Calculations of the Temperature Evolution of a Repository for Spent Fuel in Crystalline and Sedimentary Rocks

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This report was prepared on behalf of Nagra. The viewpoints presented and conclusions reached are those of the author(s) and do not necessarily represent those of Nagra.
ABSTRACT

Thermal evolution is a factor influencing repository design, and must be considered in safety assessment, since many of the processes that affect the long-term safety are temperature dependent. This report presents calculations of the thermal evolution of a repository for spent nuclear fuel. The calculations are based on a provisional repository near-field design in which spent fuel is encapsulated in composite copper-steel canisters, which are emplaced centrally along the horizontal axes of repository tunnels, with the space around the canisters backfilled with bentonite.

The temperature of these near-field components varies with time, due to the radiogenic heat produced by the spent fuel. The rate of heat production per canister depends on the initial composition of the fuel, its reactor history, the period of intermediate storage before final disposal and the loading of the canisters. The rate decreases with time, as shorter-lived radionuclides decay. The base-case calculation considers spent fuel that is assumed to generate 1000 Watts per canister, 40 years after unloading of the fuel from the reactor. The results of the base case calculation indicate that the temperatures at the bentonite/host rock interface, at the centre of the bentonite and at the bentonite/canister interface rise to 98 °C, 103 °C and 126 °C, respectively, before declining towards the ambient temperature of the host rock which, in the base case, is taken to be the crystalline basement of Northern Switzerland.

In addition to the base case, parameter variations are examined that investigate the sensitivity of thermal evolution to alternative heat output, design specifications and to uncertainties in material properties. Key findings include (i), that an increase in heat generation to 1500 W per canister 40 years after unloading results in a significant increase of repository temperatures (e.g. at the bentonite/host rock interface, an increase of 22 °C is observed), (ii), that a decrease in tunnel spacing from 20 m (base case) to 10 m gives significantly increased temperatures, while an increase to 40 m has a less pronounced effect on thermal evolution, (iii), that the thermal properties of the bentonite and host rock are less sensitive parameters, with lower near-field temperatures calculated for increased thermal conductivities and heat capacities, (iv) that the presence of air gaps within and around the bentonite has little effect on thermal evolution, as do changes to longitudinal canister pitch and tunnel diameter and (v), that lower temperatures are calculated for a repository at a depth of 600 m in the Opalinus Clay host rock (principally due to the shallower repository depth and therefore lower ambient rock temperature) than for a repository at 1200 m depth in the crystalline basement of Northern Switzerland. Temperatures in the middle and outer parts of the bentonite are reduced by about 10 °C if the depth of the repository in crystalline is reduced to 900 m.
ZUSAMMENFASSUNG


Zusätzlich zum Referenzfall werden Parametervariationen untersucht, um die Sensitivität der Temperaturentwicklung auf alternative Wärmeleitwerte und Auslegungs-Spezifikationen sowie auf Ungewissheiten in den Materialeigenschaften zu prüfen. Wichtige Resultate sind im folgenden kurz zusammengefasst: (i) Eine Erhöhung der Wärmeleitrate auf 1500 W pro Behälter 40 Jahre nach Entnahme des Brennstoffs hat eine deutliche Zunahme der Endlagertemperaturen zur Folge (z.B. eine Zunahme um 22°C an der Grenzfläche Bentonit/Wirtgestein). (ii) Eine Verringerung des Stollenabstands von 20 m (Referenzfall) auf 10 m führt zu deutlich erhöhten Temperaturen; eine Erhöhung des Abstands auf 40 m hat dagegen einen weniger markanten Einfluss auf die Wärmeentwicklung. (iii) Die thermischen Eigenschaften des Bentonits und des Wirtgesteins sind weniger sensitive Parameter, wobei generell bei erhöhter Wärmeleitfähigkeit und Wärmeleitfähigkeit niedrigere Temperaturen im Nahfeld resultieren. (iv) Allfällig vorhandene, mit Luft gefüllte Spalten innerhalb und um den Bentonit, Änderungen des Abstands zwischen den Behältern entlang der Tunnelachse sowie Änderungen des Stollendurchmessers haben nur einen beschränkten Einfluss auf die Temperaturentwicklung. (v) Die berechneten Temperaturen für ein Endlager in 600 m Tiefe im Opalinuston sind niedriger als für ein Endlager in 1200 m Tiefe im kristallinen Grundgebirge der Nordschweiz. Der Hauptgrund ist die kleinere Endlagertiefe mit entsprechend niedrigerer Gesteinstemperatur. Entsprechend werden die Temperaturen in der Mitte und in den äußeren Bereichen des Bentonits um ca. 10°C reduziert, wenn die Endlagertiefe im Kristallin von 1200 m auf 900 m verringert wird.
RÉSUMÉ

L’évolution thermique est un facteur à prendre en considération dans les analyses de sûreté lors de la conception d’un dépôt de déchets radioactifs. En effet, de nombreux processus qui conditionnent la sûreté à long terme sont dépendants de la température. Ce rapport présente les résultats de calculs d’évolution thermique pour un dépôt de combustible nucléaire usagé. Ces calculs reposent sur un concept provisoire décrivant le champ proche d’un dépôt dans lequel le combustible usagé est placé dans des fûts composites d’acier et de cuivre entreposés suivant l’axe horizontal de galeries, les vides étant comblés à l’aide de bentonite.

La température des éléments de ce champ proche varie avec le temps, en raison de la chaleur émise par le combustible usagé. Le taux de chaleur qui se dégage des fûts dépend de la composition du combustible à l’origine, des conditions auxquelles il était exposé dans le réacteur, de la période de stockage intermédiaire avant le dépôt final et du taux de remplissage des fûts. Le taux de chaleur émis décroît avec le temps en raison de la désintégration des radionucléides à vie courte. Les calculs sont basés sur l’hypothèse d’un dégagement de chaleur de 1000 Watts par fût, ceci 40 ans après le retrait du combustible du réacteur. Ils indiquent que les températures à l’interface roche d’accueil / bentonite, au centre de la masse de bentonite et à l’interface bentonite / fût s’élèvent respectivement à 98°C, 103°C et 126°C, avant de décroître à la température ambiante de la roche d’accueil, ici le socle cristallin du nord de la Suisse (cas d’étude de base).

Par ailleurs, l’étude a porté sur les variations de paramètres permettant de déterminer la sensibilité de l’évolution thermique par rapport à la production de chaleur, aux spécifications conceptuelles du dépôt et aux incertitudes vis-à-vis des propriétés des matériaux. Les principaux résultats sont les suivants: (i) Un accroissement de la production de chaleur à 1500 Watts par fût 40 ans après le retrait du combustible du réacteur conduit à une augmentation significative des températures dans le dépôt (par exemple à l’interface roche d’accueil / bentonite, on observe une augmentation de la température de 22°C). (ii) Une réduction de l’espacement des galeries de 20 m (cas d’étude de base) à 10 m produit une augmentation substantielle de la température, tandis qu’une augmentation de cet espacement à 40 m produit un effet inverse moins prononcé. (iii) Les propriétés thermiques de la bentonite et de la roche d’accueil sont des paramètres moins sensibles (les températures du champ proche sont réduites si les conductivités et les capacités thermiques sont accrues). (iv) La présence d’air emprisonné dans la bentonite, ou autour d’elle, a peu d’influence sur l’évolution thermique du site, ce qui est également vrai pour l’espacement longitudinal des fûts et le diamètre des galeries. (v) Les températures calculées pour un dépôt à 600 m de profondeur dans les Argiles à Opalinus sont inférieures à celles calculées pour un dépôt à 1200 m de profondeur dans le socle cristallin du nord de la Suisse, principalement en raison de la moindre profondeur de dépôt et donc d’une température ambiante de la roche d’accueil plus faible. Les températures au milieu et dans les parties périphériques de la bentonite sont réduites d’environ 10°C si la profondeur du dépôt dans le socle cristallin est réduite à 900 m.
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1  INTRODUCTION

Temperature is a parameter affecting many of the safety-relevant processes occurring within the engineered barriers of a repository for spent fuel. Radioactive decay may generate high temperatures in the waste itself, in the canister that contains the waste and in the surrounding engineered materials. The aim of the present study is to examine the temperature distribution as a function of time, for a provisional repository design, in order to support future design studies and safety assessments.

The provisional repository design for spent-fuel disposal is broadly similar to that of Project Gewähr 1985 (NAGRA 1985) for vitrified high-level waste. Spent fuel is encapsulated in canisters that are emplaced centrally along the axes of parallel, horizontal repository tunnels, with the void space around the canisters backfilled with bentonite (Fig. 1). The following aspects of the repository design, however, differ from Project Gewähr 1985:

- **Canister materials.** The present spent-fuel calculations assume a steel canister with a copper outer shell (the outer shell is not present in the Project Gewähr 1985 design). Fuel rods are held in a steel rack with void spaces filled with quartz sand. This canister concept is based on the Finnish ACP canister (VIENO et al. 1992): Fig. 1. Further geometrical simplifications of the steel rack and spent fuel are made (radial symmetry) in order to facilitate calculations of temperature evolution (Fig. 2).

- **Canister dimensions.** The composite copper-steel canister has a diameter of 0.822 m and a length of 4.8 m (compared to 0.94 m and 1.7 m, respectively, in Project Gewähr 1985).

- **Thermal output.** The canister inventory for spent-fuel has not yet been fixed (the results of temperature-evolution calculations will provide input for these considerations). For the present study, two alternative hypothetical fuels are considered (a base-case fuel and a variation with higher thermal output). In both cases, heat production is based on a scaling of data from TVO 92 (VIENO et al. 1992), with different scaling factors to cover uncertainties associated with, for example, burn-up.
In order to determine the sensitivity of temperature evolution to alternative design specifications and to uncertainties in material properties, a base-case repository layout is defined and the temperature evolution calculated. A number of variations on the base case are then evaluated. The specifications of the base case and variations are presented in Chapter 2. The method used for the modelling of temperature evolution is described in Chapter 3. Results of the base case and variations are given in Chapter 4. Finally, the results are discussed and conclusions are drawn in Chapter 5.
Fig. 2: Dimensions of geometrically simplified, analytical model of spent fuel and canister [mm]. The radii for the spent fuel and the steel rack are obtained assuming unchanged volumes of these units in the radially symmetric representation.
2 BASE CASE AND VARIATIONS

In the present study, the sensitivity to the following parameters is investigated:

- Horizontal emplacement tunnel spacing (centre of one tunnel to the next).

  A base case tunnel spacing (Fig. 1) of $Sh = 20$ m is selected, with parameter variations of $Sh = 10$ m and $Sh = 40$ m.

- The thermal properties of the bentonite.

  The thermal properties of bentonite are complex, with the thermal conductivity and heat capacity being functions of water content and, in the case of thermal conductivity, temperature (water content may itself be a function of temperature, although the form of this function is highly uncertain). This complexity is not explored in detail in the present study. Rather, the following two sets of (fixed) bentonite properties are selected as being representative of "wet" and "dry" bentonite:

  Type A ("dry"): Thermal conductivity $0.7 \text{ W m}^{-1} \text{ K}^{-1}$, heat capacity $1.1 \text{ MJ m}^{-3} \text{ K}^{-1}$ (base case),

  Type B ("wet"): Thermal conductivity $1.7 \text{ W m}^{-1} \text{ K}^{-1}$, heat capacity $2.1 \text{ MJ m}^{-3} \text{ K}^{-1}$.

- The existence of air gaps within the bentonite.

  At the time of repository closure, air gaps may exist between the canister and the bentonite, between bentonite blocks (i.e. midway between the canister and the tunnel wall) and between the bentonite and the rock. As the bentonite resaturates and swells, these gaps will close but, while they exist, they may affect the evolution of the temperature field (which will itself affect resaturation). The lifetime of the air gaps is uncertain due to uncertainties in the rate of resaturation. Air gaps are not considered in the base case, but additional calculations are performed to evaluate their effects. In these additional calculations, two air gaps are assumed, each with a width of 10 mm, and located at the canister/bentonite interface and the bentonite/host-rock interface, respectively.

- Canister pitch: i.e. the distance from the centre of one canister to the next along an emplacement tunnel.

  A pitch (Fig. 1) of $L_p = d + 3$ m is taken as the base case, where $d = 4.8$ m is the canister length, with parameter variations of $d + 5$ m and $d + 7$ m.

- Heat production from the spent fuel.

  In the present study, heat production from the spent fuel is based on data from TVO 92 (VIENO et al. 1992). Because of uncertainties associated with, for example, burn-up, these data are normalised to yield, in the base case, 1000 W at 40 years after unloading of the fuel from the reactor (the starting time for temperature-evolution calculations). This fuel is referred to as "Type 1". A variation of this fuel, "Type 2", is defined as
having a heat production 1.5 times higher than Type 1. The evolutions of heat production for spent fuel of Type 1 and Type 2 are presented in Table 1 and in Fig. 3.

Fig. 3: Heat production of a single spent-fuel canister assumed for the thermal calculations of the present study (based on VIENO et al. 1992).

- The host rock.

The crystalline basement of Northern Switzerland and the Opalinus Clay have been identified as potential repository host rocks and both rocks are considered in the present study. In the base case, the repository is assumed to be located in the crystalline basement of Northern Switzerland, at a depth of 1200 m. Alternative cases are based on a shallower repository (900 m depth) in the crystalline basement of Northern Switzerland and on a repository at a depth of 600 m in the Opalinus Clay. The following properties relevant to temperature evolution are assumed for the two rock types:

- Crystalline Basement: initial temperature at repository depth = 55 °C at 1200 m (base case), and also, in a variant case, 45°C at 900 m, thermal conductivity =
2.5 W m\(^{-1}\) K\(^{-1}\) (base case), with variants of 2.0 W m\(^{-1}\) K\(^{-1}\) and 3.0 W m\(^{-1}\) K\(^{-1}\), heat capacity = 2.3 MJ m\(^{-3}\) K\(^{-1}\) (base case), with variants of 1.8 MJ m\(^{-3}\) K\(^{-1}\) and 2.8 MJ m\(^{-3}\) K\(^{-1}\), temperature gradient = 3°C per 100 m.

- Opalinus Clay: initial temperature at repository depth (600 m) = 35°C, temperature gradient = 4.12°C per 100 m, thermal conductivity = 2.2 W m\(^{-1}\) K\(^{-1}\), heat capacity = 2.0 MJ m\(^{-3}\) K\(^{-1}\).

- The tunnel diameter.

For the crystalline basement, a base-case tunnel diameter of 3.7 m is assumed, with a parameter variation of 2.4 m. For Opalinus Clay, the 3.7 m tunnel diameter is not considered to be a practical option for reasons of mechanical stability. A tunnel diameter of 2.4 m is thus assumed for all Opalinus Clay calculations.

The thermal properties and initial temperatures of the various materials modelled in the present study are presented in Table 2. The combinations of parameters in the base-case calculations and in parameter-variation studies are given in Table 3.

Table 1: Evolution of decay heat from Type 1 and Type 2 hypothetical spent fuels.

<table>
<thead>
<tr>
<th>Cooling Time (a)</th>
<th>Decay Heat (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type-1 Spent Fuel</td>
</tr>
<tr>
<td>0</td>
<td>1.90 x 10(^6)</td>
</tr>
<tr>
<td>1</td>
<td>12 135</td>
</tr>
<tr>
<td>40</td>
<td>1 000</td>
</tr>
<tr>
<td>100</td>
<td>486</td>
</tr>
<tr>
<td>1 000</td>
<td>89</td>
</tr>
<tr>
<td>10 000</td>
<td>20</td>
</tr>
<tr>
<td>100 000</td>
<td>1.35</td>
</tr>
<tr>
<td>1 000 000</td>
<td>0.68</td>
</tr>
</tbody>
</table>
### Table 2: Thermal properties and initial temperatures of materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W m⁻¹ K⁻¹)</th>
<th>Heat Capacity (MJ m⁻³ K⁻¹)</th>
<th>Initial Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spent fuel</td>
<td>6.1</td>
<td>3.19</td>
<td>65</td>
</tr>
<tr>
<td>Steel Rack</td>
<td>52</td>
<td>3.05</td>
<td>65</td>
</tr>
<tr>
<td>Quartz Sand</td>
<td>52</td>
<td>1.26</td>
<td>65</td>
</tr>
<tr>
<td>Carbon Steel</td>
<td>52</td>
<td>3.05</td>
<td>65</td>
</tr>
<tr>
<td>Copper</td>
<td>380</td>
<td>3.44</td>
<td>65</td>
</tr>
<tr>
<td>Air</td>
<td>3.17 x 10⁻²</td>
<td>9.56 x 10⁻⁴</td>
<td>65</td>
</tr>
<tr>
<td>Bentonite:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type A</td>
<td>0.7</td>
<td>1.1</td>
<td>35</td>
</tr>
<tr>
<td>Type B</td>
<td>1.7</td>
<td>2.1</td>
<td>35</td>
</tr>
<tr>
<td>Host Rock:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crystalline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KRI-1</td>
<td>2.5</td>
<td>2.3</td>
<td>55 (at 1200 m)</td>
</tr>
<tr>
<td>KRI-2</td>
<td>2.5</td>
<td>2.3</td>
<td>45 (at 900 m)</td>
</tr>
<tr>
<td>KRI-3</td>
<td>2.0</td>
<td>2.3</td>
<td>55 (at 1200 m)</td>
</tr>
<tr>
<td>KRI-4</td>
<td>3.0</td>
<td>2.3</td>
<td>55 (at 1200 m)</td>
</tr>
<tr>
<td>KRI-5</td>
<td>2.5</td>
<td>1.8</td>
<td>55 (at 1200 m)</td>
</tr>
<tr>
<td>KRI-6</td>
<td>2.5</td>
<td>2.8</td>
<td>55 (at 1200 m)</td>
</tr>
<tr>
<td>Opalinus Clay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPA</td>
<td>2.2</td>
<td>2.0</td>
<td>35 (at 600 m)</td>
</tr>
</tbody>
</table>

1. Does not include contribution of radiation across the gap.
2. Temperature gradient is 0.03 °C m⁻¹ for crystalline.
3. Temperature gradient is 0.0412 °C m⁻¹ for Opalinus Clay.
Table 3: Calculations performed for the study of the temperature evolution of a repository for the direct disposal of spent fuel. Highlighted boxes indicate variations from the base case.

<table>
<thead>
<tr>
<th>Analysis Case</th>
<th>Lp* (m)</th>
<th>Sh** (m)</th>
<th>Bentonite Type</th>
<th>Air Gaps</th>
<th>Heat Production (type)</th>
<th>Tunnel Diameter (m)</th>
<th>Host Rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (base case)</td>
<td>d+3</td>
<td>20</td>
<td>A</td>
<td>no</td>
<td>1</td>
<td>3.7</td>
<td>KRI-1</td>
</tr>
<tr>
<td>2</td>
<td>d+5</td>
<td>20</td>
<td>A</td>
<td>no</td>
<td>1</td>
<td>3.7</td>
<td>KRI-1</td>
</tr>
<tr>
<td>3</td>
<td>d+7</td>
<td>20</td>
<td>A</td>
<td>no</td>
<td>1</td>
<td>3.7</td>
<td>KRI-1</td>
</tr>
<tr>
<td>4</td>
<td>d+3</td>
<td>10</td>
<td>A</td>
<td>no</td>
<td>1</td>
<td>3.7</td>
<td>KRI-1</td>
</tr>
<tr>
<td>7</td>
<td>d+3</td>
<td>40</td>
<td>A</td>
<td>no</td>
<td>1</td>
<td>3.7</td>
<td>KRI-1</td>
</tr>
<tr>
<td>10</td>
<td>d+3</td>
<td>20</td>
<td>B</td>
<td>no</td>
<td>1</td>
<td>3.7</td>
<td>KRI-1</td>
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<tr>
<td>11</td>
<td>d+3</td>
<td>20</td>
<td>A</td>
<td>yes</td>
<td>1</td>
<td>3.7</td>
<td>KRI-1</td>
</tr>
<tr>
<td>1B</td>
<td>d+3</td>
<td>20</td>
<td>A</td>
<td>no</td>
<td>2</td>
<td>3.7</td>
<td>KRI-1</td>
</tr>
<tr>
<td>7B</td>
<td>d+3</td>
<td>40</td>
<td>A</td>
<td>no</td>
<td>2</td>
<td>3.7</td>
<td>KRI-1</td>
</tr>
<tr>
<td>1C</td>
<td>d+3</td>
<td>20</td>
<td>A</td>
<td>no</td>
<td>1</td>
<td>2.4</td>
<td>KRI-1</td>
</tr>
<tr>
<td>7C</td>
<td>d+3</td>
<td>40</td>
<td>A</td>
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</table>

(*): Lp: longitudinal canister pitch (d [m] = canister length),
(**): Sh: horizontal tunnel spacing.
3 NUMERICAL MODELLING OF TEMPERATURE EVOLUTION

In the present study, the three-dimensional governing equations for temperature evolution are solved using the ADINA-T program (Automatic Dynamic Incremental Non-linear Analysis of Temperatures). The solution methodology is based on the finite-element formulation of the non-steady and non-linear heat-flow algorithm described in ROLPH & BATHE (1982). In reality, heat transport occurs predominantly by conduction and, if air gaps are present, by radiation. In the model, only conduction is considered, with the thermal conductivity of air (i.e. the value in Table 2) modified to take the effect of radiation into account. The temperature-dependence of the thermal properties of near-field materials is likely to be unimportant in its effects compared to other uncertainties. In the present study, therefore, the thermal conductivities and heat capacities of all materials are assumed to be temperature independent.

The geometry of the computational-analysis domain is illustrated in Figs. 4 and 5. The boundary conditions are illustrated in Fig. 6. For reasons of symmetry, the vertical sides of the analysis domain are all assumed to be zero-flux boundaries. The vertical extent of the domain above and below the repository is assumed to be sufficient that the ambient temperature of the rock at the top and bottom boundaries is unperturbed by the presence of the repository, so that these can be assigned constant temperatures. Fig. 7 illustrates one example of the three-dimensional finite-element meshes used in the present study.

Fig. 4: Vertical section of the analysis domain.
Fig. 5: Horizontal section of the analysis domain.

Fig. 6: Three-dimensional model representation and boundary conditions.
Fig. 7: Three-dimensional finite-element mesh for the present study.
4 RESULTS OF TEMPERATURE EVOLUTION

4.1 Output Points

Fig. 8 shows the locations of points within the computational-analysis domain where the temperature evolution is output in the numerical simulations of a spent-fuel repository. Point 0 lies at the centre of the canister. Points \( L_1 \), \( L_2 \) and \( L_3 \) lie along the tunnel/canister axis, with \( L_3 \) lying in the tunnel, midway between canisters. Points \( H_1 \), \( H_2 \), \( H_3 \), \( H_4 \) and \( H_5 \) lie along the horizontal radial direction, with \( H_5 \) lying in the rock, midway between tunnels.

Fig. 8: Nodes indicated in the results of the present study.
4.2 Base-Case Results

The base-case results are presented in Figs. A1.1.1, A1.1.2, and A5.1. The following points are noted:

- for the base-case spent-fuel type, with a heat output per canister of 1000 W at 40 a after unloading from the reactor, the bentonite furthest away from the canister never experiences temperatures above 98°C,
- the maximum bentonite temperature in the base case is 126°C and occurs at the canister/bentonite interface at about 15 a after emplacement,
- at about 800 a after emplacement, the temperature at the canister/bentonite interface falls below 100°C.

4.3 Parameter Variations

4.3.1 Horizontal Tunnel Spacing

The base-case tunnel spacing of 20 m is reduced to 10 m in analysis no. 4 (Figs. A1.4.1 and A1.4.2), and increased to 40 m in analysis no. 7 (Figs. A1.7.1 and A1.7.2). Comparing the temperature evolutions at various points in these figures with the corresponding points in the base case (Figs. A1.1.1 and A1.1.2), it can be seen that a reduction in tunnel spacing to 10 m causes marked increases in temperature, whereas an increase in tunnel spacing to 40 m has a less pronounced impact.

Temperature profiles at the times of maximum bentonite temperature in analyses nos. 1, 4 and 7 are plotted in Fig. A4.1. Considering the temperature at the inner boundary, the middle and the outer boundary of the bentonite (i.e. points H1, H2 and H3):

- A reduction in tunnel spacing from the base case (20 m) to 10 m causes:
  - an increase in the maximum temperature in the middle of the bentonite from 103°C to 143°C and, at the outer boundary of the bentonite, from 98°C to 139°C (see Fig. 9),
  - an increase in the length of time during which higher temperatures exist in the bentonite (see Figs. 10, A3.1.1 and A3.1.2).

- An increase in tunnel spacing from the base case to 40 m causes:
  - a decrease in the maximum temperature in the middle of the bentonite from 103°C to 90°C and, at the outer boundary of the bentonite, from 98°C to 79°C (see Fig. 9),
  - a decrease in the length of time during which higher temperatures exist in the bentonite (see Figs. 10, A3.1.1 and A3.1.2).
In conclusion:

**Horizontal tunnel spacing becomes a sensitive parameter for spacings less than about 20 m. For higher spacings, the maximum bentonite temperature is less sensitive to tunnel spacing, although the period over which higher temperatures exist remains sensitive.**

---

**Fig. 9: Maximum bentonite temperature of each analysis.**
Fig. 10: Duration of the period when bentonite temperature exceeds 100 °C in each analysis. 100 °C is selected as an (arbitrary) reference temperature, in order to indicate the period of time over which higher temperatures persist.
4.3.2 **Longitudinal Pitch of Spent-Fuel Canisters**

The base-case longitudinal canister pitch of \( d + 3 \) m (where \( d \) is the canister length of 4.8 m) is increased to \( d + 5 \) m in analysis no. 2 (Figs. A1.2.1 and A1.2.2), and further increased to \( d + 7 \) m in analysis case 3 (Figs. A1.3.1 and A1.3.2). Comparing the temperature evolutions at various points in these figures with the corresponding points in the base case (Figs. A1.1.1 and A1.1.2), it can be seen that increases in canister pitch reduce the calculated temperatures but that the impact is relatively small (compared, for example, to tunnel spacing) and there is less difference between results for the \( d + 5 \) m pitch and the \( d + 7 \) m pitch than there is between results for the \( d + 3 \) m pitch and the \( d + 5 \) m pitch.

Temperature profiles at the times of maximum bentonite temperature in analyses nos. 1, 2 and 3 are plotted in Fig. A4.2. Considering the temperature at the inner boundary, the middle and the outer boundary of the bentonite (i.e. points H1, H2 and H3):

- An increase in longitudinal canister pitch from the base case (\( d + 3 \) m) to \( d + 5 \) m causes:
  - a decrease in the maximum temperature in the middle of the bentonite from 103 °C to 96 °C and, at the outer boundary of the bentonite, from 98 °C to 90 °C (see Fig. 10),
  - a decrease in the length of time during which higher temperatures exist in the bentonite (see Figs. 10, A3.2.1 and A3.2.2).

- A further increase in longitudinal canister pitch to \( d + 7 \) m causes:
  - a further decrease in the maximum temperature in the middle of the bentonite to 92 °C and, at the outer boundary of the bentonite, to 84 °C (see Fig. 9),
  - a (relatively small) further decrease in the length of time during which higher temperatures exist in the bentonite (see Figs. 10, A3.2.1 and A3.2.2).

In conclusion:

> Longitudinal pitch for spent-fuel canisters is a relatively insensitive parameter.

4.3.3 **Thermal Properties of Bentonite**

The base-case thermal conductivity and heat capacity of bentonite are increased from 0.7 W m\(^{-1}\) K\(^{-1}\) and 1.1 MJ m\(^{-3}\) K\(^{-1}\), respectively (Type A) to 1.7 W m\(^{-1}\) K\(^{-1}\) and 2.1 MJ m\(^{-3}\) K\(^{-1}\), respectively (Type B) in analysis no. 10. Temperature evolutions at various points in analysis no. 10 are plotted in Figs. A1.10.1 and A1.10.2.

Temperature profiles at the times of maximum bentonite temperature in analyses nos. 1 and 10 are plotted in Fig. A4.3. Considering the temperature at the inner boundary, the middle and the outer boundary of the bentonite (i.e. points H1, H2 and H3):
• An increase in the assumed thermal conductivity and heat capacity for bentonite causes:
  
  - a decrease in the maximum temperature in the middle of the bentonite from 103 °C to 100 °C, but almost no change in the maximum temperature at the outer boundary of the bentonite (see Fig. 9),
  
  - a decrease in the length of time during which higher temperatures exist in the bentonite (see Fig. 10).

In conclusion:

Slightly lower temperatures in the spent-fuel repository near field are calculated if the assumed thermal conductivity and heat capacity of bentonite are increased.

4.3.4 Consideration of the Existence of Air Gaps

The presence of air gaps between the canister and the bentonite, between bentonite blocks and between the bentonite and the rock is disregarded in the base case, but is included in analysis no. 11. Temperature evolutions at various points in analysis no. 11 are plotted in Figs. A1.11.1 and A1.11.2.

Temperature profiles at the times of maximum bentonite temperature in analyses nos. 1 and 11 are plotted in Fig. A4.4. Considering the temperature at the inner boundary, the middle and the outer boundary of the bentonite (i.e. points H1, H2 and H3):

• The presence of air gaps in temperature-evolution calculations causes:
  
  - an increase in the maximum temperature in the middle of the bentonite from 103 °C to 106 °C and, at the outer boundary of the bentonite, from 98 °C to 99 °C (see Fig. 9),
  
  - a (small) decrease in the length of time during which higher temperatures exist in the bentonite (see Fig. 10).

In conclusion:

Higher temperatures are calculated in the bentonite if the presence of air gaps is assumed, but the effect of air gaps is small.

4.3.5 Heat Production by the Spent Fuel (Crystalline Host Rock)

Heat production by the spent fuel is increased by a factor of 1.5 in analyses nos. 1B and 7B (hypothetical fuel Type 2) with respect to the base case (Type 1). In analysis no. 1B, the base-case horizontal tunnel spacing of 20 m is assumed (as in analysis no. 1 for Type
In analysis no. 7B, an increased horizontal tunnel spacing of 40 m is assumed (as in analysis no. 7 for Type 1 fuel). Temperature evolutions at various points in analysis no. 1B are plotted in Figs. A1.1b.1 and A1.1b.2. Temperature evolutions at various points in analysis no. 7b are plotted in Figs. A1.7b.1 and A1.7b.2.

Temperature profiles at the times of maximum bentonite temperature in analyses nos. 1 and 1B (20 m horizontal tunnel spacing) are plotted in Fig. A4.5 and, for analyses 7 and 7B (40 m tunnel spacing), in Fig. A4.6. The profiles for an increased heat production and for 20 m and for 40 m tunnel spacings are compared in Fig. A4.11. Considering the temperature at the inner boundary, the middle and the outer boundary of the bentonite (i.e. points H1, H2 and H3):

- For a 20 m horizontal tunnel spacing, an increase in the heat production by the spent fuel by a factor of 1.5 causes:
  - an increase in the maximum temperature in the middle of the bentonite from 103 °C to 128 °C and, at the outer boundary of the bentonite, from 98 °C to 120 °C (see Fig. 9),
  - an increase in the length of time during which higher temperatures exist in the bentonite (see Fig. 10).

- For a 40 m horizontal tunnel spacing, the same increase in the heat production by the spent fuel causes:
  - an increase in the maximum temperature in the middle of the bentonite from 90 °C to 108 °C and, at the outer boundary of the bentonite, from 79 °C to 91 °C (see Fig. 9),
  - an increase in the length of time during which higher temperatures exist in the bentonite (see Fig. 10).

In conclusion:

Heat production by spent fuel is a significant factor in the prediction of the temperature evolution of the repository. The finding for the base-case heat production (Section 4.3.1) that, for horizontal tunnel spacings exceeding 20 m, the maximum bentonite temperature becomes less sensitive to tunnel spacing, but that the time during which elevated temperatures exist in the bentonite is a more sensitive parameter, is also true for an increased heat production.

4.3.6 Tunnel Diameter

The base-case tunnel diameter of 3.7 m in crystalline rock is decreased to 2.4 m in analyses 1C and 7C. In analysis no. 1C, the base-case horizontal tunnel spacing of 20 m is assumed (as in analysis no. 1 for a 3.7 m tunnel diameter). In analysis no. 7C, an increased
horizontal tunnel spacing of 40 m is assumed (as in analysis no. 7 for a 3.7 m tunnel di-
ameter). Temperature evolutions at various points in analysis no. 1C are plotted in Figs. A1.1c.1 and A1.1c.2. Temperature evolutions at various points in analysis no. 7C are plotted in Figs. A1.7c.1 and A1.7c.2.

Temperature profiles at the times of maximum bentonite temperature in analyses nos. 1 and 1C (20 m horizontal tunnel spacing) are plotted in Fig. A4.7 and, for analyses 7 and 7C (40 m tunnel spacing), in Fig. A4.8. The profiles for a reduced tunnel diameter and for 20 m and for 40 m tunnel spacings are compared in Fig. A4.12. Considering the temperature at the inner boundary, the middle and the outer boundary of the bentonite (i.e. points H1, H2 and H3):

- For a 20 m horizontal tunnel spacing, a decrease in the tunnel diameter from 3.7 m to 2.4 m causes:
  - a slight increase in the maximum temperature in the middle of the bentonite from 103 °C to 104 °C and, at the outer boundary of the bentonite, a slight increase from 98 °C to 99 °C (see Fig. 9),
  - a small decrease in the length of time during which higher temperatures exist in the bentonite (see Fig. 10).

- For a 40 m horizontal tunnel spacing, the same decrease in tunnel diameter causes:
  - an increase in the maximum temperature in the middle of the bentonite from 90 °C to 91 °C and, at the outer boundary of the bentonite, from 79 °C to 81 °C (see Fig. 9),
  - again, a small decrease in the length of time during which higher temperatures exist in the bentonite (see Fig. 10).

In conclusion:

The tunnel diameter is an insensitive parameter from the point of view of thermal evolution of the repository, for horizontal tunnel spacings of both 20 m and 40 m.
4.3.7 Host-Rock Type

The thermal properties of the host rock are varied from those of the base-case rock type (the crystalline basement of Northern Switzerland) to those of the Opalinus Clay in analyses 1D and 7D (hypothetical fuel Type 1) and in analyses 1E and 7E (hypothetical fuel Type 2)\(^1\). The effects of fuel type within the Opalinus Clay host rock are discussed in Section 4.3.8. For the Opalinus Clay, a reduced tunnel diameter of 2.4 m is assumed for reasons of mechanical stability, and therefore an appropriate comparison is with analyses 1C and 7C (crystalline rock with a reduced tunnel diameter of 2.4 m - see Section 4.3.6). Also, the depth of the repository in the Opalinus Clay is considerably less than in the crystalline, resulting in a lower initial temperature. In analyses nos. 1D (and 1E), the base-case horizontal tunnel spacing of 20 m is assumed (as in analysis no. 1C for a crystalline host rock). In analyses nos. 7D (and 7E), an increased horizontal tunnel spacing of 40 m is assumed (as in analysis no. 7C for a crystalline host rock). Temperature evolutions at various points in analyses nos. 1D and 1E are plotted in Figs. A1.1d.1, A1.1d.2, A1.1e.1 and A1.1e.2. Temperature evolutions at various points in analyses nos. 7D and 7E are plotted in Figs. A1.7d.1, A1.7d.2, A1.7e.1 and A1.7e.2.

Temperature profiles at the times of maximum bentonite temperature in analyses nos. 1C and 1D (20 m horizontal tunnel spacing) are plotted in Fig. A4.9 and, for analyses 7C and 7D (40 m tunnel spacing), in Fig. A4.10. The profiles for an Opalinus Clay host rock and for 20 m and for 40 m tunnel spacings are compared in Fig. A4.13. Considering the temperature at the inner boundary, the middle and the outer boundary of the bentonite (i.e. points H1, H2 and H3):

- For a 20 m horizontal tunnel spacing, the change in host-rock thermal properties from those of the crystalline basement of Northern Switzerland to those of the Opalinus Clay causes:
  - a decrease in the maximum temperature in the middle of the bentonite from 104 °C to 90 °C and, at the outer boundary of the bentonite, from 99 °C to 85 °C (see Fig. 9),
  - a decrease in the length of time during which higher temperatures exist in the bentonite (see Fig. 10).

- For a 40 m horizontal tunnel spacing, the same change in thermal properties (host-rock type) causes:
  - a decrease in the maximum temperature in the middle of the bentonite from 91 °C to 75 °C and, at the outer boundary of the bentonite, from 81 °C to 65 °C (see Fig. 9),
  - there to exist no time during which the (arbitrary) reference temperature of 100 °C is exceeded in the bentonite.

\(^1\) Variations around the base case of the thermal properties of the crystalline basement of Northern Switzerland are discussed in Sections 4.3.9 and 4.3.10.
In conclusion:

In spite of its slightly lower thermal conductivity, lower temperatures are calculated for a repository in the Opalinus Clay host rock, because of the shallower depth and therefore lower ambient temperature. The effects are relatively small in the inner parts of the repository (e.g. the canister/bentonite interface).

4.3.8 Heat Production by the Spent Fuel (Opalinus Clay Host Rock)

Temperature profiles at the times of maximum bentonite temperature in analyses nos. 1D and 1E (20 m horizontal tunnel spacing) are plotted in Fig. A4.16 and, for analyses 7D and 7E (40 m tunnel spacing), in Fig. A4.17. The profiles for an increased heat production and for 20 m and for 40 m tunnel spacings are compared in Fig. A4.18. Considering the temperature at the inner boundary, the middle and the outer boundary of the bentonite (i.e. points H1, H2 and H3):

- For a 20 m horizontal tunnel spacing, an increase in the heat production by the spent fuel by a factor of 1.5 causes:
  - an increase in the maximum temperature in the middle of the bentonite from 90 °C to 118 °C and, at the outer boundary of the bentonite, from 85 °C to 111 °C (see Fig. 9),
  - a (relatively large) increase in the length of time during which higher temperatures exist in the bentonite (see Fig. 10).

- For a 40 m horizontal tunnel spacing, the same increase in the heat production by the spent fuel causes:
  - an increase in the maximum temperature in the middle of the bentonite from 75 °C to 95 °C and, at the outer boundary of the bentonite, from 65 °C to 80 °C (see Fig. 9),
  - there to exist a short period during which temperatures in the bentonite exceed the (arbitrary) reference value of 100 °C; no such period exists for the lower heat production (see Fig. 10).

In conclusion:

As in the case of a crystalline host rock, heat production by spent fuel is a significant factor in the prediction of the temperature evolution of a repository in Opalinus Clay. Again, for horizontal tunnel spacings exceeding 20 m, the maximum bentonite temperature becomes less sensitive to tunnel spacing.
4.3.9 Repository Depth

The base-case ambient rock temperature at repository depth in the crystalline basement of Northern Switzerland is decreased from 55 °C to 45 °C in analysis 1F (fuel Type 1) and analyses 7F and 1G (fuel Type 2). For the assumed geothermal temperature gradient of 0.03 °C m⁻¹, this corresponds to a reduction in repository depth of about 300 m. In analysis no. 7F, an increased horizontal tunnel spacing of 40 m is assumed. Temperature evolutions at various points in analyses nos. 1F and 1G are plotted in Figs. A1.1f.1, A1.1f.2, A1.1g.1 and A1.1g.2. Temperature evolutions at various points in analysis no. 7F are plotted in Figs. A1.7f.1 and A1.7f.2.

Temperature profiles at the times of maximum bentonite temperature in analyses nos. 1F, 1G and 7F are plotted in Fig. A4.20. Considering the temperature at the inner boundary, the middle and the outer boundary of the bentonite (i.e. points H1, H2 and H3):

- For a 20 m tunnel spacing, assuming hypothetical fuel Type 1, a 300 m decrease in repository depth causes:
  - a decrease in the maximum temperature in the middle of the bentonite from 103 °C to 93 °C and, at the outer boundary of the bentonite, a decrease from 98 °C to 88 °C (see Fig. 9),
  - a decrease in the length of time during which higher temperatures exist in the bentonite (see Fig. 10).

- For a 20 m tunnel spacing, assuming hypothetical fuel Type 2, a 300 m decrease in repository depth causes:
  - a decrease in the maximum temperature in the middle of the bentonite from 128 °C to 118 °C and, at the outer boundary of the bentonite, a decrease from 120 °C to 110 °C (see Fig. 9),
  - a (relatively small) decrease in the length of time during which increased temperatures exist in the bentonite (see Fig. 10).

- For a 40 m horizontal tunnel spacing, again assuming hypothetical fuel Type 2, the same decrease in repository depth causes:
  - a decrease in the maximum temperature in the middle of the bentonite from 108 °C to 98 °C and, at the outer boundary of the bentonite, from 91 °C to 81 °C (see Fig. 9),
  - again, a decrease in the length of time during which increased temperatures exist in the bentonite (see Fig. 10).
In conclusion:

A 300 m decrease in repository depth in the crystalline basement of Northern Switzerland results in a 10 °C lower ambient rock temperature around the tunnels and, therefore, correspondingly lower temperatures throughout the near field.

4.3.10 Thermal Properties of the Rock (Crystalline Host Rock)

The base-case thermal conductivity and heat capacity assumed for the crystalline basement of Northern Switzerland are changed from 2.5 W m⁻¹ K⁻¹ and 2.3 MJ m⁻³ K⁻¹, respectively (KRI-1&2) to:

- 2.0 W m⁻¹ K⁻¹ and 2.3 MJ m⁻³ K⁻¹, respectively (KRI-3) in analysis no. 1H,
- 3.0 W m⁻¹ K⁻¹ and 2.3 MJ m⁻³ K⁻¹, respectively (KRI-4) in analysis no. 1J,
- 2.5 W m⁻¹ K⁻¹ and 1.8 MJ m⁻³ K⁻¹, respectively (KRI-5) in analysis no. 1K,
- 2.5 W m⁻¹ K⁻¹ and 2.8 MJ m⁻³ K⁻¹, respectively (KRI-6) in analysis no. 1L.

Temperature evolutions at various points in analysis nos. 1H, 1J, 1K and 1L are plotted in Figs. A1.1h.1, A1.1h.2, A1.1j.1, A1.1j.2, A1.1k.1, A1.1k.2, A1.1l.1 and A1.1l.2.

Temperature profiles at the times of maximum bentonite temperature in analyses nos. 1H, 1J, 1K and 1L are plotted in Fig. A4.19. Considering the temperature at the inner boundary, the middle and the outer boundary of the bentonite (i.e. points H1, H2 and H3):

- A decrease from 2.5 W m⁻¹ K⁻¹ to 2.0 W m⁻¹ K⁻¹ in the assumed thermal conductivity of the rock, while leaving the heat capacity unchanged, causes:
  - an increase in the maximum temperature in the middle of the bentonite from 103 °C to 109 °C, and an increase in the maximum temperature at the outer boundary of the bentonite from 98 °C to 103 °C (see Fig. 9),
  - an increase in the length of time during which increased temperatures exist in the bentonite (see Fig. 10).

- An increase from 2.5 W m⁻¹ K⁻¹ to 3.0 W m⁻¹ K⁻¹ in the assumed thermal conductivity of the rock, while leaving the heat capacity unchanged, causes:
  - a decrease in the maximum temperature in the middle of the bentonite from 103 °C to 100 °C, and a decrease in the maximum temperature at the outer boundary of the bentonite from 98 °C to 94 °C (see Fig. 9),
- a decrease in the length of time during which increased temperatures exist in the bentonite (see Fig. 10).

**•** A decrease from 2.3 MJ m\(^{-3}\) K\(^{-1}\) to 1.8 MJ m\(^{-3}\) K\(^{-1}\) in the assumed heat capacity of the rock, while leaving the thermal conductivity unchanged, causes:

- an increase in the maximum temperature in the middle of the bentonite from 103 °C to 109 °C, and an increase in the maximum temperature at the outer boundary of the bentonite from 98 °C to 104 °C (see Fig. 9),

- an increase in the length of time during which increased temperatures exist in the bentonite (see Fig. 10).

**•** An increase from 2.3 MJ m\(^{-3}\) K\(^{-1}\) to 2.8 MJ m\(^{-3}\) K\(^{-1}\) in the assumed heat capacity of the rock, while leaving the thermal conductivity unchanged, causes:

- a decrease in the maximum temperature in the middle of the bentonite from 103 °C to 100 °C, and a decrease in the maximum temperature at the outer boundary of the bentonite from 98 °C to 94 °C (see Fig. 9),

- a decrease in the length of time during which increased temperatures exist in the bentonite (see Fig. 10).

In conclusion:

| Lower temperatures in the spent-fuel repository near field are calculated if either the assumed thermal conductivity or the assumed heat capacity of the host rock is increased, higher temperatures are calculated for either lower thermal conductivities or lower heat capacities. |

### 4.4 Summary of Results

Table 4 presents, for each of the parameter variations described in Section 4.3, the maximum temperature calculated at the centre and outer boundary of the bentonite. These results, and their implications, are discussed further in Chapter 5.
Table 4: Maximum temperatures calculated at the middle ($T_{H2}$) and outer boundary ($T_{H3}$) of the bentonite, for each of the analyses performed in the present study. Highlighted boxes indicate variations from the base case.

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<th>$T_{H2}$; $T_{H3}$</th>
<th>Lp$^*$ (m)</th>
<th>Sh$^{**}$ (m)</th>
<th>Bentonite Type</th>
<th>Air Gaps</th>
<th>Heat Production (type)</th>
<th>Tunnel Diameter (m)</th>
<th>Host Rock</th>
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<td>103; 98 (base case)</td>
<td>d+3</td>
<td>20</td>
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<td>1</td>
<td>3.7</td>
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</tr>
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<td>96; 90 (case 2)</td>
<td>d+5</td>
<td>20</td>
<td>A</td>
<td>no</td>
<td>1</td>
<td>3.7</td>
<td>KRI-1</td>
</tr>
<tr>
<td>92; 84 (case 3)</td>
<td>d+7</td>
<td>20</td>
<td>A</td>
<td>no</td>
<td>1</td>
<td>3.7</td>
<td>KRI-1</td>
</tr>
<tr>
<td>143; 139 (case 4)</td>
<td>d+3</td>
<td>10</td>
<td>A</td>
<td>no</td>
<td>1</td>
<td>3.7</td>
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</tr>
<tr>
<td>90; 79 (case 7)</td>
<td>d+3</td>
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<td>A</td>
<td>no</td>
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<td>3.7</td>
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</tr>
<tr>
<td>100; 98 (case 10)</td>
<td>d+3</td>
<td>20</td>
<td>B</td>
<td>yes</td>
<td>1</td>
<td>3.7</td>
<td>KRI-1</td>
</tr>
<tr>
<td>106; 99 (case 11)</td>
<td>d+3</td>
<td>20</td>
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<td>2</td>
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<tr>
<td>128; 120 (case 1B)</td>
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<tr>
<td>108; 91 (case 7B)</td>
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<tr>
<td>104; 99 (case 1C)</td>
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</tr>
<tr>
<td>91; 81 (case 7C)</td>
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<td>2.4</td>
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<td>90; 85 (case 7D)</td>
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<td>2.4</td>
<td>OPA</td>
</tr>
<tr>
<td>75; 65 (case 7D)</td>
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<td>OPA</td>
</tr>
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<td>2</td>
<td>2.4</td>
<td>OPA</td>
</tr>
<tr>
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<td>OPA</td>
</tr>
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</tr>
<tr>
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<td>40</td>
<td>A</td>
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<td>2</td>
<td>3.7</td>
<td>KRI-2</td>
</tr>
<tr>
<td>118; 110 (case 1G)</td>
<td>d+3</td>
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<td>A</td>
<td>no</td>
<td>2</td>
<td>3.7</td>
<td>KRI-2</td>
</tr>
<tr>
<td>109; 103 (case 1H)</td>
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<td>A</td>
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<td>KRI-3</td>
</tr>
<tr>
<td>100; 94 (case 1J)</td>
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<td>A</td>
<td>no</td>
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<tr>
<td>109; 104 (case 1K)</td>
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<td>A</td>
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<td>3.7</td>
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<td>3.7</td>
<td>KRI-6</td>
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(*) Lp: longitudinal canister pitch (d [m] = canister length),
(**) Sh: horizontal tunnel spacing.
5 DISCUSSION AND CONCLUSIONS

The aim of this report was to examine the temperature distribution, as a function of time, for a provisional design of a repository for spent-fuel disposal, in order to support future design studies and safety assessments. Figs. 11 - 15 summarise the effects of variations in the parameters describing heat production, tunnel spacing, tunnel diameter, rock type, repository depth (i.e. ambient rock temperature) and the thermal properties of the (crystalline) host rock on maximum temperatures in the outer region of the bentonite.

To explore the effect of changing the heat output of spent-fuel canisters, calculations were performed for two different heat production data sets. The conclusion is that:

- Changing the heat production has a significant effect on the predicted temperature evolution of the repository. For example, increasing the assumed heat output per canister from 1000 W (base case) to 1500 W at 40 years after unloading results in an increase of the maximal bentonite temperature at the bentonite/host rock interface from 98 °C to 120 °C.

Regarding the geometric parameters describing the repository, the calculations that have been presented show that:

- Increasing the tunnel spacing from 20 m (the base-case assumption) to 40 m has a less severe impact on the evolution of the temperature distribution (in particular, on the maximum temperature at a particular location in the bentonite, although the time during which higher temperatures exist in the bentonite is more sensitive). A marked increase in temperature is, however, observed if the tunnel spacing is reduced to 10 m.

- The longitudinal pitch of the spent-fuel canisters and the tunnel diameter are relatively insensitive parameters. Increased canister pitch and reduced tunnel diameter cause relatively small changes in temperature in the bentonite.

The finding that, for horizontal tunnel spacings exceeding 20 m, the maximum bentonite temperature is becoming less sensitive to tunnel spacing, but that the time during which higher temperatures exist in the bentonite is more sensitive, is true across the range of parameter variations investigated in this study.

Regarding the heat-transfer properties of the bentonite and the host rock:

- Lower temperatures in the repository near field are calculated if the assumed thermal conductivity and heat capacity of bentonite are increased. Thermal conductivity and heat capacity of the bentonite are not varied independently in the present study.

- Lower temperatures are calculated in the waste, the canister and the bentonite if the possible presence of air gaps between the canister and the bentonite, between bentonite blocks and between the bentonite and the rock is disregarded. The effect of air gaps is, however, small.
- Lower temperatures are calculated if either the assumed thermal conductivity or the assumed heat capacity of the host rock is increased, with higher temperatures for either lower thermal conductivities or lower heat capacities.

Regarding the host-rock type and emplacement depth:

- Lower temperatures are calculated for a repository in the Opalinus Clay host rock than in the crystalline basement of Northern Switzerland, because of the shallower depth envisaged for Opalinus Clay and therefore lower ambient temperature. The effects are smaller in the inner parts of the repository (i.e. canister/bentonite interface).

- A decrease in repository depth in either rock type (although calculations were only performed for the crystalline basement of Northern Switzerland) results in a lowering of the ambient rock temperature around the tunnels and, therefore, lower temperatures throughout the near field.
Fig. 11: Maximum temperature reached at the centre (bottom-right number) and outer boundary (top-left number) of the bentonite for the crystalline and Opalinus Clay host-rock options, for a range of tunnel spacings (Sh), two fuel types and, for crystalline, two repository depths.

<table>
<thead>
<tr>
<th>Crystalline Host Rock (1200 m Repository Depth)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2.4 m Tunnel Diameter</strong></td>
</tr>
<tr>
<td>Sh</td>
</tr>
<tr>
<td>40 m</td>
</tr>
<tr>
<td>20 m</td>
</tr>
<tr>
<td>10 m</td>
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<table>
<thead>
<tr>
<th>3.7 m Tunnel Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sh</td>
</tr>
<tr>
<td>40 m</td>
</tr>
<tr>
<td>20 m</td>
</tr>
<tr>
<td>10 m</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Opalinus-Clay Host Rock</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2.4 m Tunnel Diameter</strong></td>
</tr>
<tr>
<td>Sh</td>
</tr>
<tr>
<td>40 m</td>
</tr>
<tr>
<td>20 m</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>3.7 m Tunnel Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sh</td>
</tr>
<tr>
<td>40 m</td>
</tr>
<tr>
<td>20 m</td>
</tr>
</tbody>
</table>
Crystalline Host Rock (1200 m Repository Depth)
Heat Production: Type 1 (lower)

3.7 m Tunnel Diameter

<table>
<thead>
<tr>
<th>Thermal Conductivity (W m⁻¹ K⁻¹)</th>
<th>Heat Capacity (MJ m⁻³ K⁻¹)</th>
<th>2.8</th>
<th>2.3</th>
<th>1.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>not calculated</td>
<td>94 °C</td>
<td>100 °C</td>
<td>not calculated</td>
</tr>
<tr>
<td>2.5</td>
<td>94 °C</td>
<td>98 °C</td>
<td>103 °C</td>
<td>104 °C</td>
</tr>
<tr>
<td>2.0</td>
<td>not calculated</td>
<td>103 °C</td>
<td>109 °C</td>
<td>not calculated</td>
</tr>
</tbody>
</table>

Fig. 12: Maximum temperature reached at the centre (bottom-right number) and outer boundary (top-left number) of the bentonite for the crystalline host-rock option, for a range of thermal conductivities and heat capacities of the host rock.
Fig. 13: The variation with heat production of the temperature calculated at the middle of the bentonite (point H2) for a repository constructed at 1200 m depth in the crystalline basement of Northern Switzerland, with 3.7 m emplacement-tunnel diameter, and at 600 m depth in the Opalinus Clay, with 2.4 m emplacement-tunnel diameter.

Fig. 14: The variation with heat production of the temperature calculated at the middle of the bentonite (point H2) for a repository constructed at 900 m depth in the crystalline basement of Northern Switzerland, with 3.7 m emplacement-tunnel diameter, and at 600 m depth in the Opalinus Clay, with 2.4 m emplacement-tunnel diameter.
Fig. 15: The variation with heat production of the temperature calculated at the middle of the bentonite (point H2) for a repository constructed at 1200 m depth in the crystalline basement of Northern Switzerland, and at 600 m depth in the Opalinus Clay, both with 2.4 m emplacement-tunnel diameter.
REFERENCES


APPENDIX 1  DETAILED RESULTS OF THERMAL ANALYSES

Part 1:  Temperature time histories
Part 2:  Maximum temperature of bentonite
Part 3:  Duration of period where maximum bentonite temperature exceeds 100 °C
Part 4:  Temperature profiles at the time of maximum bentonite temperature
Part 5:  Temperature profile and temperature distributions of Analysis No. 1 (base case)
Part 1: Temperature time histories

Fig. A1.1.1: Temperature time history of Analysis No. 1 (radius direction).

Fig. A1.1.2: Temperature time history of Analysis No. 1 (longitudinal direction).
Fig. A1.1b.1: Temperature time history of Analysis No. 1B (radius direction).

Fig. A1.1b.2: Temperature time history of Analysis No. 1B (longitudinal direction).
Fig. A1.1c.1: Temperature time history of Analysis No. 1C (radius direction).

Fig. A1.1c.2: Temperature time history of Analysis No. 1C (longitudinal direction).
Fig. A1.1d.1: Temperature time history of Analysis No. 1D (radius direction).

Fig. A1.1d.2: Temperature time history of Analysis No. 1D (longitudinal direction).
Fig. A1.1e.1: Temperature time history of Analysis No. 1E (radius direction).

Fig. A1.1e.2: Temperature time history of Analysis No. 1E (longitudinal direction).
Fig. A1.1f.1: Temperature time history of Analysis No. 1F (radius direction).

Fig. A1.1f.2: Temperature time history of Analysis No. 1F (longitudinal direction).
Fig. A1.1g.1: Temperature time history of Analysis No. 1G (radius direction).

Fig. A1.1g.2: Temperature time history of Analysis No. 1G (longitudinal direction).
Fig. A1.1h.1: Temperature time history of Analysis No. 1H (radius direction).

Fig. A1.1h.2: Temperature time history of Analysis No. 1H (longitudinal direction).
Fig. A1.1j.1: Temperature time history of Analysis No. 1J (radius direction).

Fig. A1.1j.2: Temperature time history of Analysis No. 1J (longitudinal direction).
Fig. A1.1k.1: Temperature time history of Analysis No. 1K (radius direction).

Fig. A1.1k.2: Temperature time history of Analysis No. 1K (longitudinal direction).
Fig. A1.1.1: Temperature time history of Analysis No. 1L (radius direction).

Fig. A1.1.2: Temperature time history of Analysis No. 1L (longitudinal direction).
Fig. A1.2.1: Temperature time history of Analysis No. 2 (radius direction).

Fig. A1.2.2: Temperature time history of Analysis No. 2 (longitudinal direction).
Fig. A1.3.1: Temperature time history of Analysis No. 3 (radius direction).

Fig. A1.3.2: Temperature time history of Analysis No. 3 (longitudinal direction).
Fig. A1.4.1: Temperature time history of Analysis No. 4 (radius direction).

Fig. A1.4.2: Temperature time history of Analysis No. 4 (longitudinal direction).
Fig. A1.7.1: Temperature time history of Analysis No. 7 (radius direction).

Fig. A1.7.2: Temperature time history of Analysis No. 7 (longitudinal direction).
Fig. A1.7b.1: Temperature time history of Analysis No. 7B (radius direction).

Fig. A1.7b.2: Temperature time history of Analysis No. 7B (longitudinal direction).
Fig. A1.7c.1: Temperature time history of Analysis No. 7C (radius direction).

Fig. A1.7c.2: Temperature time history of Analysis No. 7C (longitudinal direction).
Fig. A1.7d.1: Temperature time history of Analysis No. 7D (radius direction).

Fig. A1.7d.2: Temperature time history of Analysis No. 7D (longitudinal direction).
Fig. A1.7e.1: Temperature time history of Analysis No. 7E (radius direction).

Fig. A1.7e.2: Temperature time history of Analysis No. 7E (longitudinal direction).
Fig. A1.7f.1: Temperature time history of Analysis No. 7F (radius direction).

Fig. A1.7f.2: Temperature time history of Analysis No. 7F (longitudinal direction).
Fig. A1.10.1: Temperature time history of Analysis No. 10 (radius direction).

Fig. A1.10.2: Temperature time history of Analysis No. 10 (longitudinal direction).
Fig. A1.11.1: Temperature time history of Analysis No. 11 (radius direction).

Fig. A1.11.2: Temperature time history of Analysis No. 11 (longitudinal direction).
Part 2: Maximum temperature of bentonite

Fig. A2.1: Relation between maximum temperature of bentonite and tunnel spacing.

Fig. A2.2: Relation between maximum temperature of bentonite and longitudinal pitch of spent fuel canisters.
Part 3: Duration of period where maximum bentonite temperature exceeds 100 °C

![Graph](image_url)

**Fig. A3.1.1:** Relation between the time duration of maximum bentonite temperature exceeding 100 °C and horizontal tunnel spacing.

![Graph](image_url)

**Fig. A3.1.2:** Relation between the time duration of maximum bentonite temperature exceeding 100 °C and horizontal tunnel spacing.
Part 4: Temperature profiles at the time of maximum bentonite temperature

Fig. A4.1 Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1, 4, 7).

Fig. A4.2 Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1, 2, 3).
Fig. A4.3  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1, 10).

Fig. A4.4  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1, 11).
Fig. A4.5  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1, 1B).

Fig. A4.6  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 7, 7B).
Fig. A4.7 Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1, 1C).

Fig. A4.8 Temperature profiles at the time of maximum bentonite temperature (Analysis No. 7, 7C).
Fig. A4.9  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1C, 1D).

Fig. A4.10  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 7C, 7D).
Fig. A4.11 Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1B, 7B).

Fig. A4.12 Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1C, 7C).
Fig. A4.13  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1D, 7D).

Fig. A4.14  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1B, 1E).
Fig. A4.15  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 7B, 7E).

Fig. A4.16  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1D, 1E).
Fig. A4.17  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 7D, 7E).

Fig. A4.18  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1E, 7E).
Fig. A4.19  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1, 1F, 1H, 1J, 1K, 1L).

Fig. A4.20  Temperature profiles at the time of maximum bentonite temperature (Analysis No. 1F, 1G, 7F).
Part 5: Temperature profile and temperature distributions of Analysis No. 1 (base case)

Fig. A5.1 Temperature profiles of Analysis No. 1.
Fig. A5.2  Temperature distributions of Analysis No. 1 at the time of 15 years (°C).
Fig. A5.3  Temperature distributions of Analysis No. 1 at the time of 75 years (°C).
Fig. A5.4  Temperature distributions of Analysis No. 1 at the time of 225 years (°C).