

**Technical Report**

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# **Heat propagation in and around the deep repository**

**Thermal calculations applied  
to three hypothetical sites:  
Aberg, Beberg and Ceberg**

Lars Ageskog, Patrik Jansson

VBB Anläggning AB

January 1999

**Svensk Kärnbränslehantering AB**

Swedish Nuclear Fuel  
and Waste Management Co  
Box 5864

SE-102 40 Stockholm Sweden

Tel 08-459 84 00

+46 8 459 84 00

Fax 08-661 57 19

+46 8 661 57 19



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*Keywords:* thermal process, thermal properties of rock, thermal modelling, ansys

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author(s) and do not necessarily coincide with those of the client.

## **Abstract**

The purpose of the present study is to demonstrate the modelling of the thermal process in and around the deep repository for spent fuel. The model was developed in the general finite element program ANSYS and applied to the three hypothetical sites Aberg, Beberg and Ceberg included in the SR 97 analyse system. The canister emplacement in the repository was analysed based on certain criteria regarding the temperature on the canister surface. This was done with consideration to natural deviations in various thermal parameters as well as to the risk of a gap opening up between the canister surface and the bentonite buffer. The consequence of the latter was analysed separately as part of the study. The heat load in the model was applied stepwise, following an assumed time schedule for the actual deposition work. The calculations were extended to 1,000 years after the commencement of the deposition work. The outcome of the calculation is presented as coloured prints of isotherms in and around the repository at certain time intervals.

## **Sammanfattning**

Föreliggande studie avser att demonstrera modellering av den termiska processen i och omkring djupförvaret för använt bränsle. Modellen har upprättats i det generella finita elementprogrammet ANSYS och applicerats på de tre hypotetiska förvarsområdena Aberg, Beberg och Ceberg, vilka ingår i det analysystem som ryms inom SR 97. Kapselpositioneringen i förvaren har beräknats för givna villkor avseende temperaturen på kapselytan. Härvid har hänsyn tagits till naturliga variationer i olika termiska parametrar samt till risken för att en spalt mellan kapsel och bentonit uppstår. Konsekvensen av det senare har analyserats separat som en del av studien. Den termiska effekten har påförts i modellen successivt efterliknande en tänkt tidplan för deponeringsarbetet. Beräkningen har utsträckts till 1 000 år efter deponeringens inledning. Resultatet redovisas som färgutskrift utvisande isotermer i och kring förvaren för olika tider.

## Executive Summary

In the Safety Report of 1997 (SR 97), SKB intend to exemplify the execution of a performance assessment (PA) of a deep repository by applying various components to three hypothetical sites in Sweden: Aberg, Beberg and Ceberg. The purpose of the present study is to model the thermal process in and around a repository and to use the model for calculating the appropriate canister spacing and the time dependent temperature elevation in the bedrock.

Although the main purpose was to demonstrate the method and, to some extent, compare the outcome with respect to the three sites, an effort was yet made to base the models on as accurate and up-to-date parameters as possible regarding environmental data, canister properties and amount of spent fuel. The major source of information was the latest report to the authorities about the cost of the waste handling system, Plan 98, and pertinent background material.

The canister spacing, i.e. the centre to centre distance between two adjacent canisters in the deposition tunnel, was calculated on the presumption that the canister surface temperature must not exceed 100°C. With reference to other studies it was concluded that a margin of 10°C should be appropriate to cover for natural deviations in environmental parameters and in fuel data. Another 10°C would be reserved for covering the risk of the occurrence of a gap between the canister and buffer. This was concluded based on a rough calculation performed as part of this study. Subsequently, a target temperature of 80°C on the canister surface was used in the calculation of canister spacing. The result gave a spacing of 7.5 m for Aberg and 6.0 m for Beberg and Ceberg.

The layouts of the three sites have been prepared in a former study and were therefore considered as fixed. With the canister spacing found in the present study, this fact gave the total number of canisters in the three repositories: Aberg - 3,650; Beberg - 4,261; Ceberg - 4,165. This corresponds to an average operation time for the Swedish reactors of 31, 37 and 36 years respectively.

The heat propagation in the bedrock at each site was calculated for a period up till 1,000 years. At that time, the heat wave has barely reached the ground surface and the peak rock temperature at repository level (30–50°C) has been passed since long. The maximum temperature on the canister surface was reached as early as after 10 to 20 years. A more detailed comparison between the three model sites is of limited interest as the conditions regarding total as well as specific heat load differ significantly.

For the two-level repository at Aberg, the interference between the two levels will occur after some 30 years causing a higher rock temperature than in a one-level repository (5–10°C difference). However, the interference between the two levels will occur well after the peak temperature on the canister surface is passed, and will therefore not affect the canister spacing and the distance between deposition tunnels.

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# 1 Introduction

## 1.1 Purpose and Scope

In the Safety Report of 1997 (SR 97), SKB intend to exemplify the execution of a performance assessment (PA) of a deep repository by applying various components to three hypothetical sites in Sweden. One component is the modelling of the thermal process with regard to the short-term development, as a basis for repository design, as well as the medium-term influence on the bedrock at a far-field scale. The latter concerns the fact that an elevated temperature in relation to the surrounding rock masses gives rise to changes in the stress field in the rock which affect the structural pattern, i.e. the fracture network, which, in turn, may affect the hydraulic situation and the ground-water movement.

The purpose of this study is to model the thermal process in and around the repository and to use the model for calculating the appropriate canister spacing and the time dependent temperature elevation in the bedrock. The model shall be applied to the following three hypothetical sites, each based on data from previous site characterisations conducted by SKB:

Aberg, based on data from the Äspö Hard Rock laboratory site;

Beberg, based on data from the Finnsjön area in central Sweden;

Ceberg, based on data from the Gideå area in northern Sweden.

## 1.2 Background

The thermal process in the deep repository depends on a number of design and material parameters related not only to the engineering aspects of the waste handling system and the anticipated overall time schedule for it, but also to fuel data depending on past, actual and future reactor operation conditions. SKB has conducted thermal analyses as an integrated part of the deep repository design studies over the years, during which time parameters have constantly changed partly as a consequence of the progress of the SKB research and development work, partly due to external technical, political or legislative factors concerning the Swedish nuclear programme as a whole. In addition, the tools for modelling and calculation of thermal processes have evolved along with the rapid development of computerisation, which lately has opened for deeper and more accurate analyses on a still cost effective basis.

This present study was based on the main stream of the SKB development program as summarised in the so called PLAN-reports, i.e. the cost estimate of the overall waste handling system that is sent to the authorities by SKB on a yearly basis. The current waste handling principle in the PLAN-reports refer to the so called KBS-3 method /1-1/. Background data for this study are based to a high extent on facts and assumptions stated in the latest PLAN report, PLAN 98, issued in June 1998 /1-2/.

In order to give an understanding of the dynamic of the repository design and the features affecting the thermal process, a few subsystems with major significance in this respect are highlighted below.

### **Reactor operation and spent fuel**

A major uncertainty in the repository design work of today is the actual amount of spent fuel to be expected and data on the pertaining residual heat. These are factors depending partly on the operation conditions of each reactor and partly on the interim storage period of the fuel before its encapsulation and deposition.

Following the amendment of 1995 to the Financing Act, the time limit of 2010 for reactor operation, generally referred to prior to the amendment, was abandoned and replaced by the present so called fiscal operation time of 25 years for each reactor. This operation time is only intended as a basis for the fund raising and is in no way referring to an actual final operation time. The technical details and cost figures presented in PLAN 98 is to an high extent based on the 25 years alternative but for most other purposes a technical and economical life time of at least 40 years should be assumed. (It should be noted that the former alternative of 2010 corresponded to an average operation time of approximately 33 years.)

### **Canister**

The canister size (outer surface area) is of importance with respect to the ability of transferring the heat energy through the buffer without the risk of an excessive temperature rise on the canister surface. The diameter as well as the length of the canister have increased over the years with a major step at the time when it was decided to encapsulate the fuel assemblies without first removing the boxes (BWR). Today, the prime alternative is a canister holding 12 BWR-assemblies or 4 PWR.

### **Bentonite**

The bentonite buffer actually functions as an insulation around the canister and is therefore the single most important element (apart from the fuel itself) with respect to temperature distribution in the near-field of the canister. The heat conduction capability of the buffer is very much depending on the water saturation of the bentonite. Along with the progress of the research and development work in this field it has been justified to allow for an increasing dimensioning water saturation and thus a better heat conduction ability of the bentonite.

### **Geology**

The geological area is one that has developed very little over the years with respect to the thermal significance. The most obvious reason for this is of course the fact that still no definite location has been assigned. The uncertainties of relevant parameters in this respect, such as initial rock temperature, heat conductivity and repository adaptation, are far more decisive for the outcome of the calculations than marginal adjustments to the same parameters due to the present long driven scientific development in areas of classification and prognosticating. (In view of this it would be of interest to notice that Aberg, Beberg and Ceberg, used in this study, each represents a total different set of rock parameters.)



### **Analysis tools**

Since mid 80's, heat propagation in and around the repository has been analysed mainly by means of general finite element programs such as ADINA and ANSYS. The difficulties of these calculations does not lie in complex algorithms but more in the size of the models and the extensive time period to be covered by the calculations (1, 000 years or longer), factors that strongly affect the need of computer resources and thus the costs. In early years, a number of simplifications were imperative in order to keep the calculation cost within a reasonable level. In recent years, however, this has become an obstacle almost without relevance which has made way for a more realistic and comprehensive modelling, giving higher accuracy and more readily available tools for variation analyses.

### **Estimated construction costs**

Over the years, the focus on costs for construction and backfilling of tunnels vs. the cost of a canister has shifted from an interest to keep rock openings to a minimum, mainly because of the very costly backfill material at that time, to the intention of today to make ultimate use of the canister (fill it to 100%) and to let tunnel length and other geometrical parameters be the subjects of necessary adjustments in order to meet temperature criteria. The canister has developed into a very expensive unit while, in the same time, the backfill material has changed to a relatively low-cost mix of crushed rock and bentonite.

## 2 Waste Handling Scenario

### 2.1 Reactor Operation and Amount of Spent Fuel

The total amount of spent fuel from the 12 Swedish reactors depends on reactor operation time (years), the energy utilisation factor and the burnup of the fuel. The burnup also influences the heat flux of the spent fuel (fuel assemblies removed from the reactor).

All operational data before 1998 can be transferred into well known fuel data covering about 4 000 tonnes of spent fuel (weight refers to the amount of uranium in the fuel assemblies). Future production, however, has to be based on prognoses regarding the three key factors mentioned in the paragraph above. In PLAN 98, a reference scenario was assumed based on a future energy utilisation factor of 80% for all reactors, and a burnup of 42 MWd/kgU for BWRs and 44 MWd/kgU for PWRs.

The reactors are generally assumed to have a technical/economical lifetime of at least 40 years. With such a lifetime and with the operation presumptions given above, the total amount of spent fuel can be estimated at 9,500 tonnes composed of 39,500 BWR-assemblies and 4,900 PWR-assemblies<sup>1</sup>.

A fiscal operation time of 25 years has been analysed in depth in PLAN 98 giving the total amount of spent fuel at approximately 6 500 tonnes composed of 26,800 BWR-assemblies and 3,100 PWR-assemblies.

For this study, it was considered adequate to obtain fuel data for other operation alternatives, i.e. average operation times between 25 and 40 years, by linear interpolation.

The heat flux situation at various reactor operation scenarios, given as canister heat output, will be addressed below in Section 2.3.

### 2.2 Interim Storage in CLAB

From the time of removal from the reactor pools till the encapsulation and deposition, the spent fuel will be temporarily stored in the underground pools in CLAB during which period the radiation level and the heat flux will decay to a level suitable for the subsequent handling. At present, these storage pools contain almost 3,000 tonnes of spent fuel. The duration of the storage period for each assembly depends on how well the overall time schedule of the encapsulation process matches the operation time of the reactors.

Considering the fact that the encapsulation and deposition will take place in a rather distant future and that the overall time schedule, in addition to other factors, inherently includes a certain political element, the interim storage period as well as the operation mode of the encapsulation process are very likely to be subject to changes from what is planned today. However, for this study (as a basis for heat load and heat load application

<sup>1</sup>It should be noted that the total number of canisters will include a few canisters in addition to those directly originating from the fuel specified here.

in the model) it was deemed necessary to establish a fixed scenario. The choice fell on the intentions stated in the particular document that reflects the most up-to-date development plans in SKB, the RDD-programme 98 /2-1/. From that document the following assumption was derived:

- The interim storage period for the fuel assemblies shall be about 30 years on an average basis.

## 2.3 Canister Data and Heat Flux

The canister, according to PLAN 98, consists of a cast steel insert with an outer shell of copper. The overall dimensions are length 4,830 mm and diameter 1,050 mm and the total weight is approximately 25 tonnes. The canister holds 12 BWR assemblies or 4 PWR assemblies.

The production rate in the encapsulation plant is at present planned to be 200 canister per year as a reference case. (This has a direct bearing on the deposition rate in the deep repository according to current plans.) Today there is no indication that this rate need be changed and for this study the following fixed condition was adopted:

- The encapsulation as well as deposition rate shall be 200 canisters per year.

As the details regarding the temperature distribution inside the canister is not included in the scope and of no other significance for this study, the canister was modelled monolithic, generating a volumetric heat load. This "equivalent canister" was given the following thermal parameters:

heat conductivity                      390 W/(m · K)

volumetric heat capacity              2.40 MJ/(m<sup>3</sup> · K)

The heat flux of the canister is depending on the actual content (number of fuel assemblies) and, as mentioned above, the decay during the cool-off period in CLAB. Due to the very high cost of the canister as such, the finding in PLAN 98 was that the most cost effective way of handling the heat problem was to fill up the canister and make necessary adjustments in other areas, for instance the time schedule (heat decay) or the canister spacing in the deep repository.

In PLAN 98, with the reference scenario based on reactor operation time of 25 years, the initial heat output from the canister at the time of emplacement was calculated at 1 625 W. With proper adjustments to the overall time schedule, according to the condition set out above regarding the storage period in CLAB, the same initial heat output can be maintained for any reactor operation scenario between 25 and 40 years. This gave the following assumption for this study regarding canister heat output:

- The initial heat output of one canister is 1,625 W, valid for all reactor operation scenarios. The phasing of the deposition work (time schedule) shall be adjusted accordingly.

The average heat flux decay of the spent fuel in a canister, from the time of emplacement of that particular canister, was modelled by the following function /2-2/:

$$Q(t) / Q_0 = \alpha_1 \cdot e^{-\alpha_2 t} + (1 - \alpha_1) \cdot e^{-\alpha_3 t}$$

$t$ =years after emplacement

$Q_0$ =initial heat output at the time of emplacement

$\alpha_1$ =7,531212-1

$\alpha_2$ =2,176060-2

$\alpha_3$ =1,277985-3

The function is valid for at least the first 1,000 years.

## 2.4 Buffer Data

Blocks of highly compacted bentonite are acting as a buffer around the canister in the deposition hole. The variation of the heat conductivity of the compacted bentonite is primarily depending on the water content, denominated for instance as the degree of water saturation,  $S_r$  /2-3/. Under certain provisions, fully saturated ( $S_r=100\%$ ) bentonite blocks can have a conductivity as high as 1,2–1,4 W/(m · K) while natural dry blocks ( $S_r=55\text{--}60\%$ ) have a conductivity of less than 0.8 W/(m · K). In recent years, compacting technique for highly saturated blocks ( $S_r=85\text{--}90\%$ ) has developed and been proven successful which in turn has made it possible to include the assumption of such blocks in the reference case of PLAN 98.

After canister emplacement, the heat of the canister will initially drive the water content outwards and shift the initial saturation balance in the blocks. There is a counteractive process in this respect by the wetting of the buffer through assimilation of water from the rock. The complete process is today not fully known but will be further studied in the ongoing full-scale test in the Äspö HRL programme (the Prototype Repository).

In addition to the uncertainty regarding water saturation, there is the question of the occurrence of gaps between canister and bentonite and between bentonite and rock. The more important of these two gaps, or rather the only one that is plausible to occur, is the gap between canister surface and bentonite. At the emplacement of the canister in the hole, this gap, nominally 10 mm wide, will be filled with water which soon after will make it close by the swelling of the bentonite. However, if the supply of water from the rock is inadequate, the heat-driven process mentioned above may dry out the bentonite closest to the canister and open up the gap for a shorter or longer period.

The situation regarding the behaviour of bentonite in the deposition hole is very complex and there are today not enough substantial evidence to support one or the other hypothesis. Therefore, for the purpose of this study, conservative assumptions were made regarding the water saturation of the bentonite and the occurrence of an inner gap.

For modelling reasons the bentonite cylinder was divided into three concentric layers. Table 2-1 below presents the properties of the bentonite layers as well the inner and outer gap.

**Table 2-1 Assumed bentonite properties**

Radial layer	Heat conductivity W/(m · K)	Heat capacity MJ/(m <sup>3</sup> · K)	Note
Gap canister/bentonite – 10 mm	see Chapter 4		Open on long-term basis
Inner bentonite layer – 90 mm	0.90 (Sr=70%)	2.20	
Middle bentonite layer – 100 mm	1.05 (Sr=90%)	2.20	
Outer bentonite layer – 100 mm	1.15 (Sr=100%)	2.20	
Gap bentonite/rock – 50 mm	1.15 (Sr=100%)	2.20	Filled with bentonite

The bottom and top plugs of bentonite were given the same properties as the outer bentonite layer in Table 2-1.

The model was setup in a way that facilitates the investigation of time dependent buffer behaviour, should such sensitivity analyses at a later stage be required. For instance the consequence if the inner gap be closed at a certain time and the water saturation uniformly levelled over the whole bentonite section.

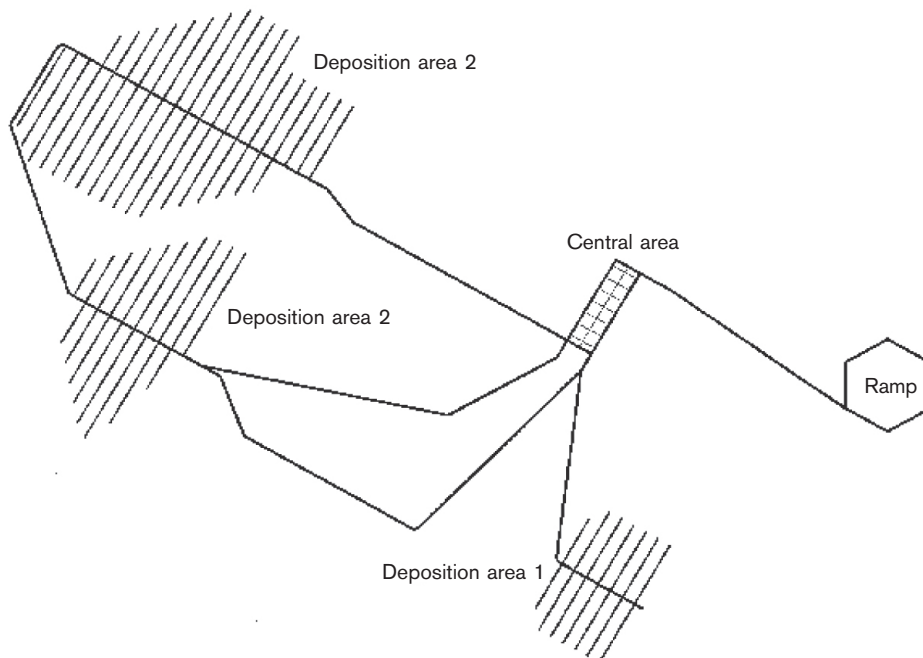
## 3 Three Model Sites

### 3.1 Repository Layout

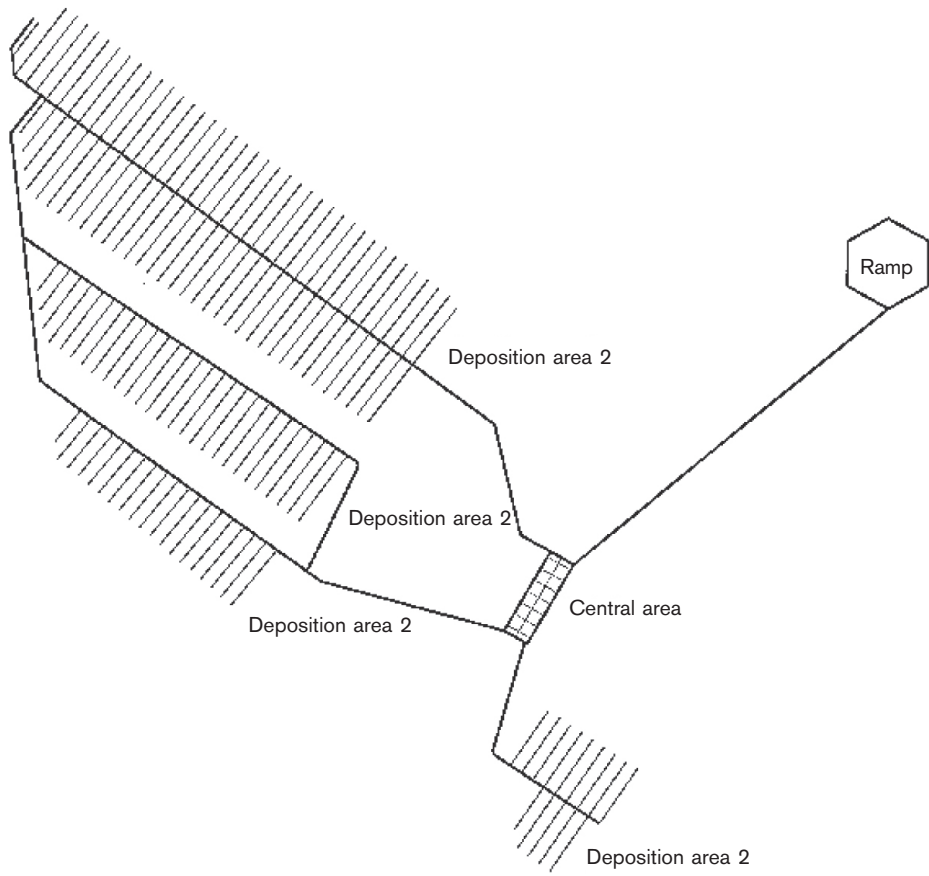
For each of the three hypothetical sites, Aberg, Beberg and Ceberg, conceptual layout studies have been performed in order to produce a background material for the modelling of essential components of the performance assessment of SR 97, including thermal processes. The applied layouts of the three sites, as presented in the report SKB R-97-09 /3-1/, were therefore considered as fixed and not allowed to be adjusted with respect to temperature criteria (even if possible). The number, length and general configuration of all deposition tunnels were thus given as a fix condition.

Depending on the layout details and the specific thermal conditions at each site, the total storage capacities, with respect to number of canisters that can be deposited, differ between the sites and, consequently, also the total heat load. This should be kept in mind when comparing the outcome with respect to temperature distributions at certain time intervals.

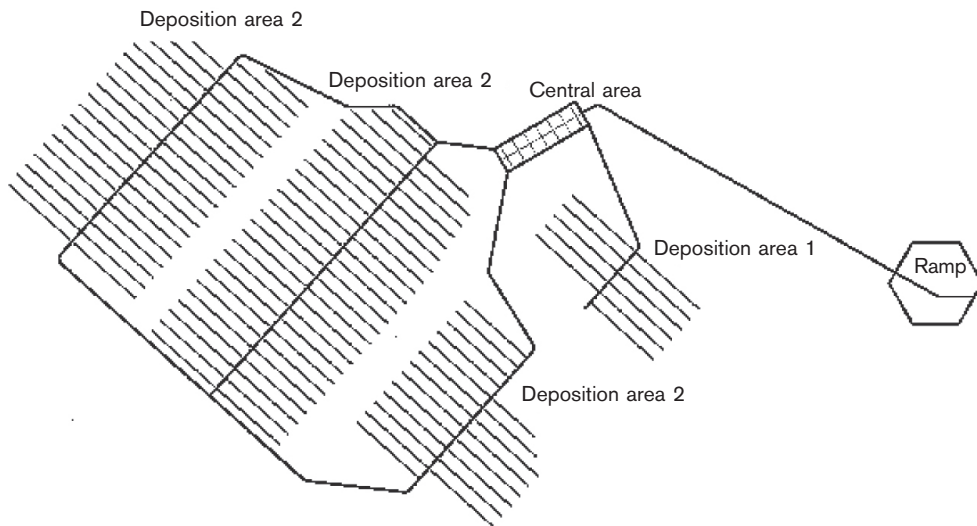
The Figures 3-1, 3-2 and 3-3 below, collected from /3-1/, present overviews of the configurations at the three sites. It should be noted that site Aberg is a two-level repository, 600 m (start-level) and 500 m below the ground surface respectively.



*Figure 3-1. General arrangement at Aberg, -500 m and -600 m /3-1/*



*Figure 3-2. General arrangement at Beberg, -600 m /3-1/*



*Figure 3-3. General arrangement at Ceberg, -500 m /3-1/*

The canister spacing (centre to centre) in the deposition tunnel was set to a minimum of 6.0 m with respect to constructability and to hydrological separation. To meet temperature criteria, it may prove necessary to increase the spacing. In addition to the nominal canister spacing an adjustment of 10% was made to cover for non-conforming tunnel sections when calculating the overall holding capacity of the repository. Furthermore, at intersections with transport tunnels, a certain section of each deposition tunnel was reserved for sealing arrangements with the first canister located 12 m from the tunnel opening.

With these provisions, a deposition tunnel with the typical length of 250 m, as an example, can hold 36 canisters if the nominal spacing between canisters is 6 m (i.e. 6.6 m including adjustments for non-conforming tunnel sections).

## **3.2 Thermal Properties of the Rock Mass and Backfill**

Information on the thermal properties of the rock at the three sites was collected from a number of sources. An overview of the thermal properties of Swedish crystalline rock in general has been presented by Jan Sundberg, Terratema AB in 1995 /3-2/. The report presented a mapping on a national basis of heat conductivity, heat flux and deep rock temperature. The heat conductivity was given as a range with indication of the most likely value.

Each of the three sites has been subject to local characterisation in various campaigns over the years, starting in the early 80's in the preparation of the KBS-3 concept. Aberg is in this respect outstanding as it in addition to that uses data from the investigations associated with the Äspö Hard Rock Laboratory (Jan Sundberg 1991) /3-3/. The most recent data (yet not published) was obtained from the background material for the test called Prototype Repository in which similar thermal calculations currently are performed.

Results from site investigations regarding temperature conditions for all three sites have been compiled by Kaj Ahlbom et al. in 1995 /3-4/. Data from that report are the prime source of information on initial rock temperature on repository level and the average temperature gradient applied in the modelled domain.

The selection of site specific thermal properties, according to Table 3-1 below, is naturally impaired by a great deal of uncertainty, should the intention have been to describe the actual situation at a number of real locations in Sweden. However, the purpose of this study is merely to describe the thermal process by referring to three hypothetical, or even fictitious, sites which in some sense could be considered as typical for their respective regional location. Therefore, the focus should be on the differences between key data rather than on absolute values. For instance, the three sites represent different rock types which affect the single most important parameter, the heat conductivity, (Aberg – diorite, Beberg – granite, Ceberg – gneiss). Further on, they represent different geographical locations which affect the initial temperature in the rock (Aberg – southern Sweden, Beberg – central Sweden, Ceberg – northern Sweden).



**Table 3-1 Thermal properties of the rock at the three sites**

Site	Heat conductivity <sup>1</sup> W/(m · K)	Heat capacity <sup>2</sup> MJ/(m <sup>3</sup> · K)	Initial temp. °C	Temp. gradient °C/km
Aberg	2.80	2.00	16.0	13.5
Beberg	3.20	2.10	13.5	12.7
Ceberg	3.80	2.30	11.0	15.5

<sup>1</sup>Heat conductivity is temperature dependent with –0.10% per °C

<sup>2</sup>Heat capacity is temperature dependent with 0.20% per °C

The material properties of the backfill in tunnels have practically no influence on the outcome of the calculations and therefore the thermal parameters used lately in numerous calculations for SKB were accepted without any further investigation. Those were:

heat conductivity for the backfill                      1.00 W/(m · K)

volumetric heat capacity for the backfill            1.75 MJ/(m<sup>3</sup> · K)

## **4 Canister Surface Temperature**

### **4.1 Temperature Considerations**

Of reasons not discussed in this report, it has been decided that the temperature on the canister surface shall be limited to a maximum of 100°C /4-1/. This implies that the target temperature in the current model, as well as in all prognostic calculations, need be substantially lower to provide for various uncertainties in input data related to the thermal process, including the properties of the spent fuel.

Due to the large number of different data involved in the process, giving a statistical relevance, it should be possible to analyse the risk of exceeding the maximum temperature by probabilistic methods. An attempt in that direction has been made recently in a study regarding optimisation of the canister size /4-2/. Under the provision that the location and rock type were still unknown, that study indicated that the safety margin should be set to approximately 12–13°C in order to give an appropriate low probability (less than 1‰) for the risk of exceeding the temperature limitation. Considering that the present study assumed definite site locations (Aberg etc.) it was deemed reasonable to reserve a marginal temperature of 10°C in order to cover for uncertainties in environmental data. Subsequently, the temperature limit was set to 90°C as a basis for the analysis of minimum canister spacing.

### **4.2 The Significance of a Gap between Canister and Buffer**

#### **4.2.1 General**

As mentioned above, a scenario which includes an initial process where the heat from the canister soon after deposition causes a gap between canister surface and bentonite to open up can not be ruled out. Therefore a rough calculation was done in order to estimate the influence on the canister temperature, should such an event occur.

The calculation was based on a so called equivalent heat conductivity over the gap. The equivalent conductivity includes the effects of conduction and radiation. The effect of a vapour/water diffusion was not considered and, due to the limited width of the gap (5–20 mm), nor was convection.

The calculation was performed by FEM-analyses with a simplified model that, in principle, referred to conditions at Aberg (not important). Sensitivity analyses were performed with respect to gap width, emissivity factor of copper and number of years the gap was assumed to remain open.

## 4.2.2 Equivalent Heat Conductivity over the Gap

### 4.2.2.1 Gap width 10 mm, “normal” emissivity of canister surface

#### Radiation

The emissivity of copper and bentonite in an environment like the one that should be expected in a hole drilled in the bottom of a tunnel and contaminated by a clay/water mix, should preferably be found by reference to a civil engineering handbook rather than in tables of physical data related to mechanical works. In the Swedish handbook Handboken Bygg (1983), Chapter A12, the following values for the emissivity factors can be found:

copper plate (new) 0.63

concrete (assumed equal to bentonite) 0.88

The effective emissivity will be:

$$e = \frac{1}{\frac{1}{0,63} + \frac{1}{0,88} - 1} = 0,58$$

Assume an average temperature of 50°C (conservative). The mean temperature  $273+50\text{K} = 323 \text{ K}$  gives:

$$\alpha_s = 0,23 \cdot 0,58 \cdot \left(\frac{323}{100}\right)^3 = 4,5$$

The heat resistance over the gap will be:

$$m_s = \frac{1}{4,5} = 0,22 \text{ m}^2 \cdot \text{K} / \text{W}$$

#### Conduction

The heat conductivity of air is depending on temperature, pressure and moist content. The moist content, however, affects the heat conductivity only marginally, hence disregarded in this rough calculation.

In Zustands- und Stoffwerte Wasser Dampf Luft, Bernd Glück, VEB Verlag für Bauwesen, Berlin the heat conductivity of air is given: 0,026 W/m°C at 20°C and 0,032 at 100°C respectively. For the temperature range of interest here, i.e. 80–100°C, the choice of one constant value of 0,030 W/mK can be justified. The heat resistance over a gap of 10 mm will then be:

$$m_l = \frac{0,01}{0,030} = 0,33 \text{ m}^2 \text{K} / \text{W}$$

### Equivalent heat conductivity

The total heat resistance over the gap will then be:

$$m = \frac{1}{\frac{1}{0,22} + \frac{1}{0,33}} = 0,13 \text{ m}^2\text{K} / \text{W}$$

(It should be noted that this value exactly conform with the heat resistance over a gap of 10 mm between non-metallic sheets as given in the Swedish VVS-Handboken.)

Equivalent heat conductivity for the gap will be:

$$\lambda_e = \frac{0,01}{0,13} = 0,08 \text{ W} / \text{m} \text{ } ^\circ\text{C}$$

#### 4.2.2.2 Gap width 5 mm, “normal” emissivity of canister surface

At a gap width of 5 mm and with the same assumptions as above, the total heat resistance will be:

$$m = \frac{1}{\frac{1}{0,22} + \frac{2}{0,33}} = 0,094 \text{ m}^2\text{K} / \text{W}$$

Equivalent heat conductivity for the gap will be:

$$\lambda_e = \frac{0,005}{0,094} = 0,05 \text{ W} / \text{m} \text{ } ^\circ\text{C}$$

#### 4.2.2.3 Gap width 10 mm, very high emissivity of the canister surface

In case of a very glossy copper surface (however unlikely) the emissivity of the copper will be lower. Assume an emissivity value of approximately half the value of the “normal” above, i.e. 0.30. The effective emissivity will then be:

$$e = \frac{1}{\frac{1}{0,30} + \frac{1}{0,88} - 1} = 0,29$$

And as above:

$$\alpha_s = 0,23 \cdot 0,29 \cdot \left(\frac{323}{100}\right)^3 = 2,2$$

$$m_s = \frac{1}{2,2} = 0,46 \text{ m}^2 \cdot \text{K} / \text{W}$$

$$m = \frac{1}{\frac{1}{0,46} + \frac{1}{0,33}} = 0,19 \text{ m}^2 \text{K} / \text{W}$$

Equivalent heat conductivity for the gap will then be:

$$\lambda_e = \frac{0,01}{0,19} = 0,05 \text{ W} / \text{m} \cdot ^\circ\text{C}$$

#### 4.2.2.4 Summary of the equivalent heat conductivity

Alternative	Equivalent heat conductivity $\lambda_e$ [W/m <sup>2</sup> K]
Gap width 10 mm, "normal" emissivity of canister surface	0,08
Gap width 5 mm, "normal" emissivity of canister surface	0,05
Gap width 10 mm, high emissivity of canister surface	0,05

### 4.2.3 Results and Conclusions

The outcome of the calculations is presented as diagrams in Figure 4-1. The following conclusions were made.

- The temperature drop over the gap is almost fully developed already at a gap width of 5 mm (upper diagram).

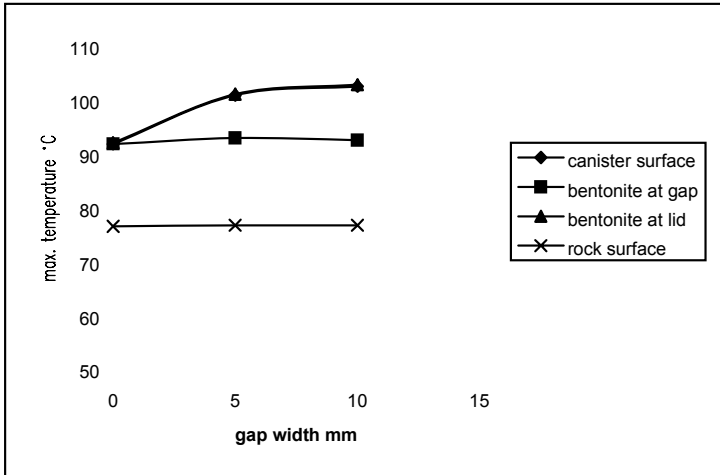
**Conclusion:** A gap of 10 mm will be adequate for the subsequent calculation of canister spacing.

- The temperature drop over the gap is sensitive for the emissivity of the copper. Glossy copper (polished) gives a temperature drop of 15–20°C (middle diagram). Considering the more realistic situation in the hole with a contaminated environment for the canister, the drop should be less than 10°C.

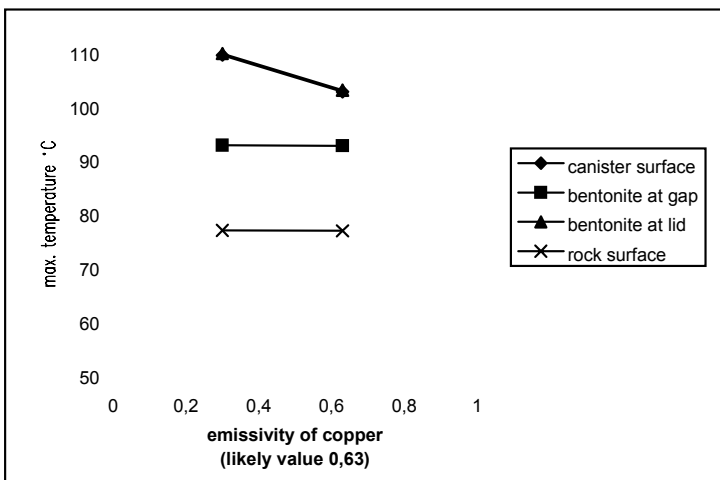
**Conclusion:** An emissivity factor of 0.63 will be adequate for the subsequent calculation of canister spacing.

- The temperature drop with respect to the maximum temperature on the canister surface is sensitive to how many years after deposition the gap is open (lower diagram). If the gap is closed two years after deposition, no significant temperature raise should be expected. After five years, however, the difference is developed and after 20 years, when the peak of the temperature curve has passed, the full difference has developed which is about 10°C.

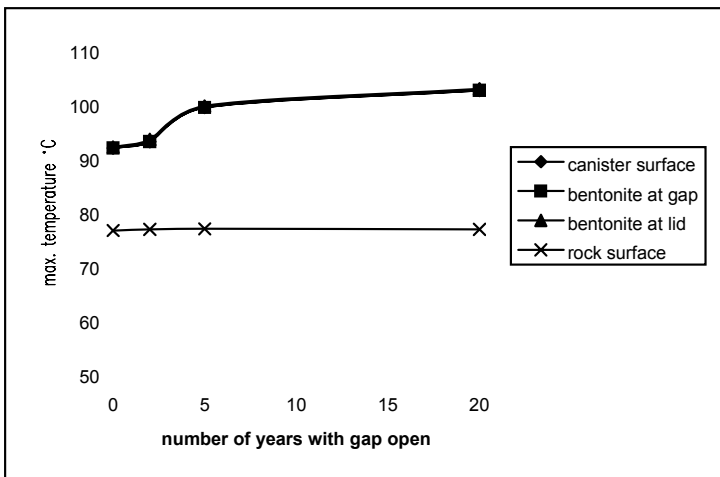
**Conclusion:** An infinitely open gap (conservative) will be adequate for the subsequent calculation of canister spacing.



gap width, mm	--
emissivity of copper	0,63
years with the gap open	>20



gap width, mm	10
emissivity of copper	--
years with the gap open	>20



gap width, mm	10
emissivity of copper	0,63
years with the gap open	--

Figure 4-1. Result of sensitivity analyses regarding the influence of a gap between canister and bentonite.

### 4.3 Target Temperature on Canister Surface

The FEM model used for the calculation of canister spacing could have been set up with the proper simulation of a gap between canister and bentonite. However, this was deemed to be an exaggerated complexity in the model in view of the general level of uncertainty in other areas and would lead to extensive run times. So instead, the outcome of the rough estimate according to Section 4.2 above was used to conclude a target temperature on the canister surface based on the following assumptions:

- With a very high level of confidence, the temperature on the canister surface must not exceed 100°C;
- The margin with respect to expected natural variations in material data and performance shall be 10°C (Section 4.1);
- The margin with respect to the risk of a gap between canister and bentonite shall be 10°C (Section 4.2).

**Conclusion:** Assume 80°C as the target temperature (maximum value) on the canister surface in the FEM analyses regarding canister spacing (Section 4.4 below).

### 4.4 Analysis of Minimum Canister Spacing

#### 4.4.1 FEM-Analyses, Model Description

The programme chosen for this study was ANSYS, a universal FEM code well established within SKB as the tool for thermal analyses in various contexts. ANSYS has been used for a number of years in analyses concerning for instance canister optimisation and layout studies of the deep repository. ANSYS was chosen in view of its powerful pre- and post-processing capabilities, a feature of importance in studies involving a great deal of variations and sensitivity analyses. The version used was ANSYS Mechanical version 5.4 release 1 from ANSYS Inc.

The model was simplified to one quarter of a canister with three symmetry planes. The simplification entails that an infinite number of rows are modelled, each with an infinite number of equidistantly located canisters. The centre to centre distance between tunnels was set to 40 m. The centre to centre distance between canisters was used as the input variable, however with a minimum of 6.0 m.

The details of the modelling in the near-field of the canister is shown in Figure 4-2. Prints of the model setup and the mesh are found in Appendix B, Figure B:1 and B:2. Figures B:3–B:5, in the same appendix, show an example of temperature Vs time from one of the Aberg calculations.



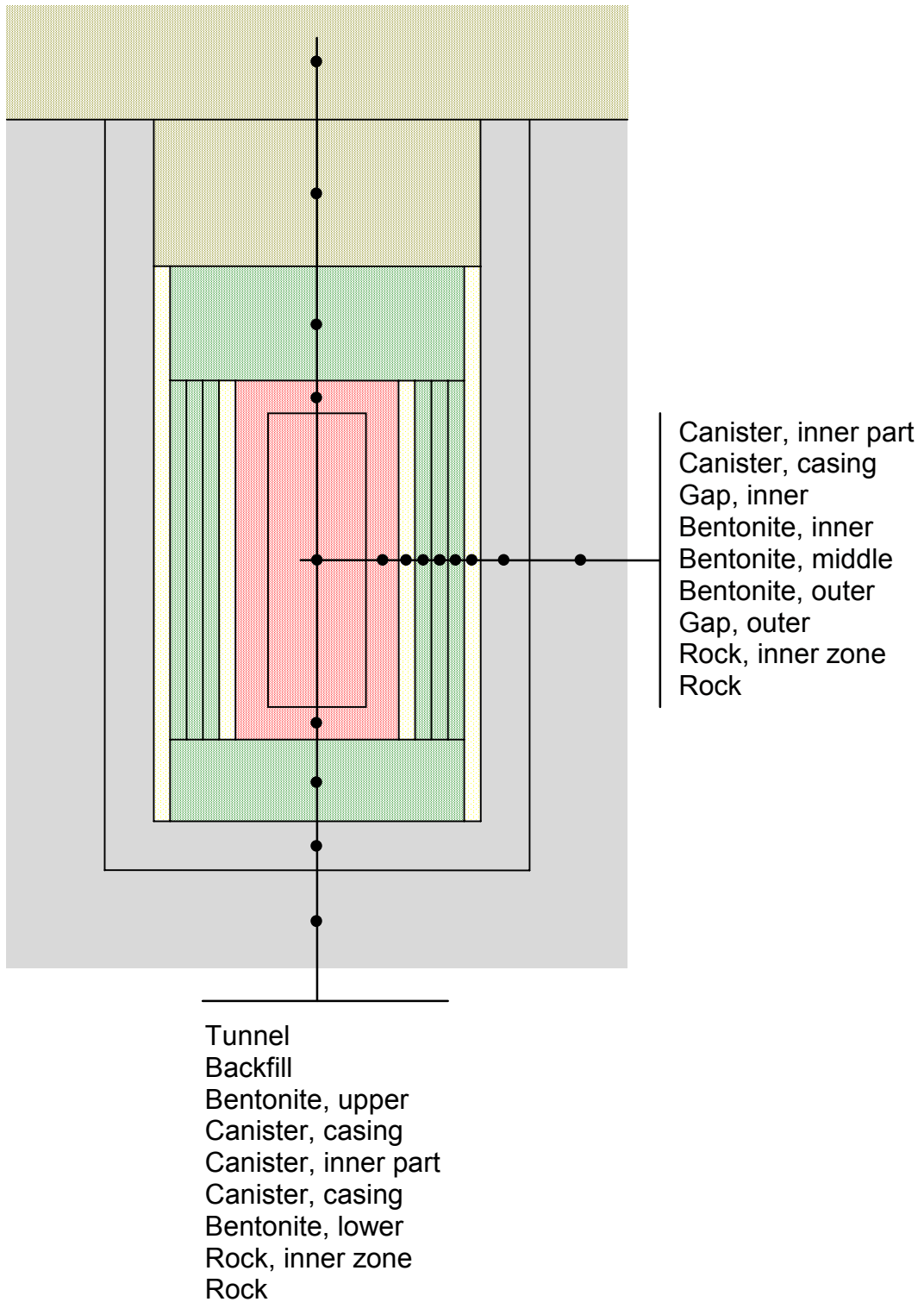
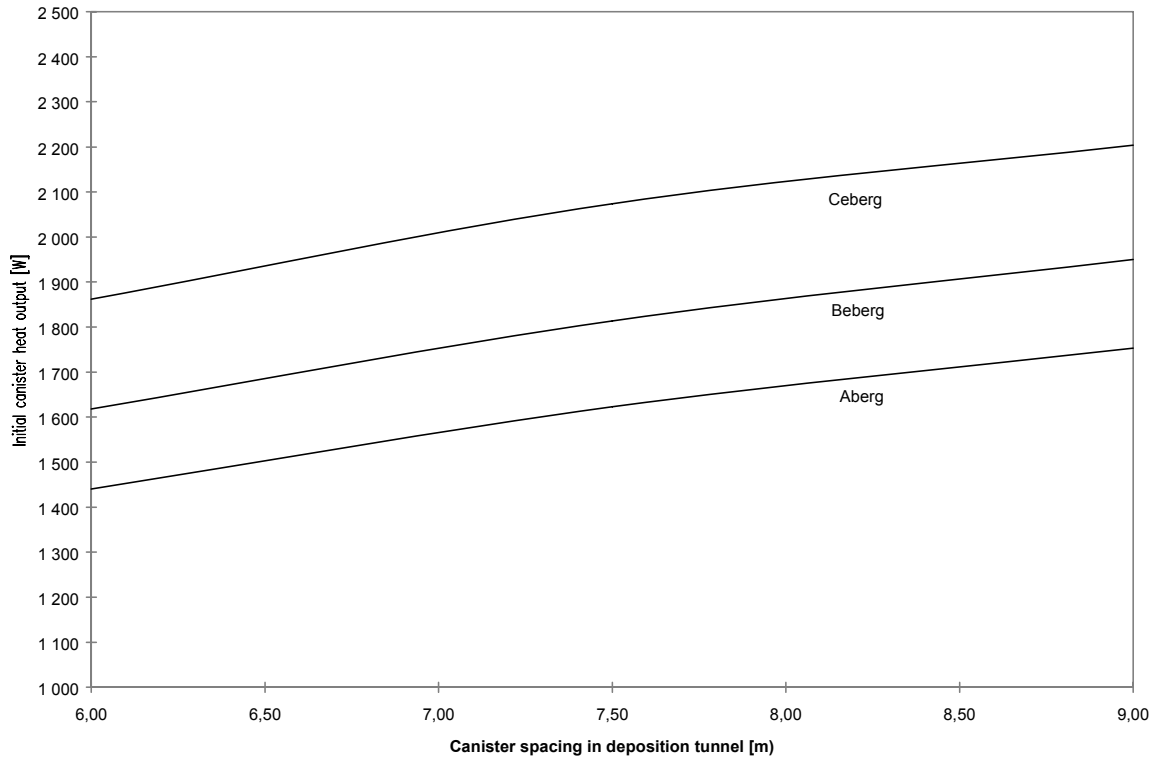


Figure 4-2. Details of the modelling around a canister.

#### 4.4.2 Canister Spacing for Aberg, Beberg and Ceberg

The results of the calculations are shown in Figure 4-3. With the assumption of an initial canister heat output of 1 625 W, the nominal canister spacing at Aberg will be 7.5 m. For Beberg and Ceberg the minimum distance of 6.0 m will be adequate. Particularly for Ceberg the margin will be large. According to the diagram, the 6.0 m distance would allow for a heat output there of approximately 1,850 W.



*Figure 4-3. Acceptable canister heat output as a function of canister spacing. Tunnel spacing 40 m, maximum temperature on canister surface 80°C.*

## 5 Heat Propagation in the Bedrock

### 5.1 FEM-analysis, Model Description

The heat propagation in the bedrock (the global calculation case), was analysed by means of a FEM model with simplified assumptions regarding the canister near-field geometrical features and the heat load application. Only the deposition tunnels were modelled, however without any details regarding the deposition hole, the canister and buffer, etc. (In principle, it would have been quite possible to combine this model with the one described in Chapter 4 above, thus getting a complete overview of the temperature distribution in the near-field as well as in the bedrock. This would, however, have resulted in an extremely large model requiring computer resources that would not be justified at present in view of the limited purpose of this study.)

The models (three) were shaped in the form of a cylinder with the extension allowing for a distance between the repository area and the boundaries of the model of at least 1,000 m in all directions except relative the given ground level. See Figure C:1, D:1 and E:1 in the Appendix section. The large extensions of the models made it possible to have the boundary conditions set to “constant temperature”.

The models were meshed by using mainly 3-D thermal solid elements (SOLID70). Typically, a model encompassed 70,000 to 100,000 elements. The mesh structures in the repository areas are illustrated by Figure C:2, D:2 and E:2 in the Appendix section.

### 5.2 Heat Load

#### 5.2.1 Number of Canisters and Phasing of Deposition Work

The deposition of canisters will take place in two phases:

- Phase 1 will encompass 400 canister and start at the time “model year 0”.
- Phase 2 will encompass the remaining canisters (the major portion) and progress with a deposition rate of 200 canisters per year. The start year of Phase 2 in the model varies between the three sites depending on differences in fuel data according to conditions set out in the table below.

#### 5.2.2 Application of Heat Load

The heat load in the model was applied as a linear heat source uniformly distributed along each deposition tunnel. The initial heat load per meter tunnel is given in Table 5-1 above and varies between the sites depending on selected canister distances.

The heat load is applied in the model on a yearly basis, according to Table 5-1, and in such a way that it reflects an assumed progress of the deposition work, starting in the deposition tunnels closest to the entrance (the central area). To allow for simultaneous, although separated, excavation and deposition works, the deposition alternates between two or three deposition panels (group of deposition tunnels) on a three year basis as described in the KBS-3 concept.

**Table 5-1 Establishing of the model time schedule**

	unit	Aberg	Beberg	Ceberg
Number of deposition tunnels in Phase 2		108	120	108
Total tunnel length in Phase 2 (given)	m	28 104	26 921	26 139
Unusable intersection parts of tunnels	m	1 296	1 440	1 296
Usable tunnel length in Phase 2	m	26 808	25 481	24 843
Min. canister distance (temp. restrictions)	m	7.5	6.0	6.0
Adjusted canister distance (+10%)	m	8.25	6.60	6.60
Number of canisters in Phase 2		3 250	3 861	3 765
Initial heat output per canister	W	1 625	1 625	1 625
Heat output per m tunnel (average)	W/m	197	246	246
Years of reactor operation		31	37	36
Number of years for Phase 2		16	19	19
<b>Time schedule for the FEM model</b>				
deposition Phase 1 (one year)	year No.	0	0	0
first year of deposition Phase 2	year No.	17	20	19
final year of deposition Phase 2	year No.	32	38	37

### 5.3 Results with Respect to Aberg, Beberg and Ceberg

The results of the calculations are presented as coloured prints in the Appendix section where Appendix C refers to Aberg, Appendix D to Beberg and Appendix E to Ceberg respectively. The following prints are included:

- On repository level (horizontal section) at the time when the Phase 2 deposition is about to start (Figure C:3, D:3 and E:3).
- On repository level (horizontal section) at the time when Phase 2 deposition just has been finished (Figure C:5, D:4 and E:4). For Aberg only, also the result when Phase 2 on level 1 (-600 m) has been finished is presented (Figure C:4).
- On repository level (horizontal section) at 200 years after the start of Phase 1 (Figure C:6, C:7, D:5, E:5).
- Aberg only: In a vertical section cutting through the Phase 1 and Phase 2 areas at 42 years after the start of Phase 1, i.e. 10 years after the deposition is finished (Figure C:9). The print illustrates the interference between level 1 and 2.
- In a vertical section cutting through the Phase 1 and Phase 2 areas at 200 years after the start of Phase 1 (Figure C:9, D:6, E:6).
- In a vertical section cutting through the Phase 1 and Phase 2 areas at 1 000 years after the start of Phase 1 (Figure C:10, D:7, E:7).

## 6 Discussion

The study has demonstrated the feasibility of modelling thermal processes in the repository by means of an universal finite element programme (in our case ANSYS). The computation was carried out on a PC platform under Windows NT and proven competent to handle temperature as well as time dependent thermal parameters (2nd order theorem). The fact that the postulated rock parameters in our case assumed homogeneous bedrock material should not be considered as a simplification with respect to the data processing. The model will be affected only insignificantly, should there in the future be justified to consider anomalies or unisotropic behaviour in the bedrock or in the bentonite.

The model has also demonstrated the heat propagation when the heat load application was based on an assumed realistic timely progression of the deposition work. The result showed a pattern for the temperature distribution in the deposition areas that in the future could be used as a tool for a further optimisation of the repository with respect to canister spacing (cooler boundary zones).

The calculations were carried out for a model time of up to 1,000 years. At that time, the heat wave has barely reached the ground surface and the peak rock temperature at repository level has been passed since long. The maximum temperature on the canister surface was reached as early as after 10 to 20 years. One reason for this early occurrence is the decay of the spent fuel. For instance, 20 years after deposition the remaining heat output is 70%, after 200 years 20% and after 1,000 years only about 7%.

Comparing the temperature distribution between different sites does not present much valuable information as the conditions regarding total as well as specific heat load differ significantly. The two most similar sites are Beberg and Ceberg. With respect to heat load capacity (W per m<sup>2</sup> repository area), Ceberg are more competent than Beberg depending on a favourable heat conductivity and a lower initial rock temperature. It should be pointed out, however, that it was not possible to take full advantage of this fact in the study as a tunnel distance of 40 m and a minimum canister spacing of 6 m were considered as fix conditions. The main difference between the two sites consists in a somewhat higher temperature in the rock (+5°C) and a less advanced heat wave front at Beberg. In a real situation, this difference could be neutralised by the possibility of a denser positioning of deposition tunnels at Ceberg.

The conditions affecting temperature distribution at Aberg are generally rather unfavourable. It is a two-level repository, giving raise to interference problems, located in rock with low heat conductivity and high initial temperature. The interference will occur already after about 30 years causing a higher rock temperature than in a one-level repository (5–10°C difference). However, the interference between the two levels will occur well after the peak temperature on the canister surface is passed, and will therefore not affect the canister spacing and the distance between deposition tunnels.

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**Table A-1. Summary of geometrical and thermal parameters**

	unit	Calculation cases					
		Canister spacing			Global heat propagation		
		Aberg	Beberg	Ceberg	Aberg	Beberg	Ceberg
<b>Repository layout</b>							
depth below ground, layer 1	m	600	600	500			
layer 2	m	500	–	–			
canister spacing	m	min 6.0					
tunnel spacing	m	40					
tunnel diameter (TBM)	m	5.0					
positioning index		1.00			0.91		
<b>Canister data</b>							
number of canisters		3,650	4,261	4,165			
length	mm	4,830					
diameter	mm	1,050					
initial heat output	W	1,625					
heat conductivity	W/m,K	390					
heat capacity	MJ/M <sup>3</sup> ,K	2.40					
target temperature	°C	80					
year number for phase 1 (400 canisters)		not applicable			0	0	0
year numbers for phase 2 (remaining canister)		not applicable			17–32	20–38	19–37
<b>Inner gap</b>							
gap width	mm	will be compensated for by an extra 10°C margin					
conductivity years 1–2	W/m,K	as bentonite, layer 1					
conductivity years 3–5	W/m,K	ditto					
conductivity after 5 year	W/m,K	ditto					
<b>Bentonite – layer 1<sup>2</sup></b>							
conductivity years 1–2	W/m,K	0.90 (70%)					
conductivity years 3–5	W/m,K	0.90 (70%)					
conductivity after 5 year	W/m,K	0.90 (70%)					
heta capacity	MJ/m <sup>3</sup> ,K	2.20					
<sup>2</sup> saturation in %							
<b>Bentonite – layer 2</b>							
conductivity years 1–2	W/m,K	1.05 (90%)					
conductivity years 3-5	W/m,K	1.05 (90%)					
conductivity after 5 year	W/m,K	1.05 (90%)					
heta capacity	MJ/m <sup>3</sup> ,K	2.20					
<b>Bentonite – layer 3 and outer gap</b>							
conductivity years 1–2	W/m,K	1.15 (100%)					
conductivity years 3–5	W/m,K	1.15 (100%)					
conductivity after 5 year	W/m,K	1.15 (100%)					
heta capacity	MJ/m <sup>3</sup> ,K	2.20					
<b>Rock</b>							
conductivity at initial temperature	W/m,K	2.83	3.20	3.80			
temperature dependence	% per °C	–0,10					
heat capacity	MJ/m <sup>3</sup> ,K	2.00	2.10	2.30			
temperature dependence	% per °C	not applicable			0.20		
initial temperature in repository	°C	16.0	13.5	11.0			
temperature gradient	°C/km	13.5	12.7	15.5			
<b>Tunnel backfill</b>							
conductivity	W/m,K	1.00					
heat capacity	MJ/m <sup>3</sup> ,K	1.75					

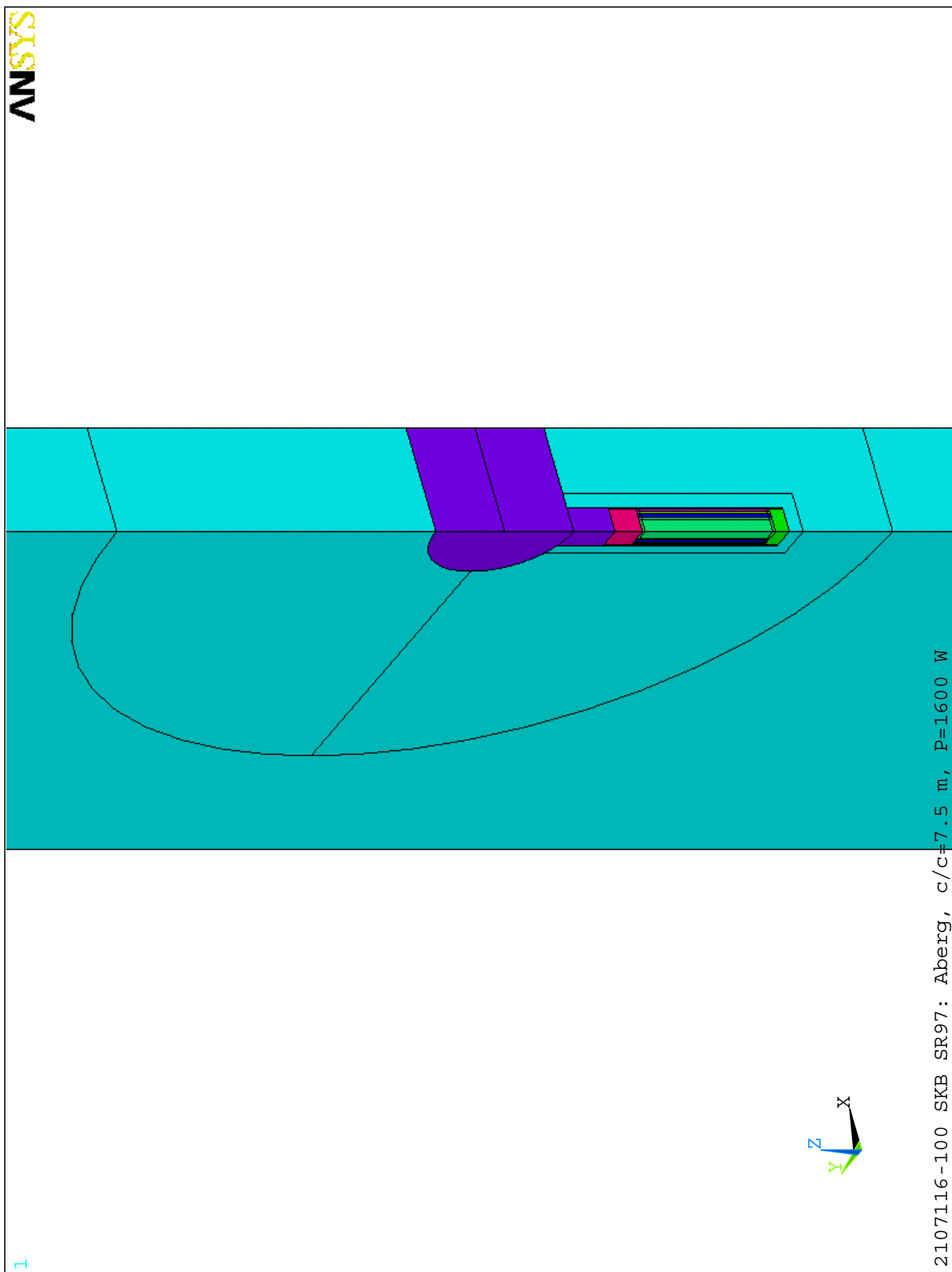


Figure B:1. Overview of the geometrical extension of the model



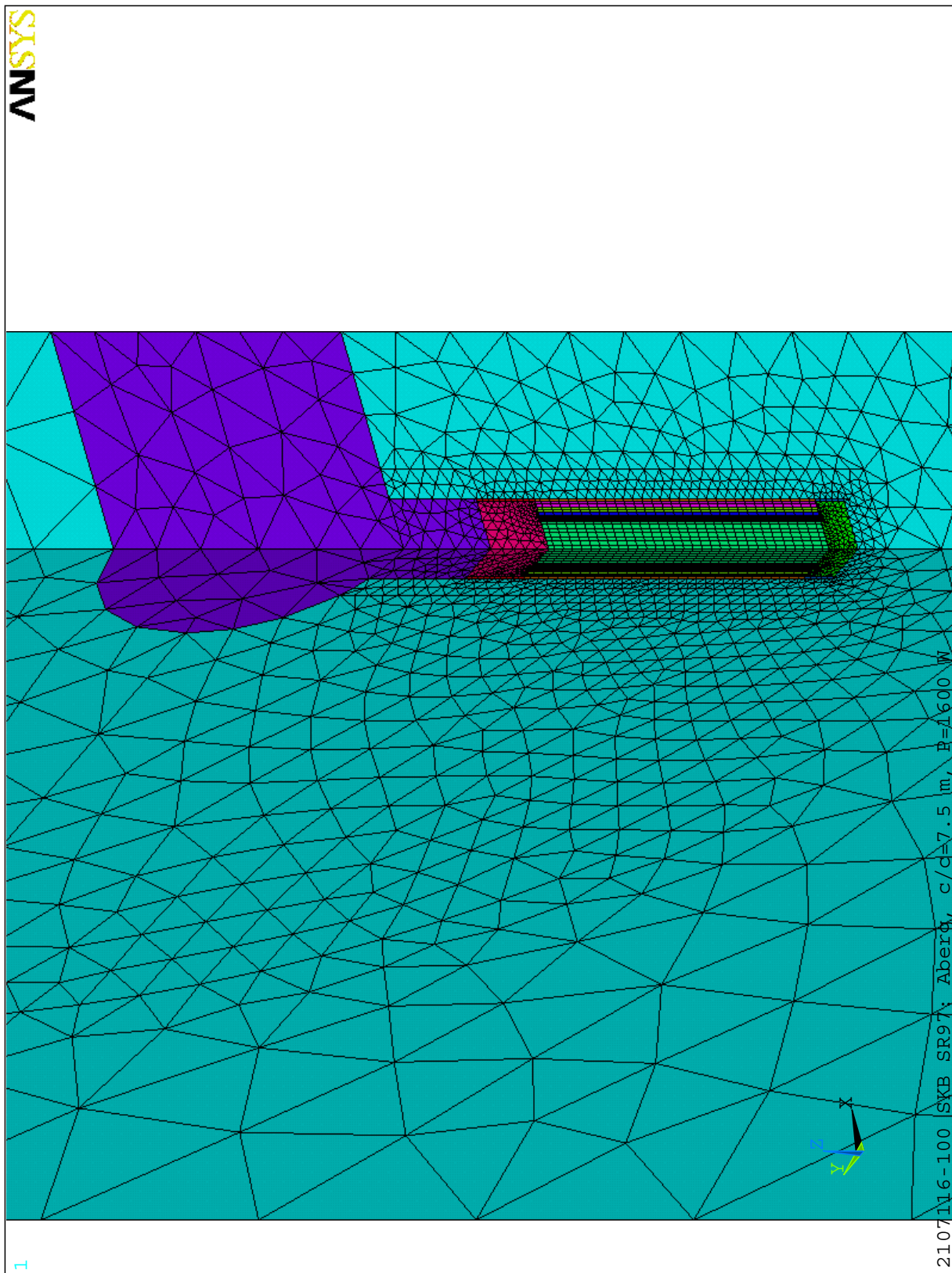


Figure B:2. Detail of the mesh modelled in the near-field of the canister.

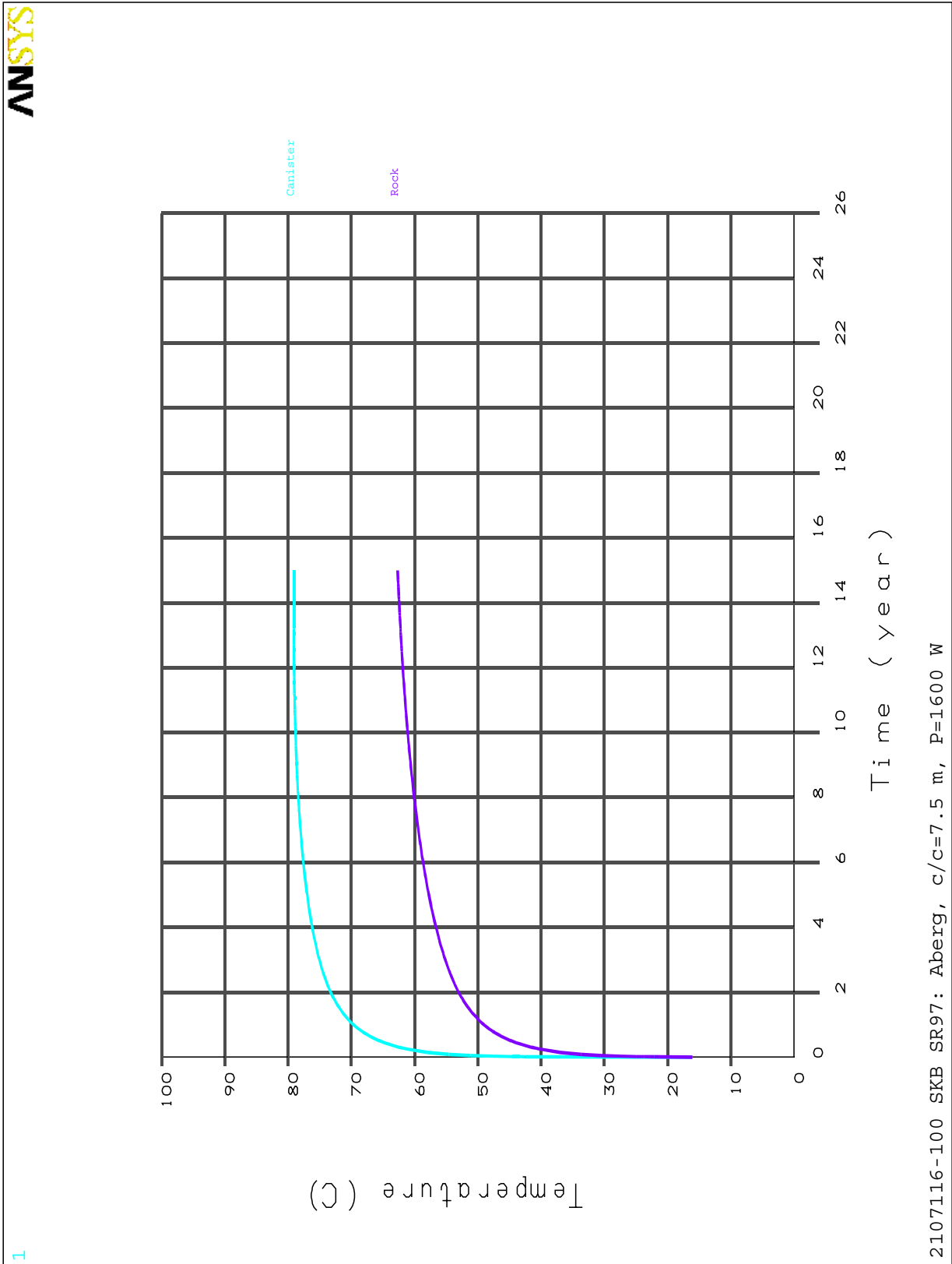


Figure B.3. Temperature as a function of time (Aberg, 1600 W, spacing 7.5 m) on the canister surface (blue) and at the interface between compacted bentonite and rock (red).

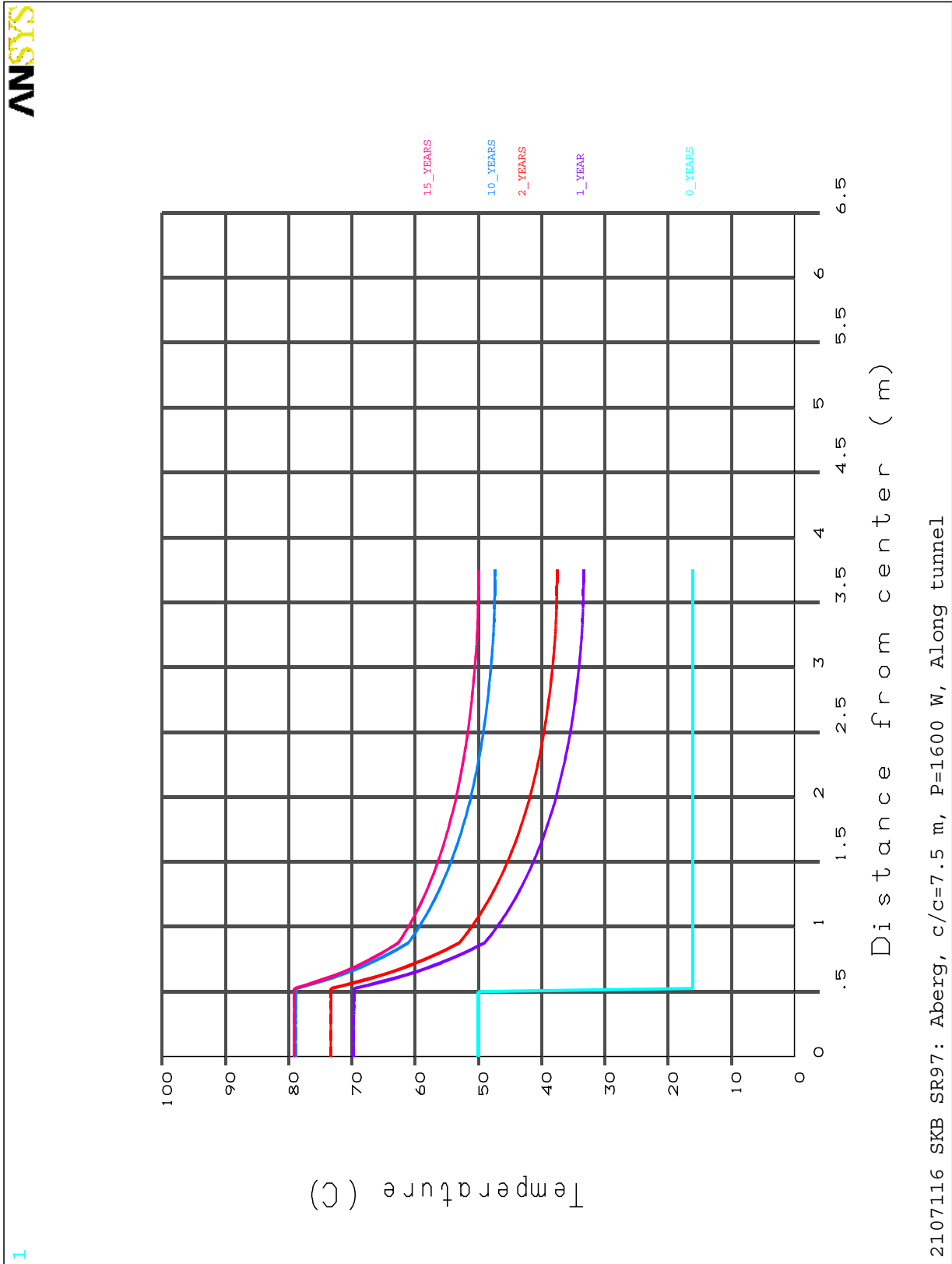


Figure B:4. Temperature profiles at certain times after deposition (canister centre for X=0. Section along the deposition tunnel (same calculation as shown in Figure B:3).

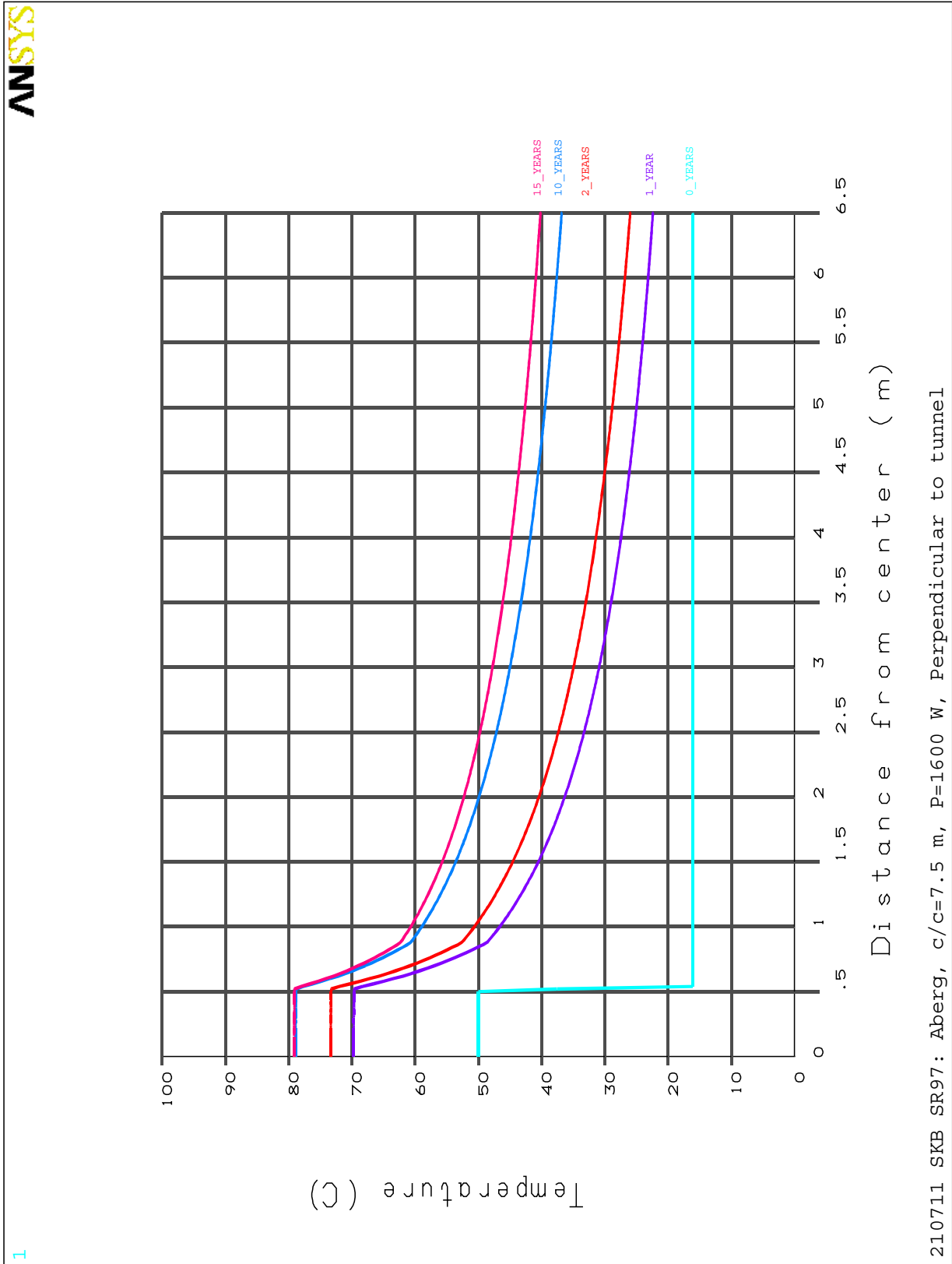


Figure B:5. Temperature profiles at certain times after deposition (canister centre for X=0). Section perpendicular to the deposition tunnel (same calculation as shown in Figure B:3).

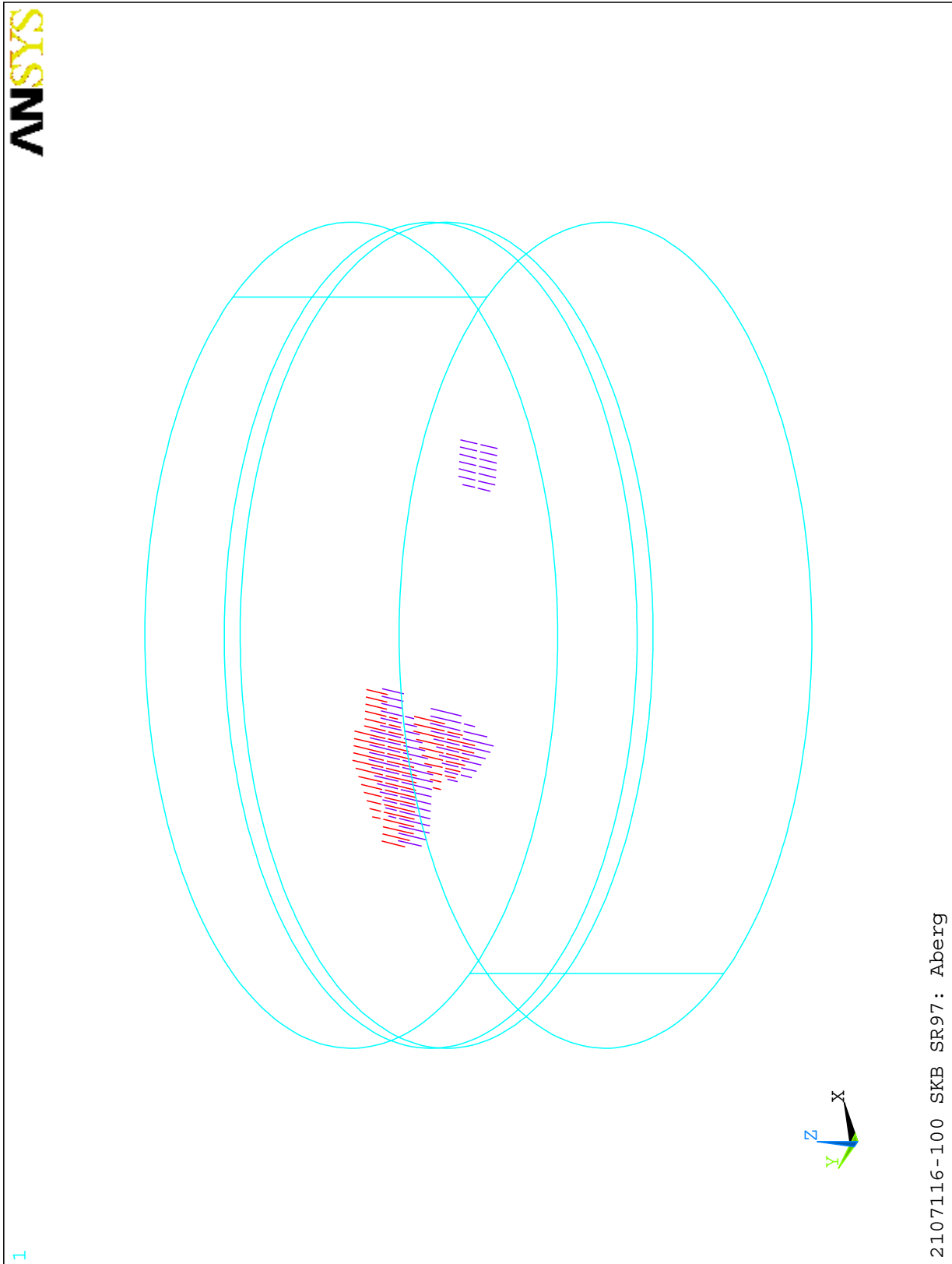


Figure C:1. Overview of the geometrical extension of the model.

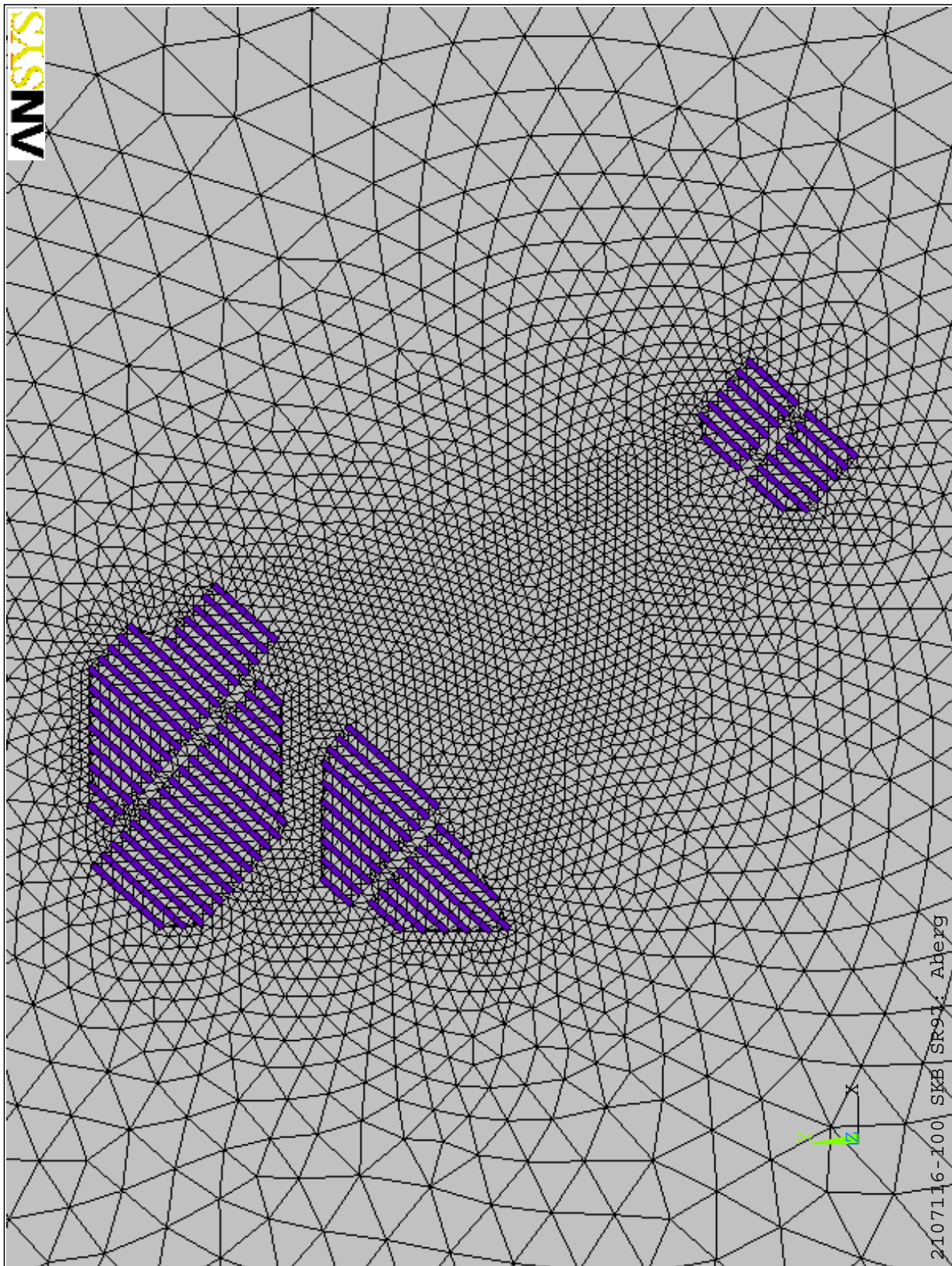
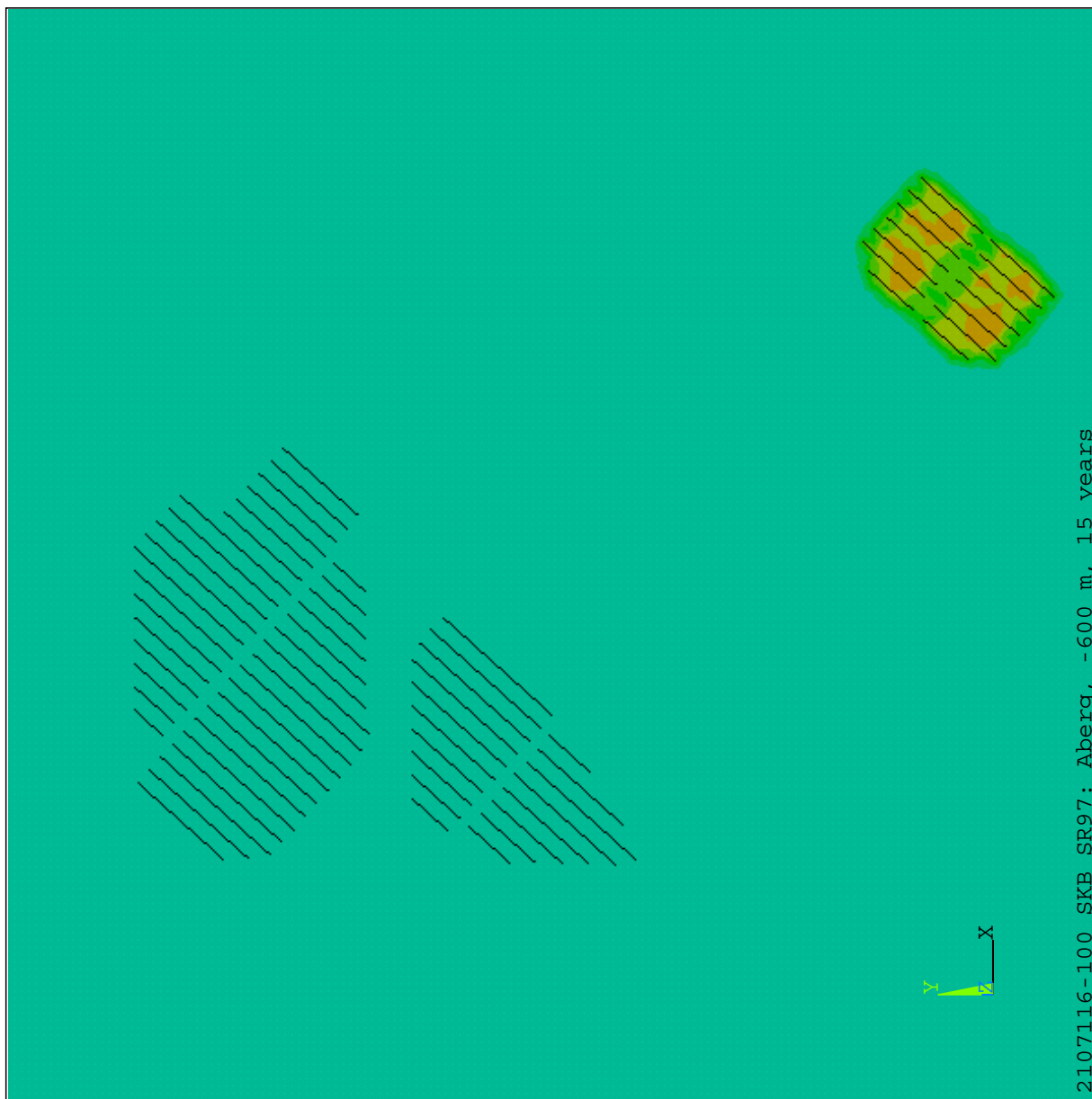


Figure C:2. Close-up of the mesh modelled in the deposition area on level 1 (-600 m).

ANSYS 5.4  
JAN 20 1999  
01:18:28  
PLOT NO. 1  
NODAL SOLUTION  
TIME=.473E+09  
TEMP  
SMN =15.945  
SMX =44.938



*Figure C.3. Heat distribution on repository level 1 (-600 m) after 15 years, i.e. just before deposition in area 2 on level 1 commences.*



ANSYS 5.4  
JAN 20 1999  
01:26:11  
PLOT NO. 1  
NODAL SOLUTION  
TIME= .757E+09  
TEMP  
SMN =15.945  
SMX =48.455

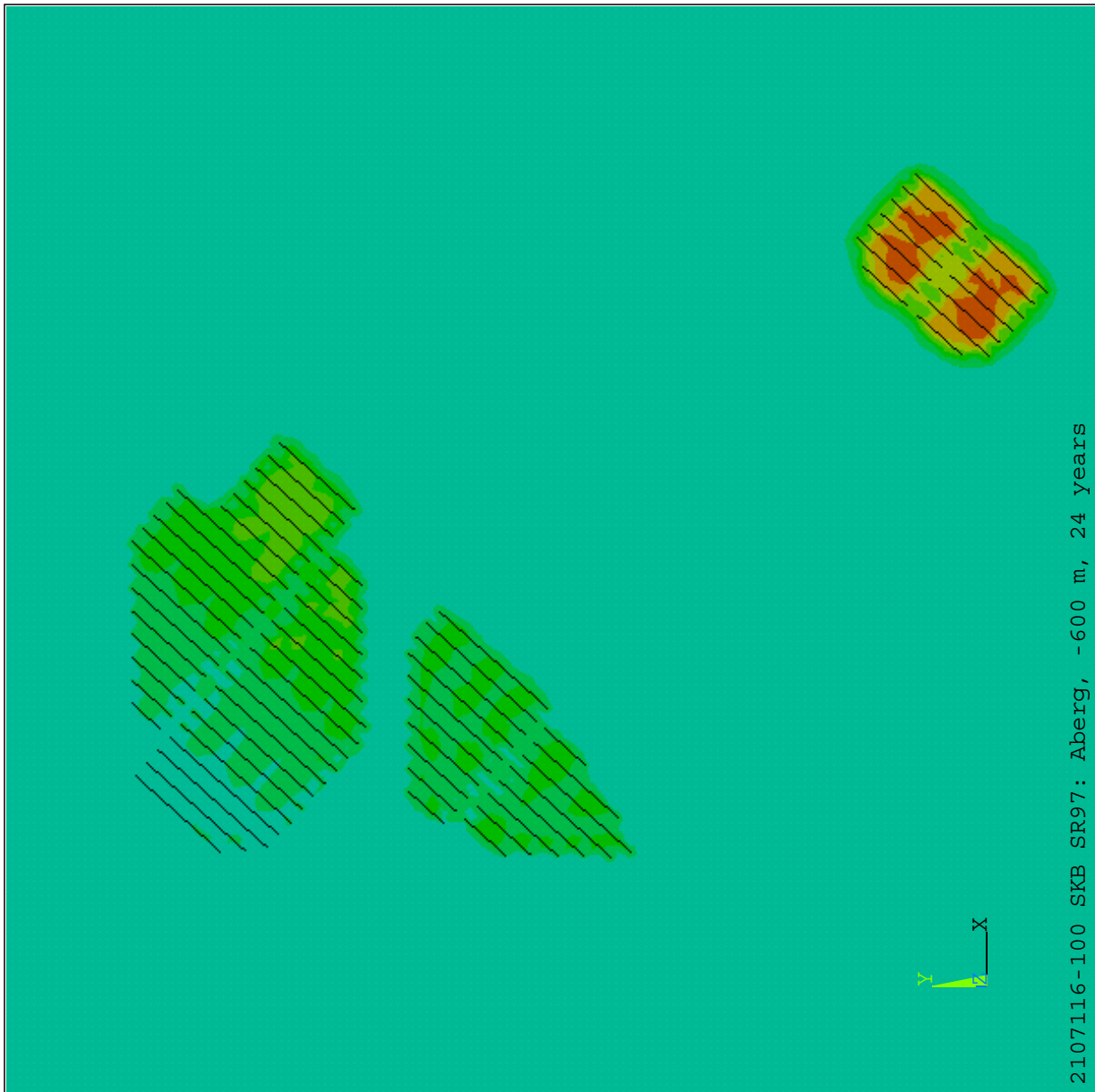
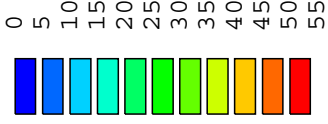
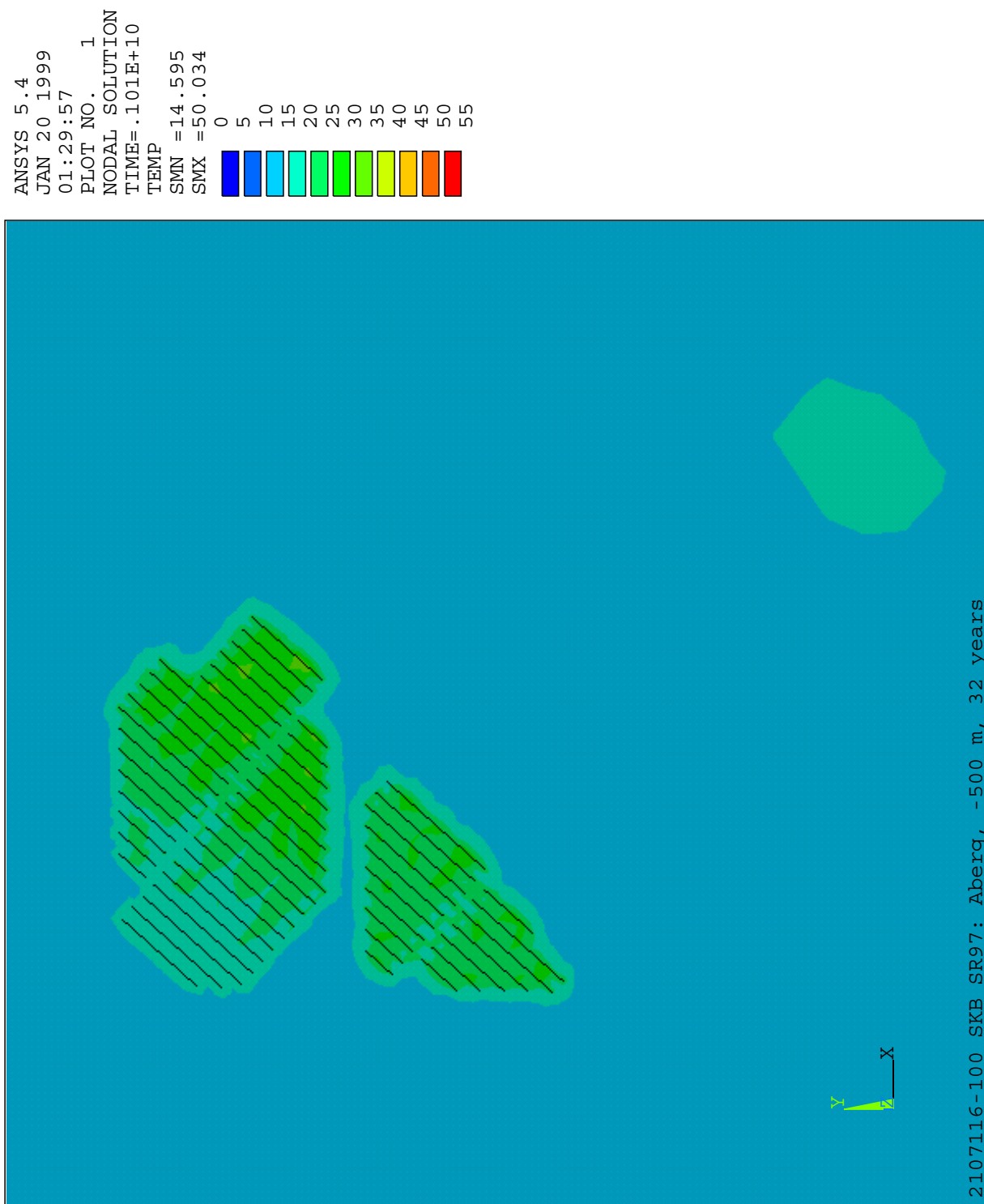


Figure C.4. Heat distribution on repository level 1 (-600 m) after 24 years, i.e. when deposition on level 1 is finished.





*Figure C.5. Heat distribution on repository level 2 (-500 m) after 32 years, i.e. when deposition in area 2 is finished.*

ANSYS 5.4  
JAN 20 1999  
01:27:35  
PLOT NO. 1  
NODAL SOLUTION  
TIME=.631E+10  
TEMP  
SMN =15.945  
SMX =53.246

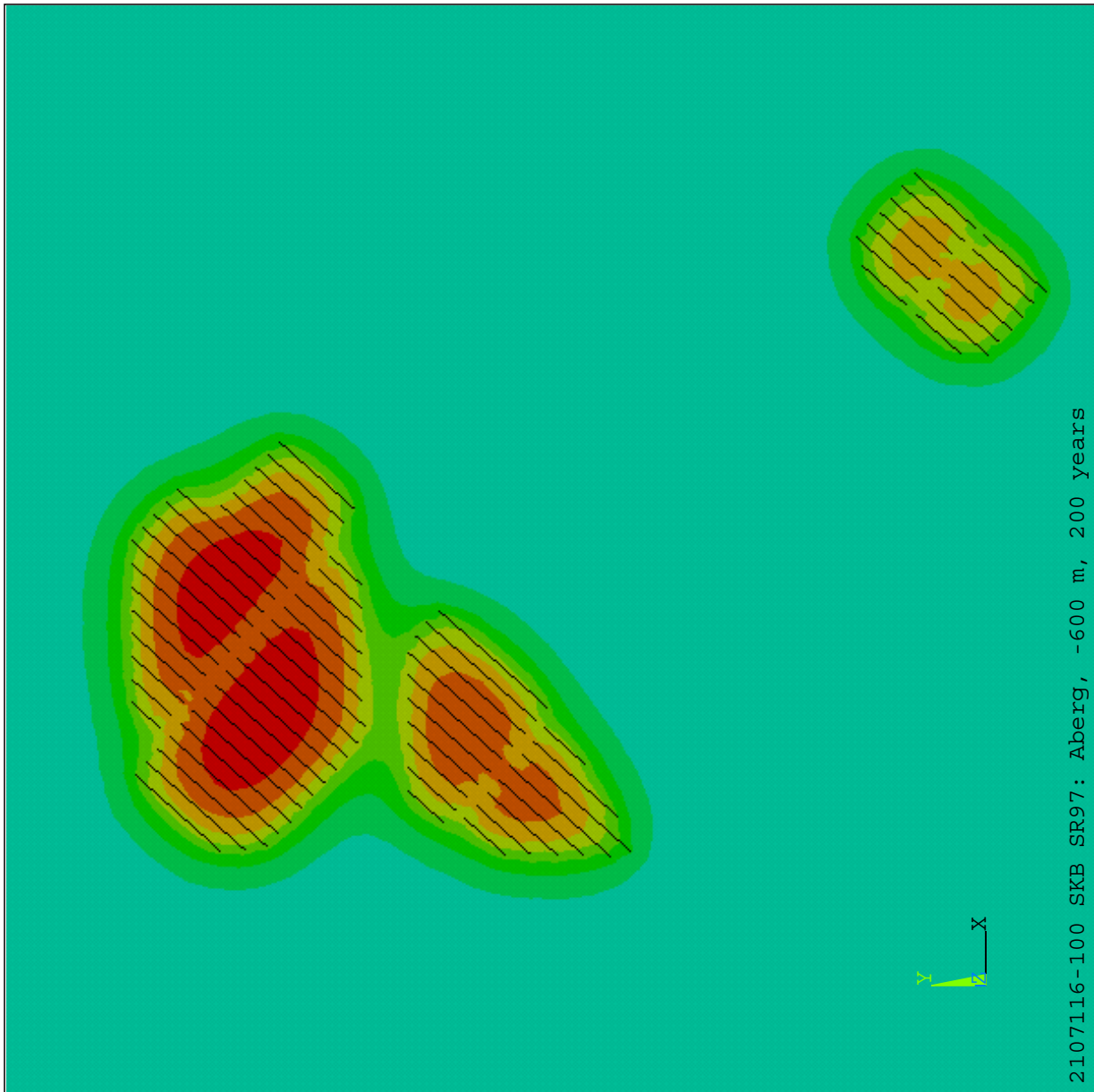
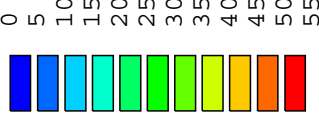


Figure C:6. Heat distribution on repository level 1 (-600 m) after 200 years.

ANSYS 5.4  
JAN 20 1999  
01:31:49  
PLOT NO. 1  
NODAL SOLUTION  
TIME=.631E+10  
TEMP  
SMN =14.595  
SMX =53.246

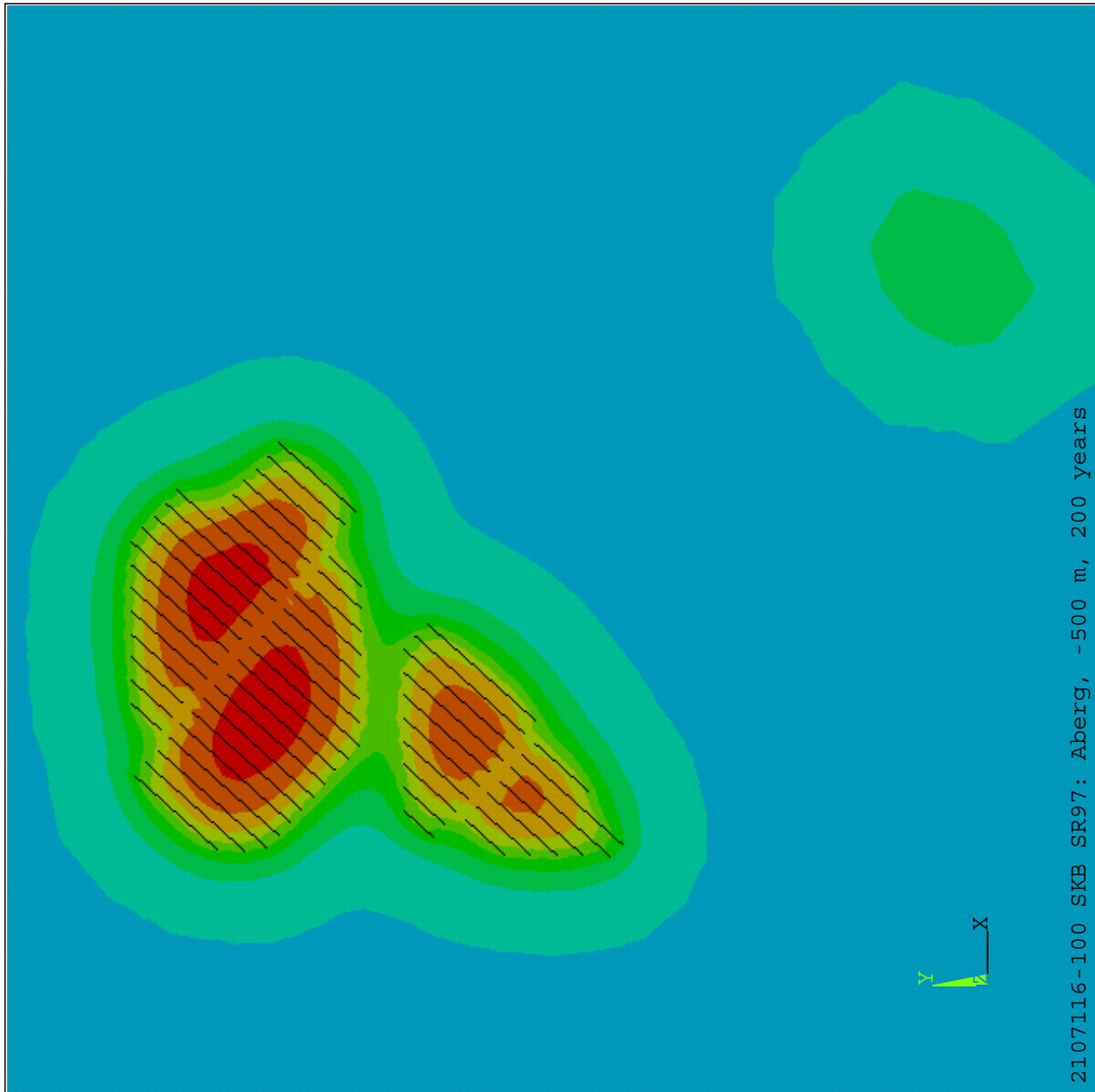
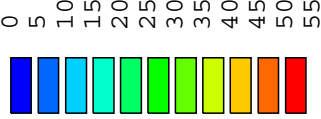
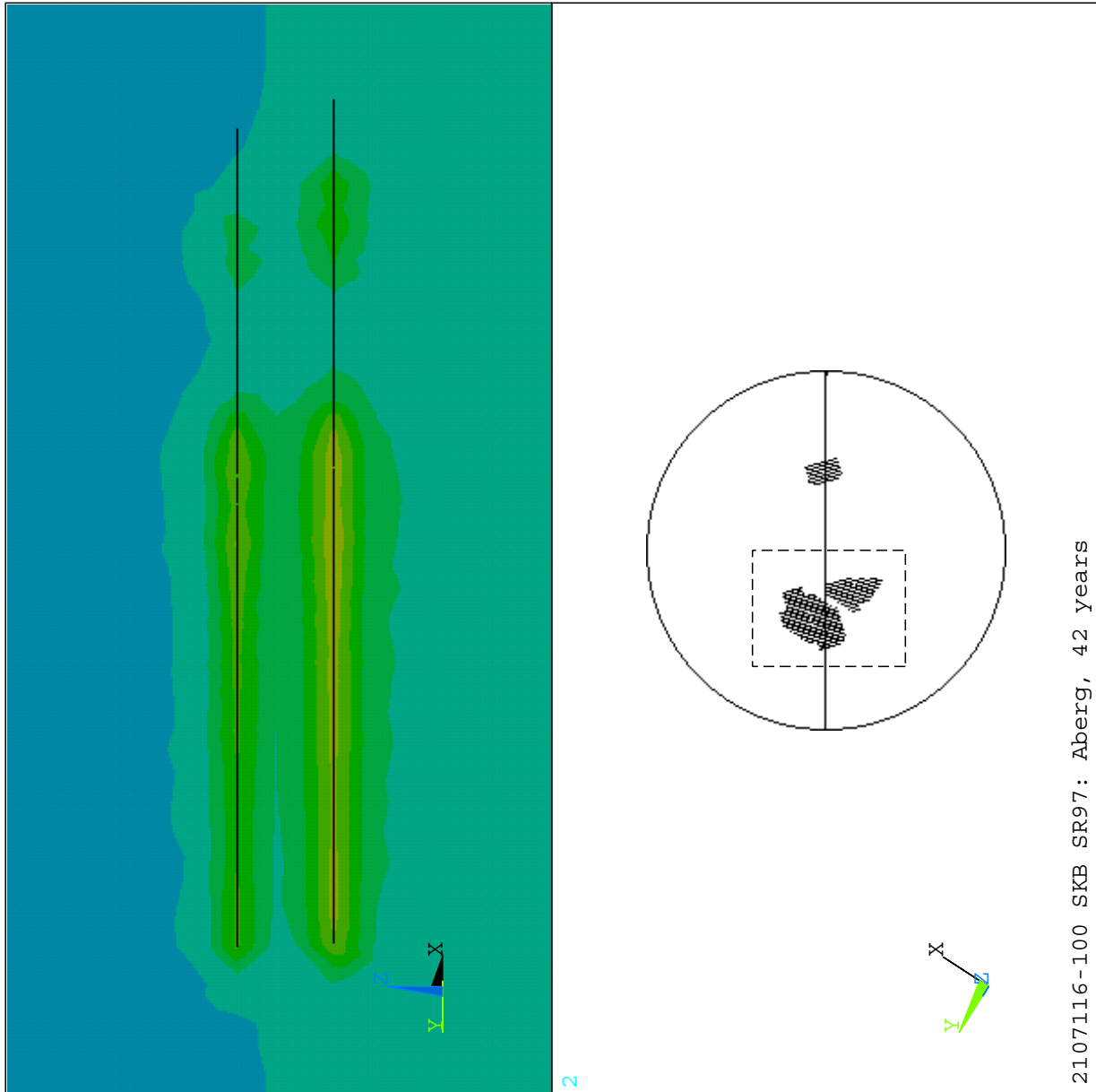


Figure C:7. Heat distribution on repository level 2 (-500 m) after 200 years.

ANSYS 5.4  
 JAN 20 1999  
 03:45:48  
 PLOT NO. 1  
 NODAL SOLUTION  
 TIME=.133E+10  
 TEMP  
 SMN =7.9  
 SMX =51.021



*Figure C:8. Close-up of heat distribution in a vertical cross-section after 42 years, i.e. 10 years after the deposition is finished (illustrates interference between level 1 and 2) (the location of the section is indicated by the attached key figure).*

ANSYS 5.4  
 JAN 20 1999  
 03:58:05  
 PLOT NO. 1  
 NODAL SOLUTION  
 TIME=.631E+10  
 TEMP  
 SMN =7.9  
 SMX =53.246

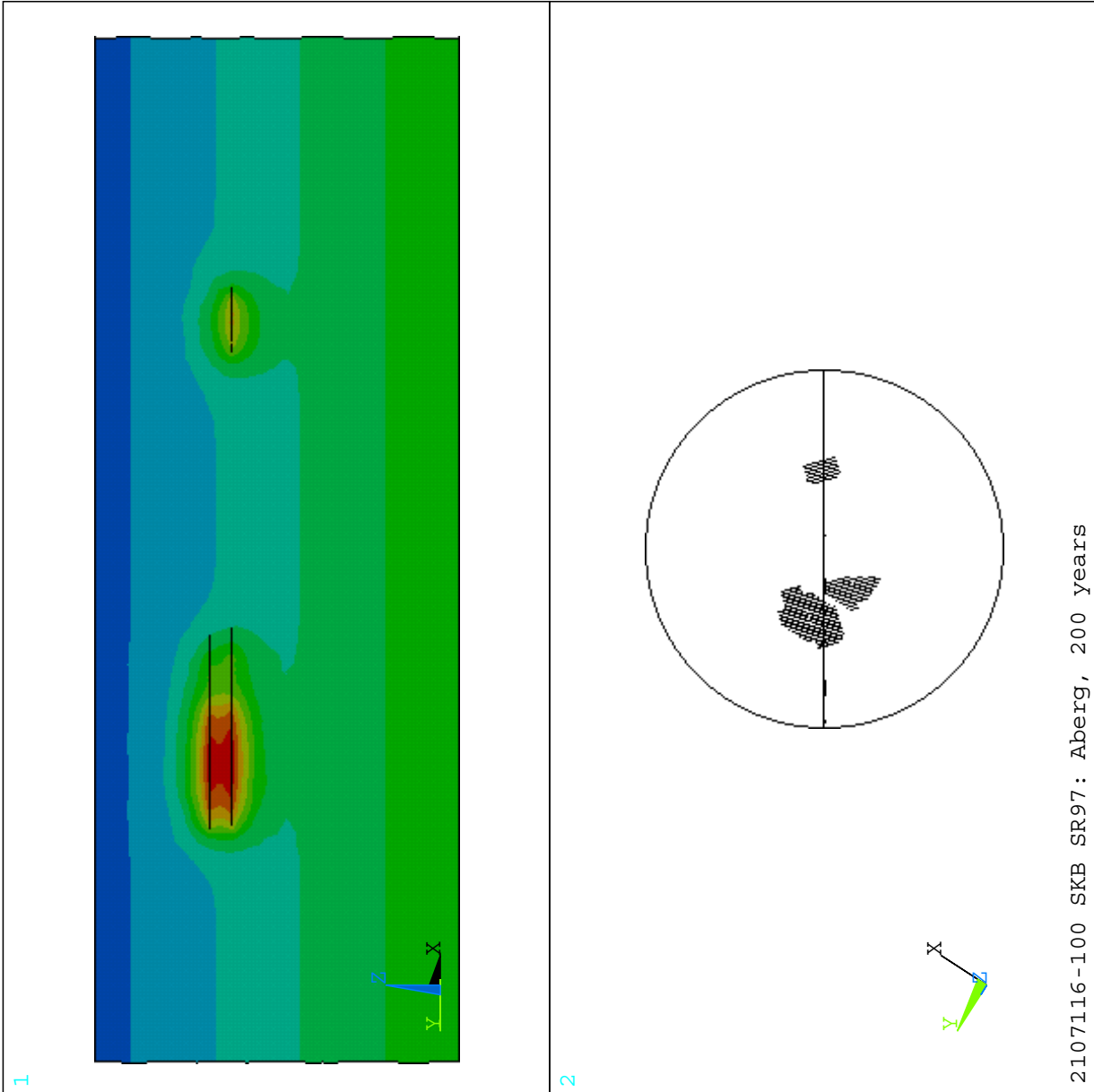


Figure C.9. Heat distribution in a vertical cross-section after 200 years (the location of the section is indicated by the attached key figure).

ANSYS 5.4  
 JAN 20 1999  
 04:03:44  
 PLOT NO. 1  
 NODAL SOLUTION  
 TIME=.316E+11  
 TEMP  
 SMN =7.9  
 SMX =49.551

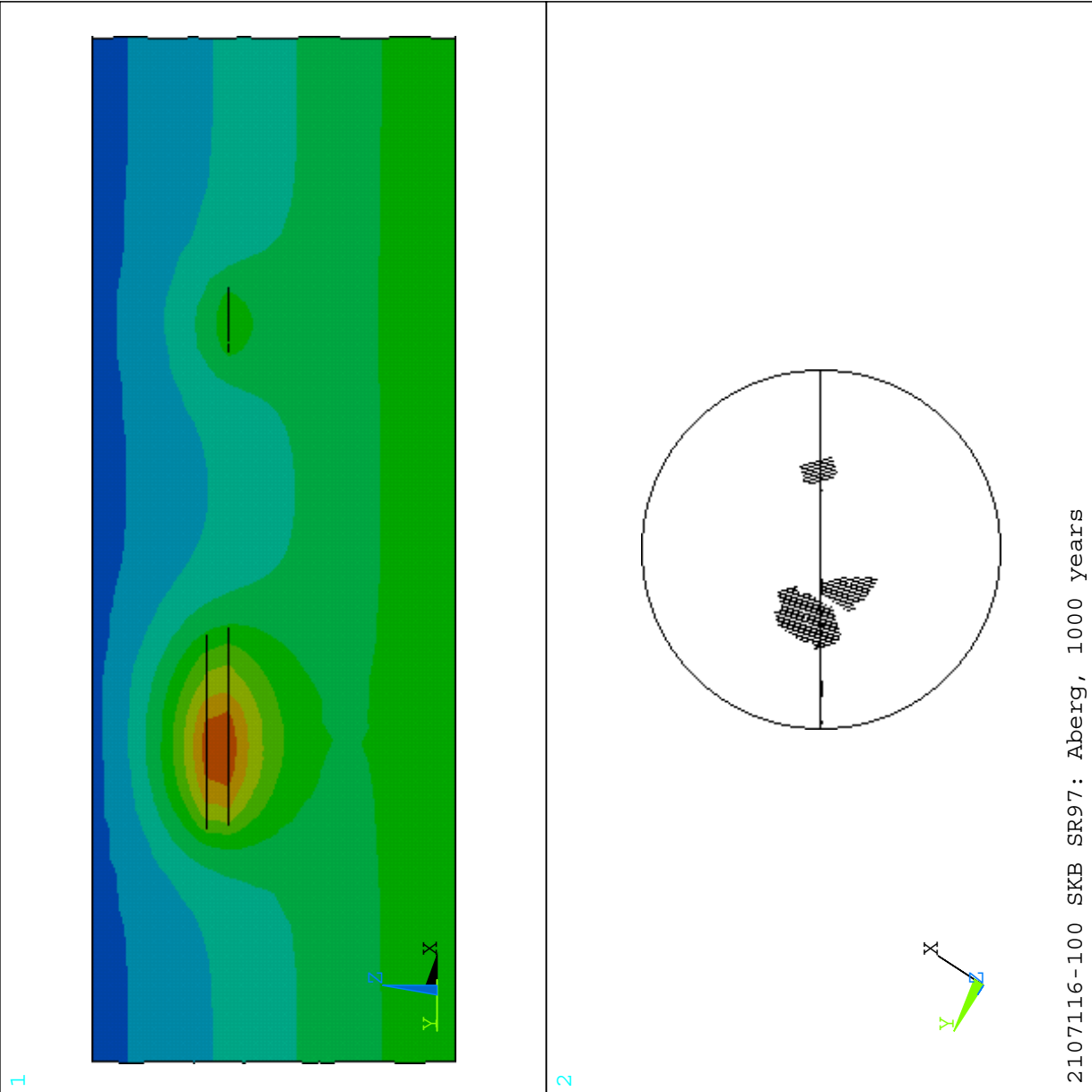


Figure C:10. Heat distribution in a vertical cross-section after 1,000 years (the location of the section is indicated by the attached key figure).

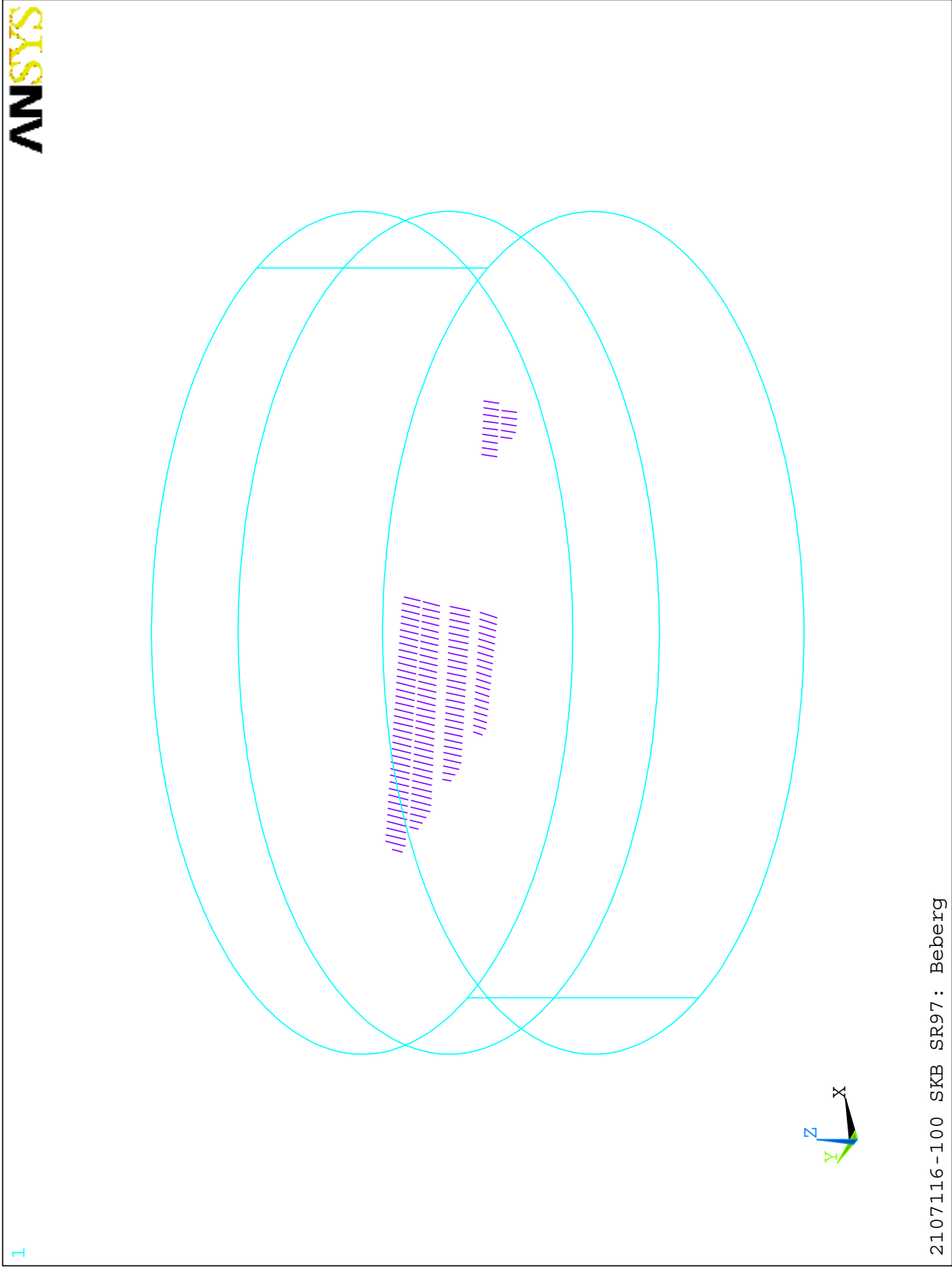


Figure D:1. Overview of the geometrical extension of the model.



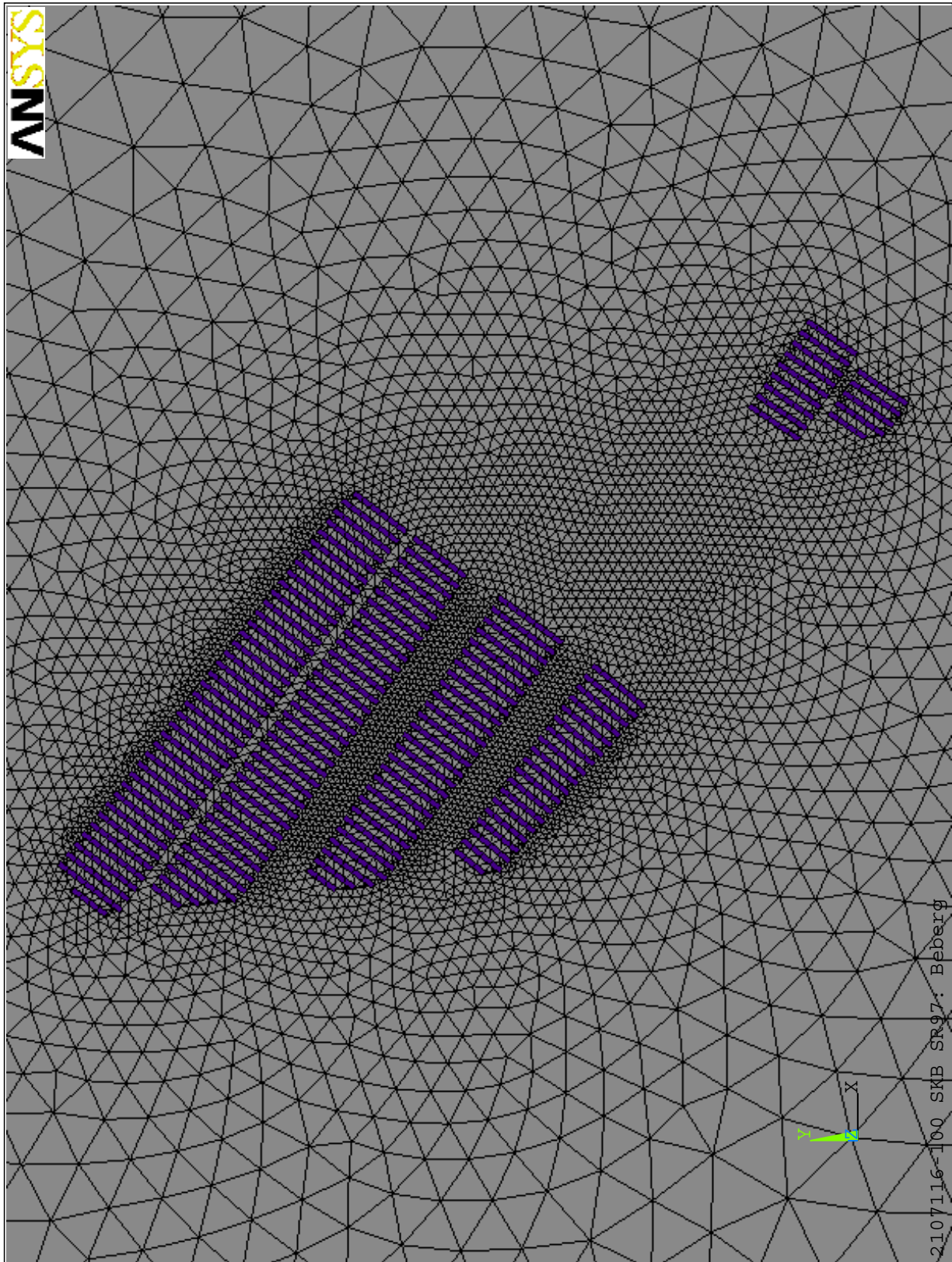
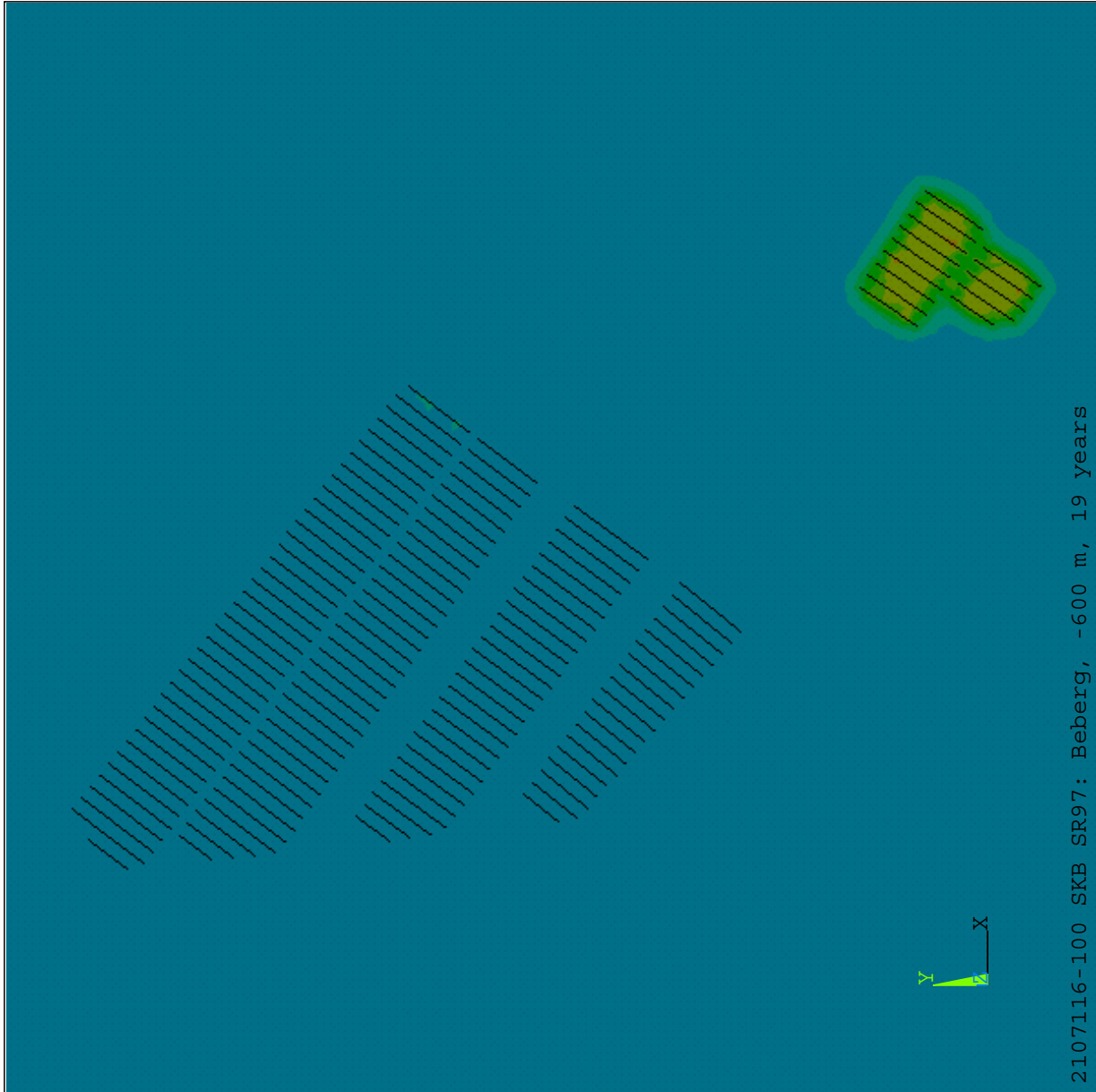


Figure D:2. Close-up of the mesh modelled in the deposition area.



ANSYS 5.4  
JAN 20 1999  
05:00:15  
PLOT NO. 1  
NODAL SOLUTION  
TIME=.600E+09  
TEMP  
SMN =5.88  
SMX =41.851



*Figure D:3. Heat distribution on repository level (-600 m) after 19 years, i.e. just before deposition in area 2 commences.*

ANSYS 5.4  
JAN 20 1999  
05:03:24  
PLOT NO. 1  
NODAL SOLUTION  
TIME= .123E+10  
TEMP  
SMN =5.88  
SMX =44.93

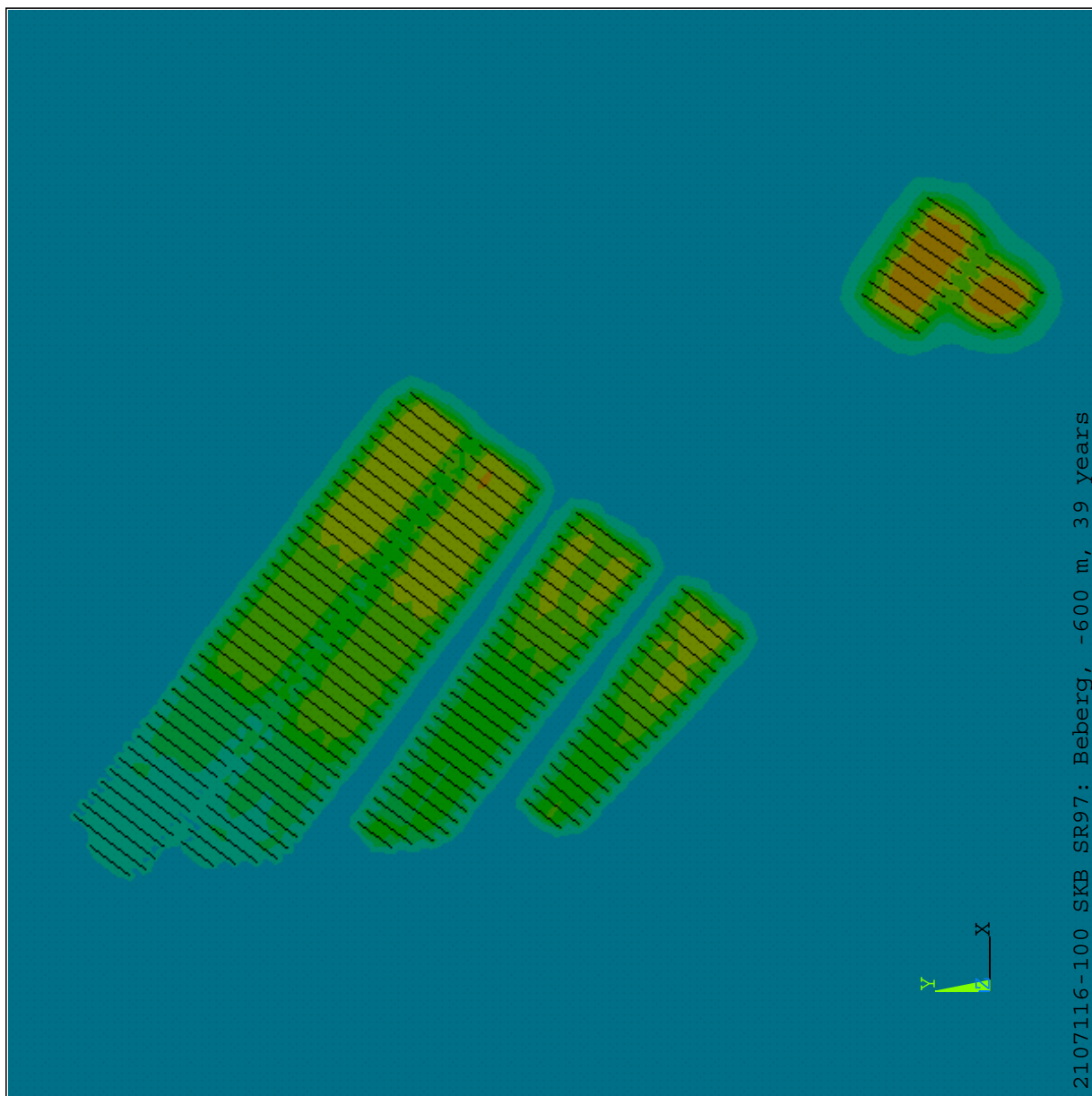
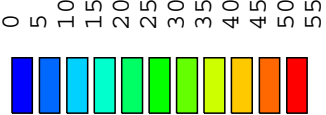


Figure D:4. Heat distribution on repository level (-600 m) after 39 years, i.e. when deposition in area 2 is finished.

ANSYS 5.4  
JAN 20 1999  
05:05:58  
PLOT NO. 1  
NODAL SOLUTION  
TIME= .631E+10  
TEMP  
SMN =5.88  
SMX =43.08

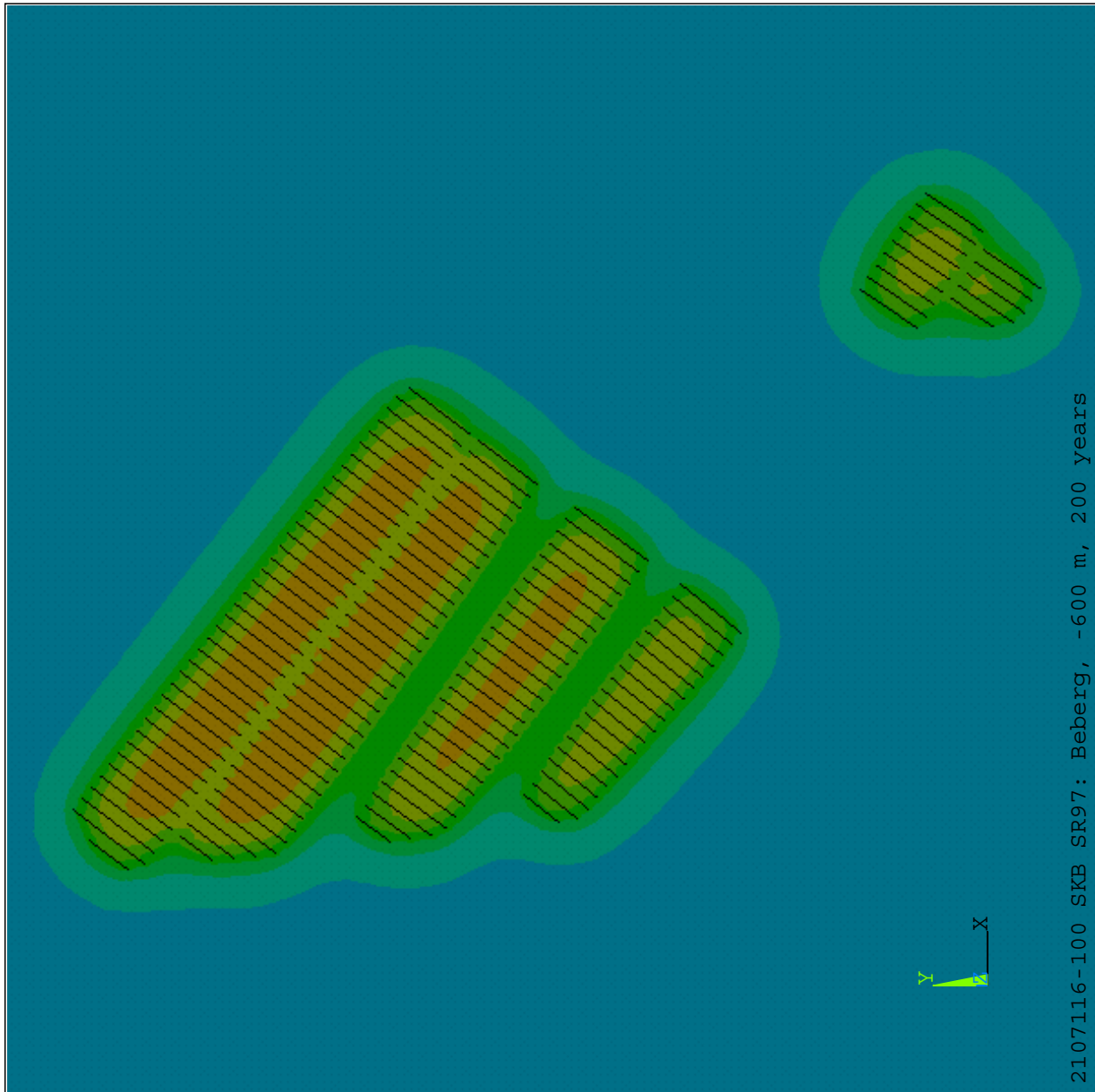
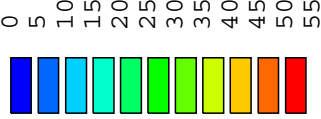


Figure D:5. Heat distribution on repository level (-600 m) after 200 years.

ANSYS 5.4  
 JAN 20 1999  
 05:48:33  
 PLOT NO. 1  
 NODAL SOLUTION  
 TIME=.631E+10  
 TEMP  
 SMN =5.88  
 SMX =43.08

0	5	10	15	20	25	30	35	40	45	50	55
Blue	Light Blue	Light Cyan	Cyan	Green	Light Green	Yellow-Green	Yellow	Orange	Red-Orange	Red	Dark Red

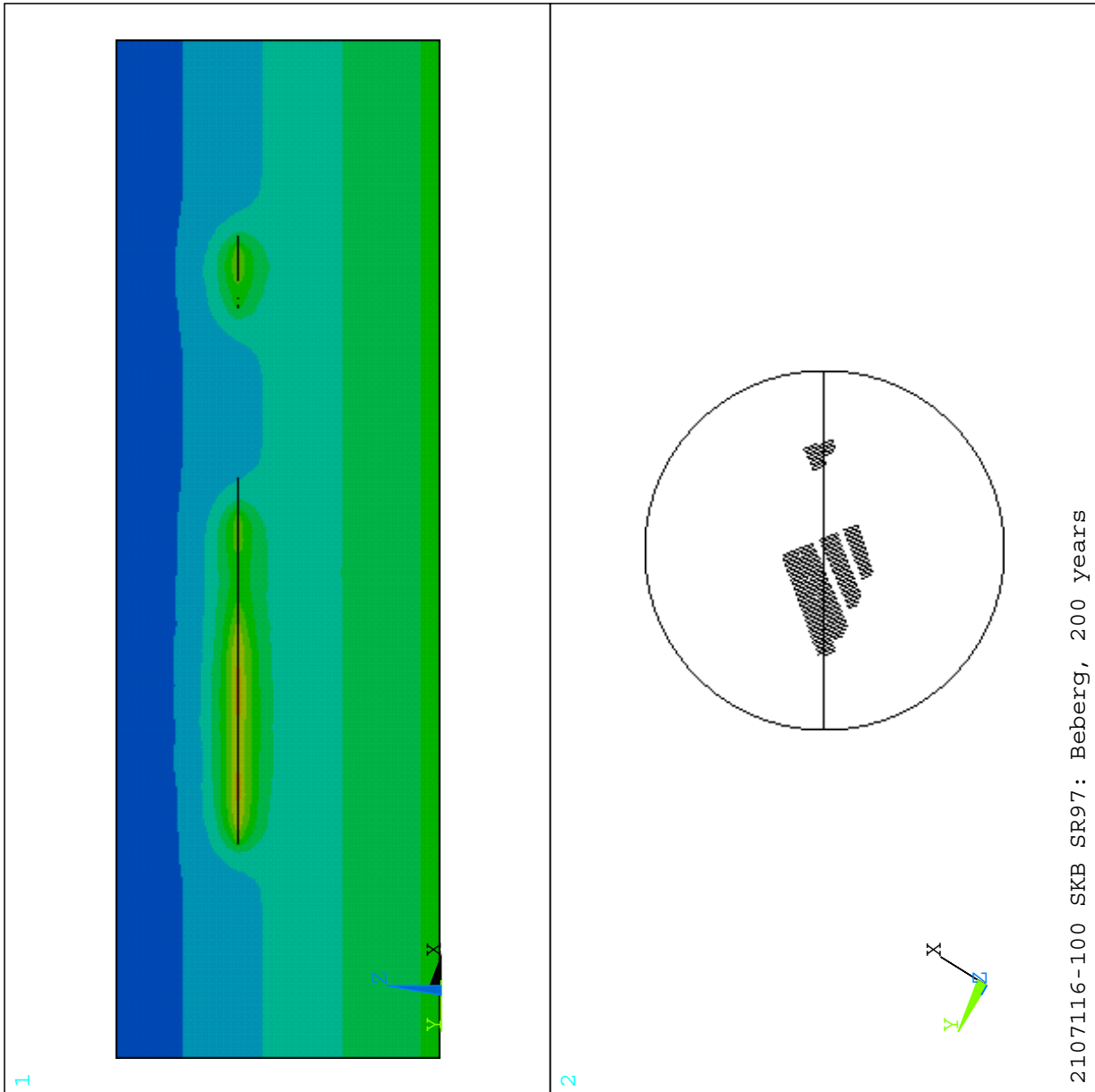


Figure D.6. Heat distribution in a vertical cross-section after 200 years (the location of the section is indicated by the attached key figure).

ANSYS 5.4  
 JAN 20 1999  
 05:53:58  
 PLOT NO. 1  
 NODAL SOLUTION  
 TIME=.316E+11  
 TEMP  
 SMN =5.88  
 SMX =37.053

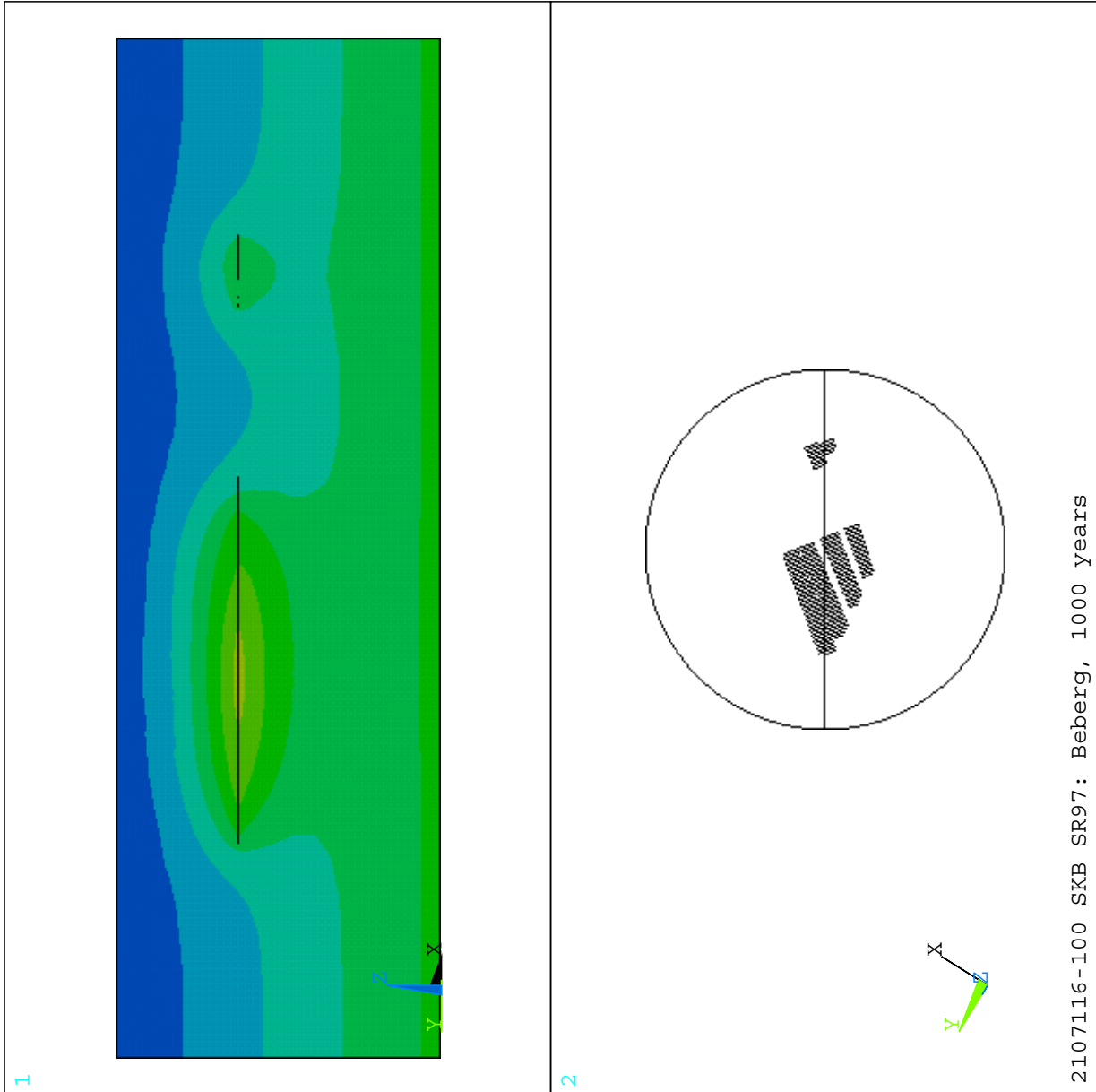


Figure D:7. Heat distribution in a vertical cross-section after 1,000 years (the location of the section is indicated by the attached key figure).

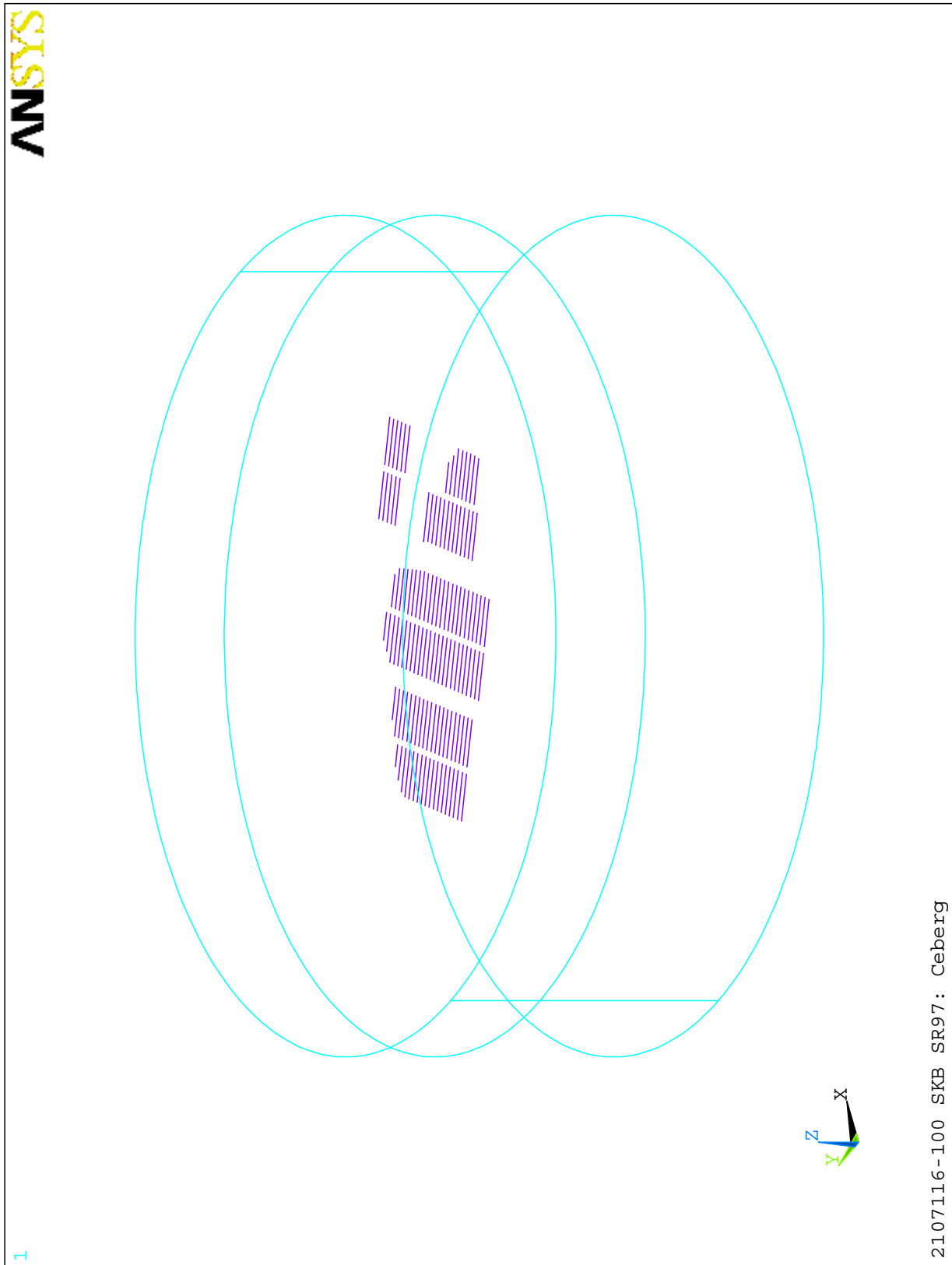


Figure E:1. Overview of the geometrical extension of the model.

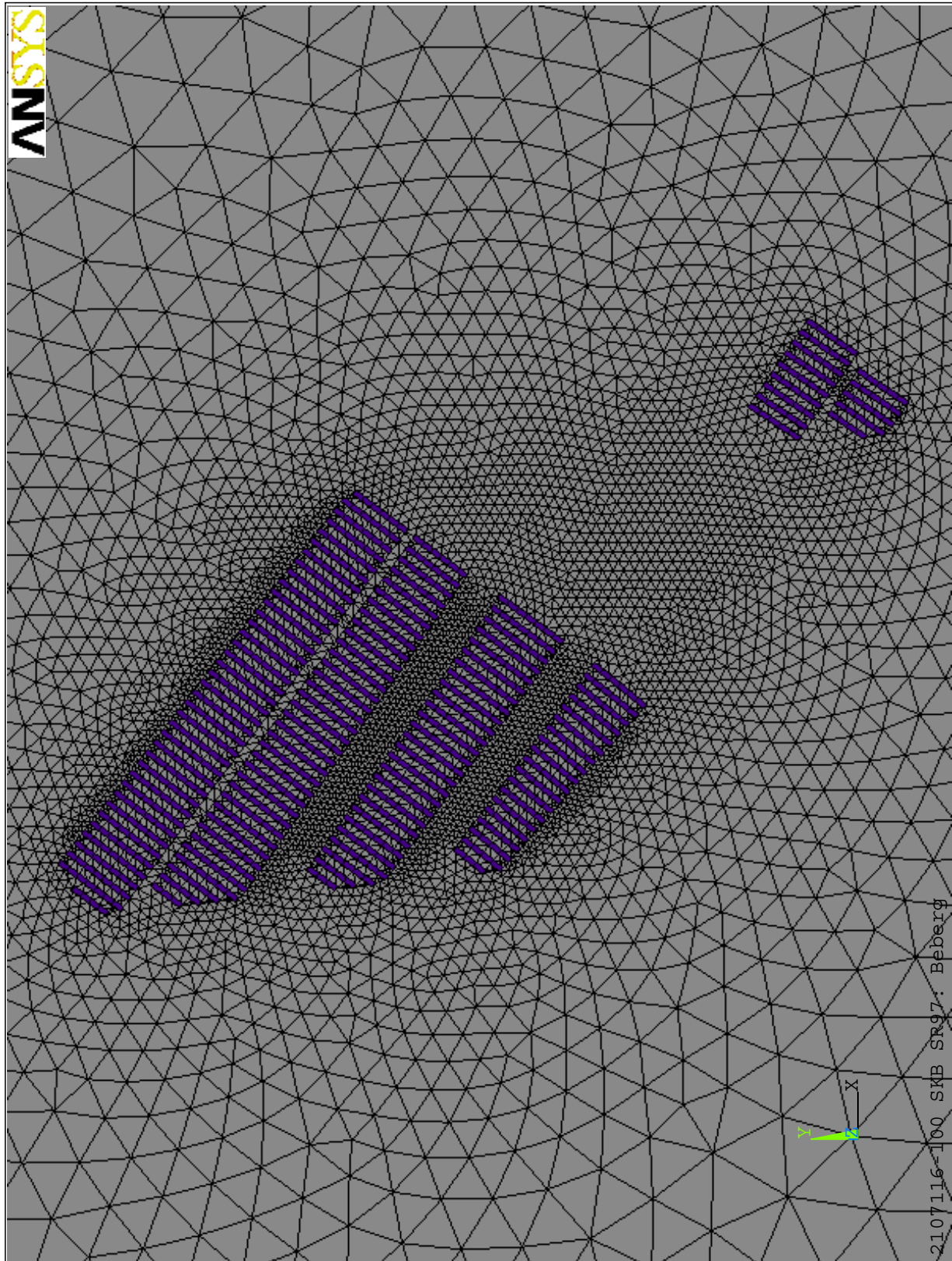
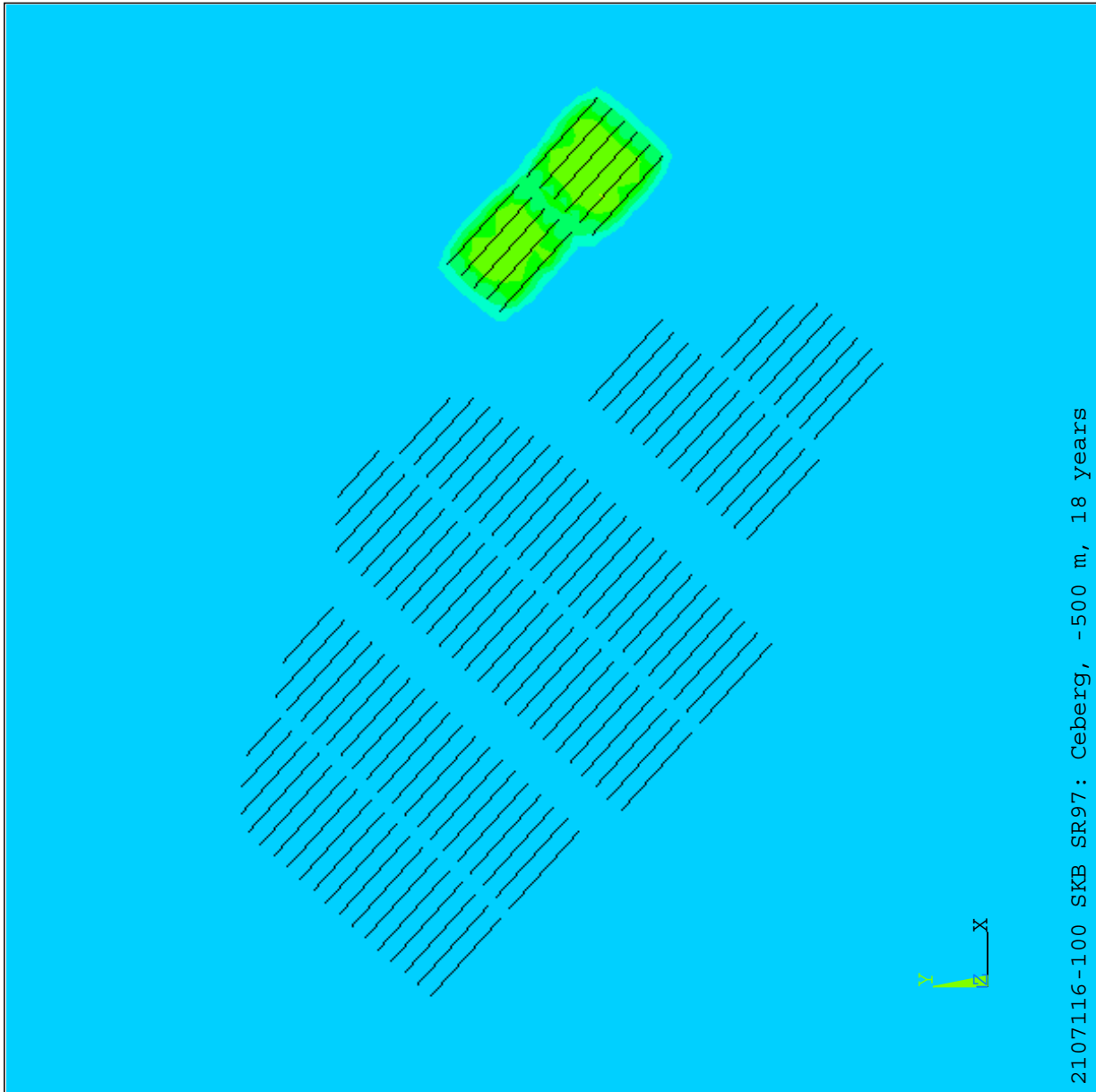


Figure E:2. Close-up of the mesh modelled in the deposition area.



ANSYS 5.4  
 JAN 20 1999  
 06:14:17  
 PLOT NO. 1  
 NODAL SOLUTION  
 TIME=.568E+09  
 TEMP  
 SMN =3.25  
 SMX =35.691

0	Blue
5	Light Blue
10	Light Cyan
15	Cyan
20	Light Green
25	Green
30	Light Green
35	Yellow-Green
40	Yellow
45	Orange
50	Red-Orange
55	Red

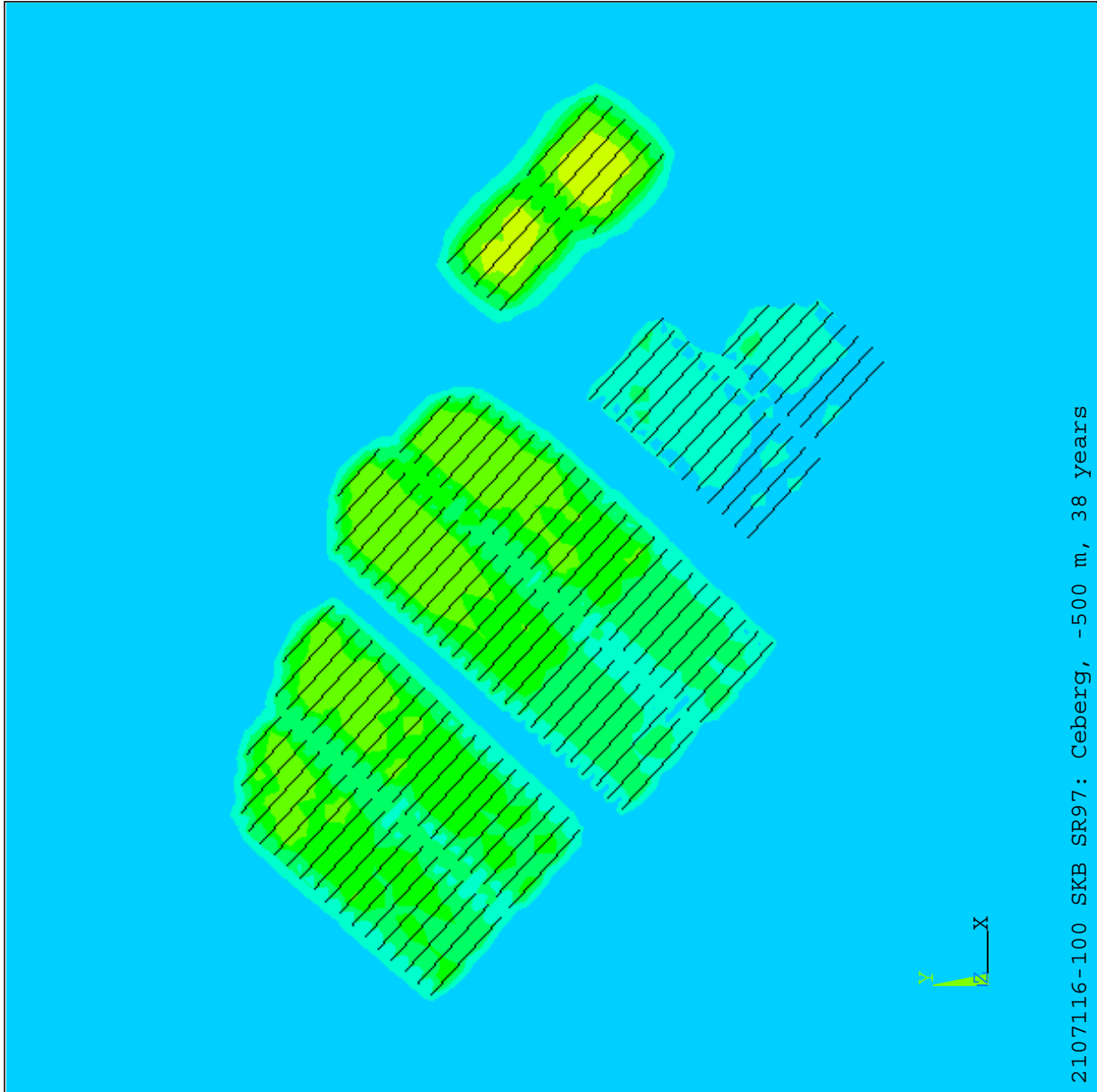


*Figure E:3. Heat distribution on repository level (-500 m) after 18 years, i.e. just before deposition in area 2 commences.*



ANSYS 5.4  
 JAN 20 1999  
 06:16:27  
 PLOT NO. 1  
 NODAL SOLUTION  
 TIME=.120E+10  
 TEMP  
 SMN =3.25  
 SMX =37.876

0	5	10	15	20	25	30	35	40	45	50	55
Blue	Light Blue	Cyan	Green	Light Green	Yellow-Green	Yellow	Orange	Red-Orange	Red	Dark Red	Black



*Figure E:4. Heat distribution on repository level (-500 m) after 38 years, i.e. when deposition in area 2 is finished.*

ANSYS 5.4  
JAN 20 1999  
06:18:30  
PLOT NO. 1  
NODAL SOLUTION  
TIME=.631E+10  
TEMP  
SMN =3.25  
SMX =37.26

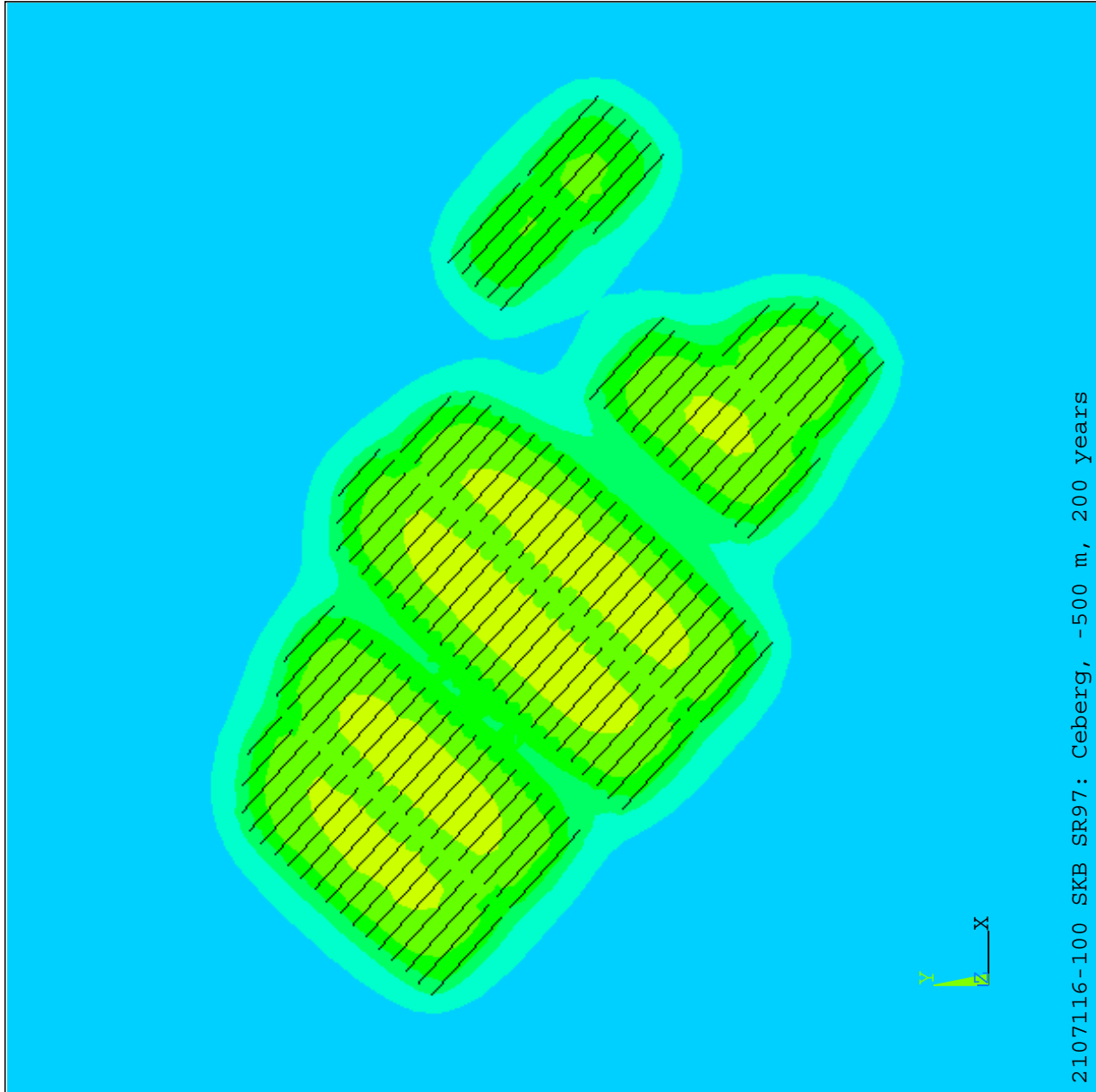
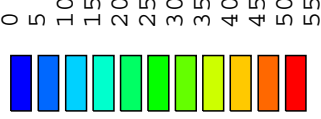
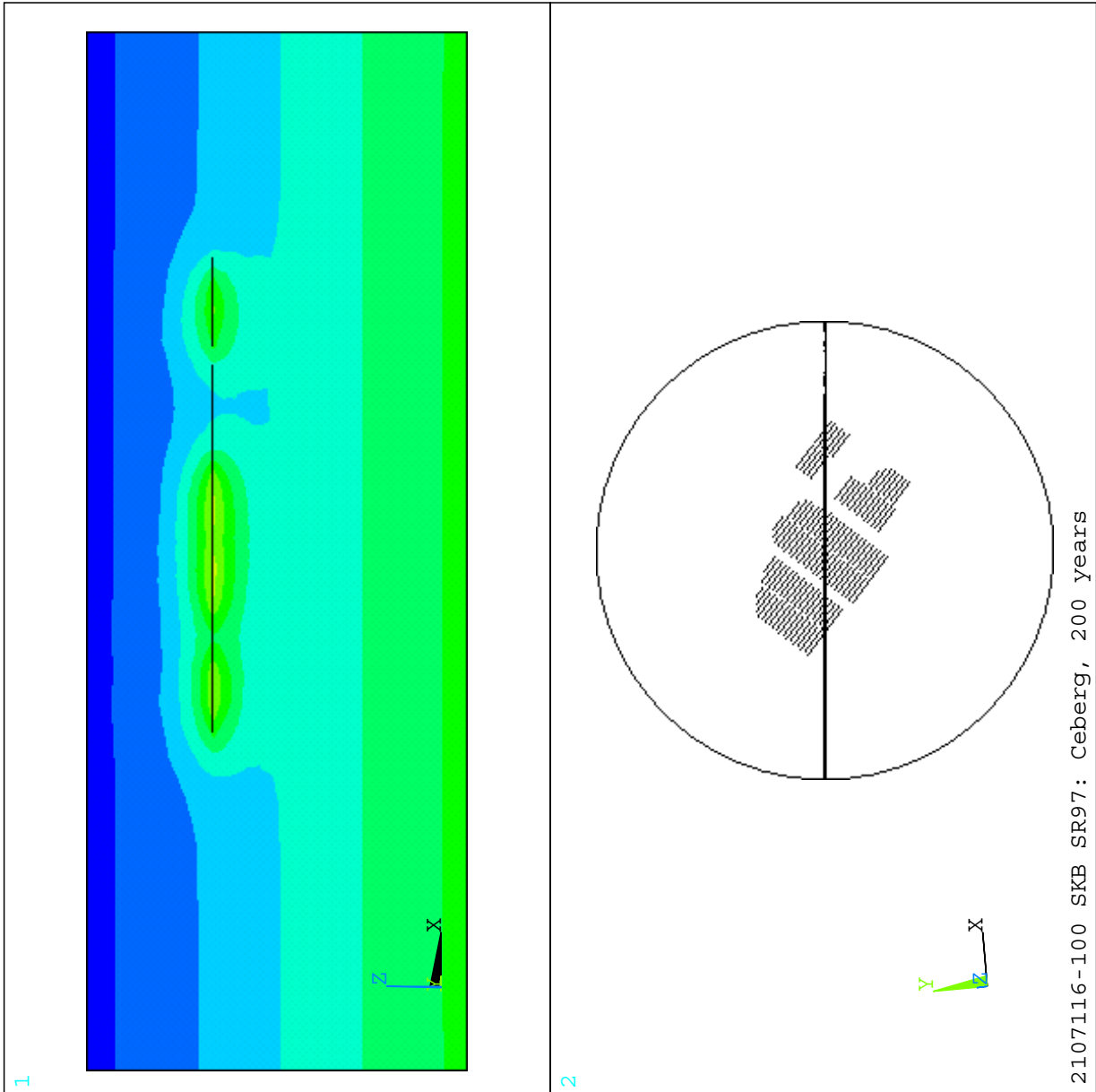


Figure E.5. Heat distribution on repository level (-500 m) after 200 years.

ANSYS 5.4  
 JAN 20 1999  
 06:35:53  
 PLOT NO. 1  
 NODAL SOLUTION  
 TIME=.631E+10  
 TEMP  
 SMN =3.25  
 SMX =37.26

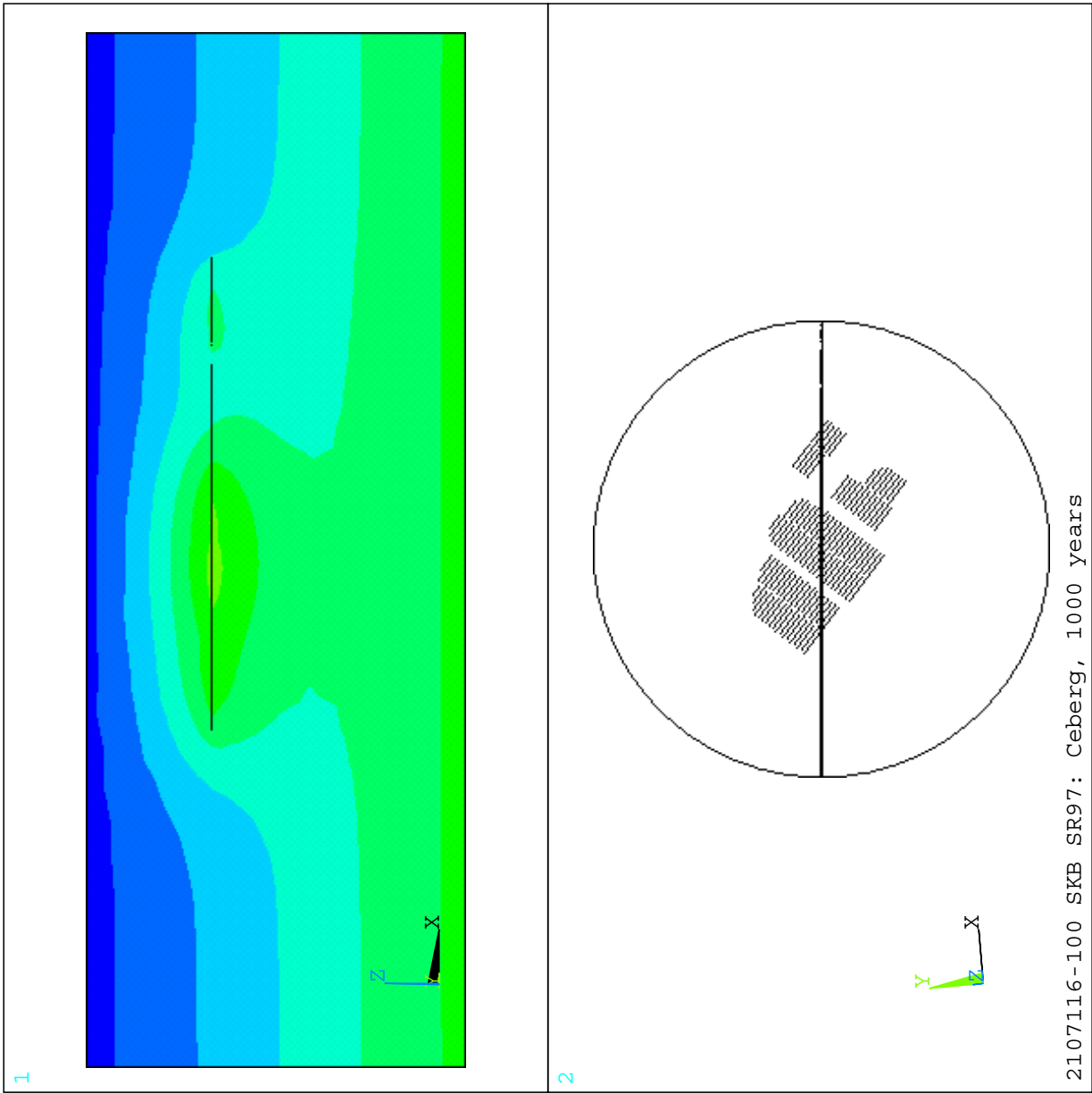
0	Blue
5	Light Blue
10	Light Cyan
15	Cyan
20	Greenish Cyan
25	Green
30	Light Green
35	Yellow-Green
40	Yellow
45	Orange
50	Red-Orange
55	Red



*Figure E.6. Heat distribution in a vertical cross-section after 200 years (the location of the section is indicated by the attached key figure).*

ANSYS 5.4  
 JAN 20 1999  
 06:39:10  
 PLOT NO. 1  
 NODAL SOLUTION  
 TIME= .316E+11  
 TEMP  
 SMN =3.25  
 SMX =31.671

0	5	10	15	20	25	30	35	40	45	50	55
Blue	Light Blue	Cyan	Green	Light Green	Yellow-Green	Yellow	Orange	Red-Orange	Red	Dark Red	Black



*Figure E:7. Heat distribution in a vertical cross-section after 1,000 years (the location of the section is indicated by the attached key figure).*