste loaded SS canisters, emplaced in a 3.55m deep pit in Ganurgarh shale. As discussed in the introduction section, the concept of clay barrier surrounding the disposal pit is not taken as a separate engineered barrier. The separation between two disposal pits is 2.5m and spacing between two disposal tunnels is taken as 12m. These values of spacing between the two disposal pits and two disposal tunnels are kept same as used for granite host rock (Pal et al., 2016). The disposal facility with capacity to accommodate few thousands such canisters is normally located in the depth range of 500-700m depth in suitable sites. A quarter symmetry of the model geometry, comprising of one disposal pit and horseshoe shape disposal tunnel section of 4m × 4m, as shown in Figure 2, was created using FLAC3D software and was used for this study. The finite difference solver of FLAC3D is used to simulate the heat diffusion process governed by Eq. (1). Volumetric source term model is utilized to model the decaying heat source of the overpack.

Results and Discussion

A geothermal gradient of 0.024ºC/m was considered to calculate initial temperature of the shale at 500m depth. Considering temperature at the surface of earth as 35ºC, the temperature at DGR depth is 47ºC. No flux boundary condition is applied at all the symmetry planes (two XZ and two YZ planes) and constant temperature boundary condition was applied at the top and bottom surfaces. The value of the constant temperature at the top surface was 35ºC and at 450m below DGR depth temperature was fixed at 57.8ºC. The thermal flux of the source is modelled as an exponentially decaying term and is mathematically represented as

$$P(t) = P_o \exp(-\lambda t)$$

where P(t) is thermal flux of each overpack at time t, P_o is thermal flux of each overpack at the time of emplacement in disposal pit, λ is a constant parameter and its value is derived from the radiological properties such as half lives, isotopic compositions, Q values of the radionuclides present in the waste material. In this

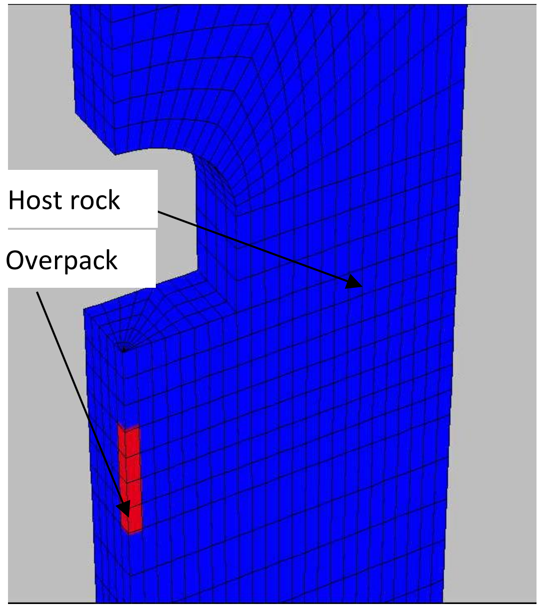

Fig. 2: FDM mesh for quarter symmetry model for near field study

study the value of λ is -7.32496×10^{-10}/s, which is a standard value used for Indian scenario. Two simulation studies were carried out with different values of initial thermal source term.

Case 1

In this case, the standard value of initial heat load of the Indian overpacks (500 W/overpack) was considered. The process was simulated for various heating periods of 1, 5 10, 20, 50 and 200 years. Results of the simulation in the form of contour plots of temperature are shown in Figs: 3.1-3.6. In order to find out maximum temperature and time required to attain that temperature, time dependent profile of temperature at various locations (canister surface, 1m, 2m, 3m, 4m, 5m and 6m away from the central canister's in a horizontal plane passing through the middle of canister's height) are plotted in Fig 3.7.

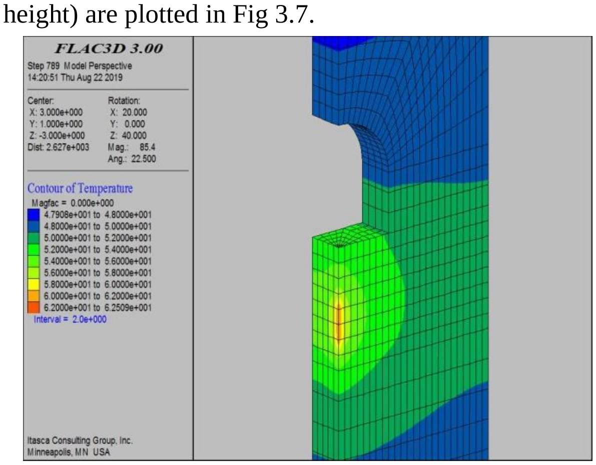

Fig 3.1. Temperature (ºC) contour after 1 years of heating

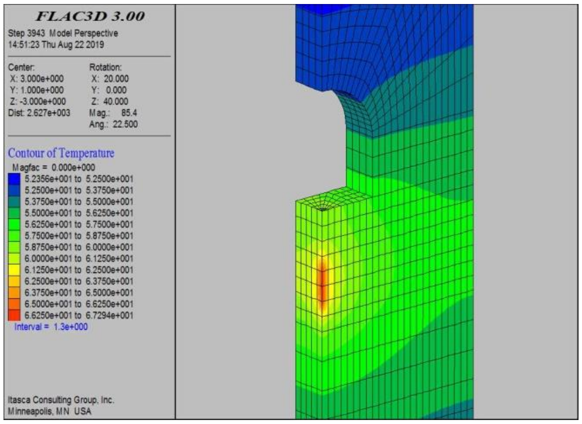

Fig 3.2. Temperature (ºC) contour after 5 years of heating

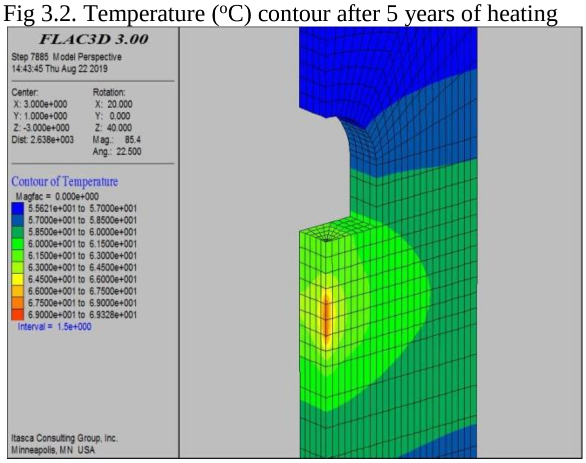

Fig 3.3. Temperature (ºC) contour after 10 years of heating

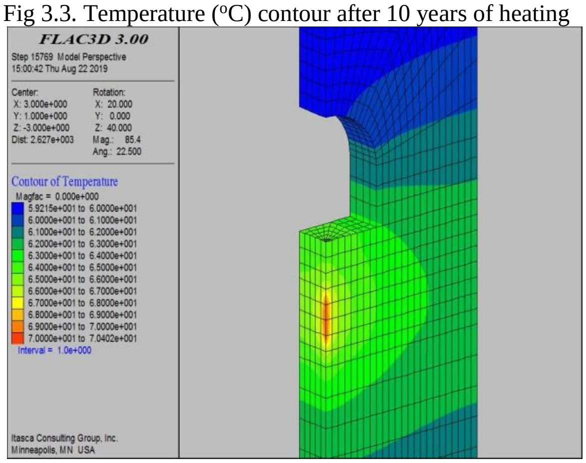

Fig 3.4. Temperature (ºC) contour after 20 years of heating

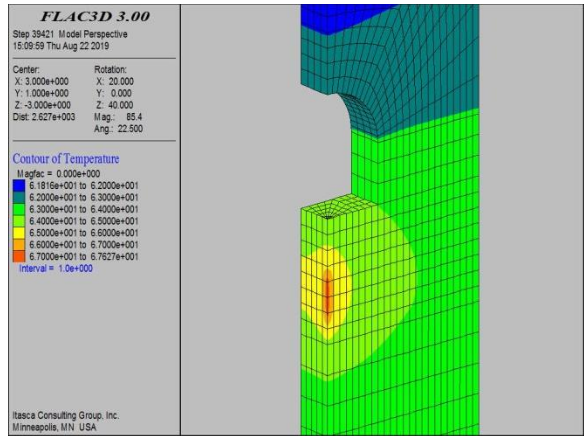

Fig 3.5. Temperature (ºC) contour after 50 years of heating

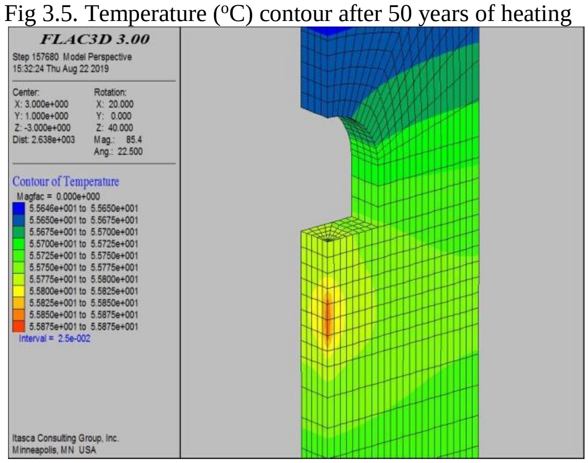

Fig 3.6. Temperature (ºC) contour after 200 years of heating

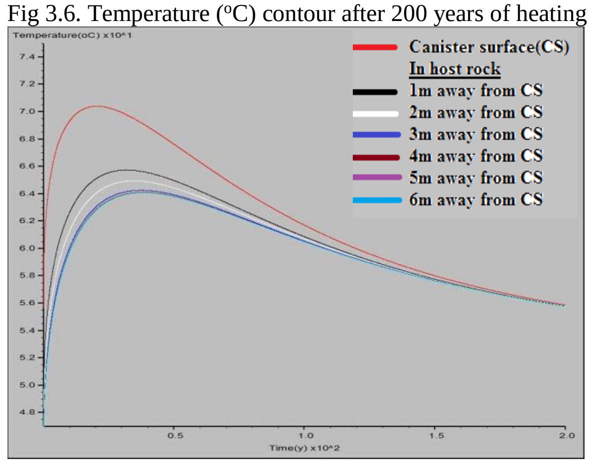

Fig 3.7. Time history of temperature at different locations in the repository.

Case 2

In this case, the initial heat load of the overpack is increased to 700 W/overpack. This higher heat load value could represent the overpacks with a lower cooling period before disposal in DGR and/or overpacks having higher waste loading factor. Similar to Case 1, this process is simulated for heating periods of 1, 5 10, 20, 50 and 200 years. Results of this simulation study in the form of contour plots of temperature are shown in Figs: 4.1-4.6 and time dependent temperature profiles are plotted in Fig 4.7

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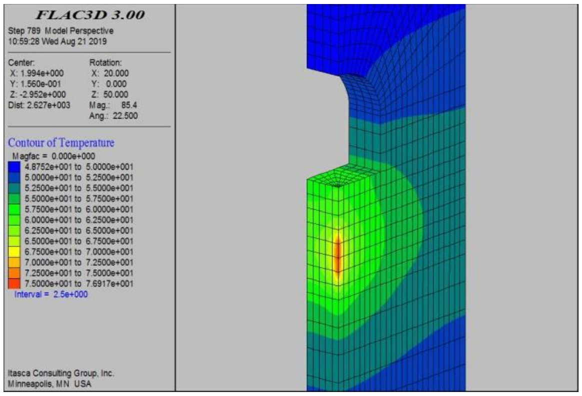

Fig 4.1. Temperature (ºC) contour after 1 year of heating

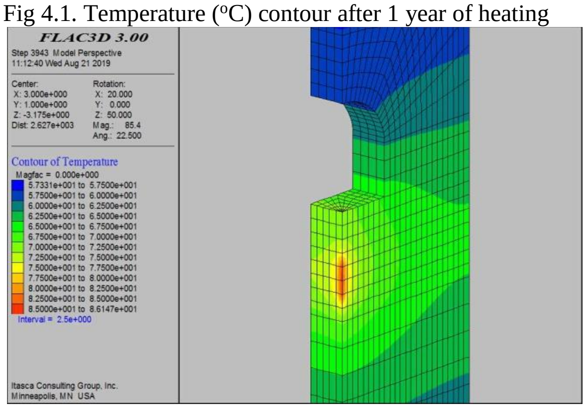

Fig 4.2. Temperature (ºC) contour after 5 years of heating

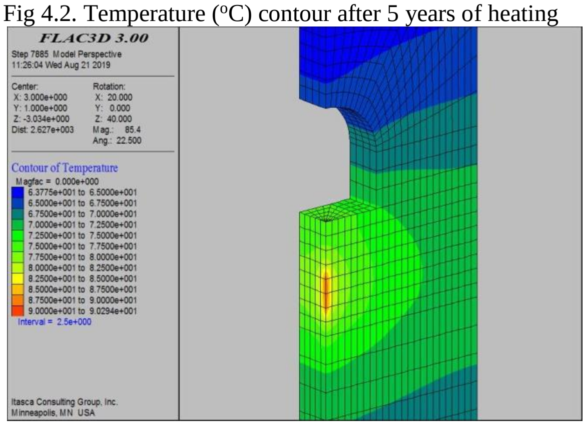

Fig 4.3. Temperature (ºC) contour after 10 years of heating

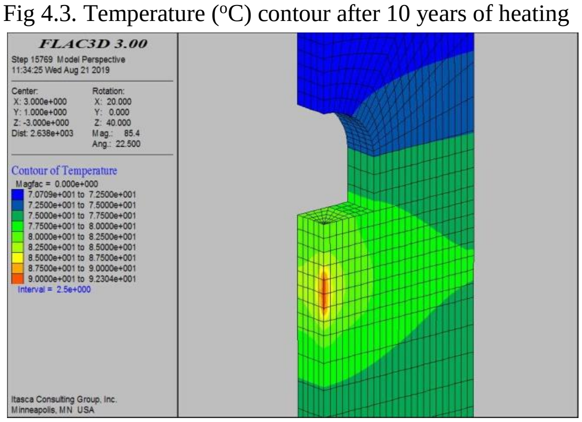

Fig 4.4. Temperature (ºC) contour after 20 years of heating

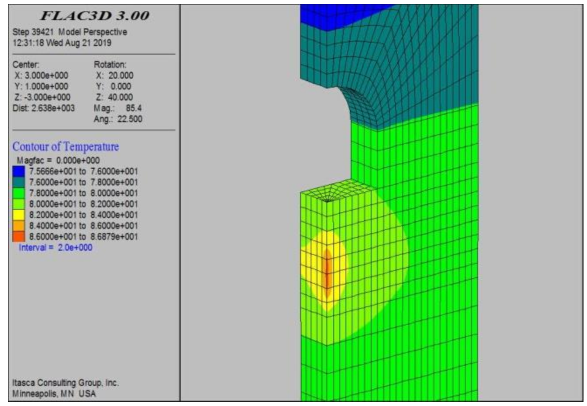

Fig 4.5. Temperature (ºC) contour after 50 years of heating

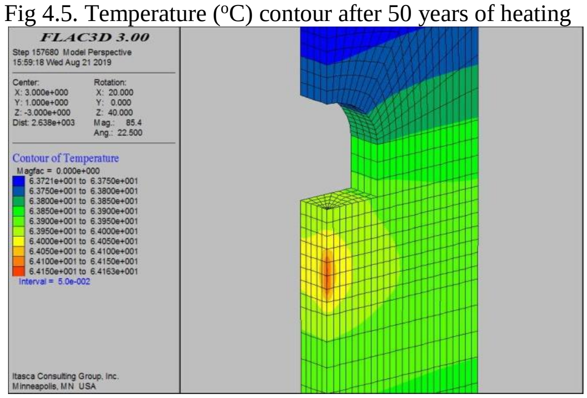

Fig 4.6. Temperature (ºC) contour after 200 years of heating

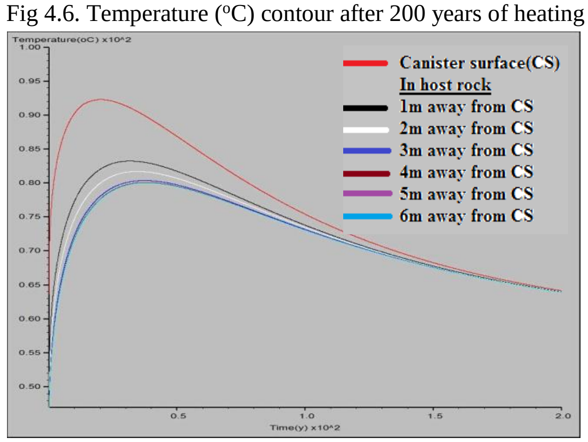

Fig 4.7. Time history of temperature at different locations in the repository

From Fig 3.1 and 4.1 it can be observed that maximum temperature of 62.5ºC and 76.92ºC are observed at canister surface after 1 year of heating. From the other contour plots, it can be found that an increase in temperature is observed up to 20 years of heating and, for 50 and 200 years of heating, decrease in temperature is observed. The time dependent plots of temperature, as shown in Fig 3.7 and 4.7, indicate that maximum temperature of 70.5ºC and 93ºC are attained at canister surface after 22 years of heating for the first and second source, respectively. Maximum temperature at other locations in the shales are observed with a slightly larger heating time periods and their values are also less than that observed at canister surface.

At a given temperature and pressure, thermal conductivity of a rock is highly dependent upon types of minerals composition and its micro and macro structural details, such as shape and size of the minerals, porosity, tortuosity, water saturation, etc. The thermal conductivity of Ganurgarh shales considered in this study is greater than other type of host rock and clay material used for such studies in India. For example, the thermal conductivities of the granite host rock and bentonite buffer used by Dutt et al. (2012) are 2.523 W/m/K and 1.47 W/m/K, respectively. The values are 2.30 W/m/K and 1.65 W/m/K as reported by Maheshwar et al. (2015b) for their studied granite host rock collected from near to Bhima basin of peninsular India. The higher thermal conductivity of the Ganurgarh shales than that of bentonite buffer material could be because of lower porosity of the shales compared to the bentonite materials reported in the above mentioned studies and for other properties which require further investigations. Bentonite buffer has less thermal conductivity than the host rock, so temperature build up occurs at the interface of canister and clay. But, since the rock studied here is argillaceous type, the concept of clay layer is not taken separately. This concept along with good thermal conductivity of the shales ensures smooth dissipation of heat in the near field of the repository.

Conclusions

Temperature field at various locations in the near field of a conceptual DGR in Ganurgarh shales of Vindhyan Super Group for different time periods of heating were calculated for two different thermal sources and the resulting temperature contour plots show that maximum temperature at any location within the near field of the DGR is below 100ºC, which is the maximum permissible limit of temperature. The results also indicate that initial heat flux of the overpack is an important parameter for the design of a DGR in terms of spacing between disposal pits and tunnels. The time dependent plots of temperature at various locations of the DGR show that maximum temperature of 70.5ºC and 93-ºC are attained at canister surface after 22 years of heating for the two sources, respectively. These plots are important for estimating time period of thermal evolution of a DGR system. It can, therefore, be concluded from this thermal analysis that the studied Ganurgarh shales possess adequate thermal characteristics to ensure smooth dissipation of heat across the waste in the near field areas. Finally, it is worth to mention here that feasibility of the site for radioactive waste disposal can never be ascertained by doing thermal analysis only. Systematic steps for site selection for DRG as recommended by international bodies, such as International Atomic Energy Agency (IAEA), Nuclear Energy Agency (NEA), World Health Organization (WHO) are needed to be followed before recommending any site for DGR. Nevertheless, the results of this thermal study show that the studied Ganurgarh shales can accommodate higher thermal load compared to the granite rocks studied in the Indian context. Therefore, from thermal point of view this type of rock having good thermal conductivity is more suitable than the granite rocks reported in Indian repository programme.

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