TECHNICAL REPORT

89-07

SKB WP-Cave Project
Some notes on technical issues

Part 1 Temperature distribution in WP-Cave: when shafts are filled with sand/water mixtures
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Part 2 Gas and water transport from WP-Cave repository
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Part 3 Transport of escaping nuclides from the WP-Cave repository to the biosphere.
Influence of the hydraulic cage
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August 1989

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SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO

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SKB-WP-CAVE PROJECT
SOME NOTES ON TECHNICAL ISSUES

PART 1: TEMPERATURE DISTRIBUTION IN WP-CAVE: WHEN SHAFTS ARE FILLED WITH SAND/WATER MIXTURES.

Abstract

The temperature field inside the sand-bentonite barrier of the WP-Cave has been computed numerically by the use of a three dimensional finite element model and the code SOLVIA-TEMP [4]. In the calculations the cave is assumed to be filled with a sand/water mixture after the completion of the ventilation period.

The highest calculated temperature is 250 °C, which is found in the filling material at the inner end of the canister column 50 years after the storage has been sealed. The spent fuel is then 190 years old.

PART 2: GAS AND WATER TRANSPORT FROM THE WP-CAVE REPOSITORY

Abstract

Gas and water transport from the WP-Cave repository has been calculated. The gas production has been estimated to be in the interval 3 500 to 74 000 Nm^3/y. The water flow during the initial period will occur with a maximum overpressure in the interior of the repository of 0.75 MPa. The gas flow requires an initial high overpressure. The gas flow through the bentonite-sand barrier starts only if the overpressure is greater than the critical pressure. The critical pressure for a mixture bentonite-sand 50/50 is about 0.5 - 1.5 MPA. An alternative design is discussed, the use of a mixture bentonite-sand with a lower content of bentonite (e.g. 10/90). In this case the critical pressure is lower and the pressure needed to maintain a given flow is lower as well.

PART 3: TRANSPORT OF ESCAPING NUCLIDES FROM THE WP-CAVE REPOSITORY TO THE BIOSPHERE. INFLUENCE OF THE HYDRAULIC CAGE

Abstract

Transport of radionuclides escaping from the WP-Cave repository to the biosphere is calculated. The effect of the hydraulic cage is taken into account. It is found that the hydraulic cage may play an important role if the transport distance to the biosphere is short. For longer distances the effect of the hydraulic cage is smaller.

SKB-WP-CAVE-PROJEKTET

TEMPERATURE DISTRIBUTION IN WP-CAVE WHEN SHAFTS ARE FILLED WITH SAND/WATER MIXTURE

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Temperature distribution in WP-Cave: when shafts are filled with sand/water mixture

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GENERAL

The temperature field inside the sand-bentonite barrier of the WP-Cave has been computed numerically by the use of a three dimensional finite element model and the code SOLVIA-TEMP [4]. In the calculations the cave is assumed to be filled with a sand/water mixture after the completion of the ventilation period.

SUMMARY

The highest calculated temperature is 250 °C, which is found in the filling material at the inner end of the canister column 50 years after the storage has been sealed. The spent fuel is then 190 years old.

FINITE ELEMENT MODEL

Cylindrical symmetry is used in the model, thus assuming infinitely many canister levels stacked above each other.
This results in a high order of symmetry, and only a small part needs to be modelled, namely 1/24 of one conical level containing one half of a canister channel (see Figures 1 and 2).
To obtain a repetition of levels, a heat link was introduced to link the top and bottom conical surfaces of the model to be studied.
By giving the link a very high thermal conductivity, and allowing it to conduct heat in the vertical direction only, the same temperature profile at the top and bottom surface of the model is assured, and thus the infinite vertical repetition is also obtained.

In the model, 938 solid elements (20-node hexahedrons and 15-node prisms) were used. The total number of degrees of freedom were 3221. Entering integrals in the conductivity matrix were evaluated using Gauss quadrature with 3 x 3 x 3 integration points.

The following geometry was used in the calculations (fig. 2 and [2]):

* Central shaft:	diameter 14 m
* Inner ventilation shafts:	diameter 2 m centre 13 m from the cave axis
* Outer ventilation shafts:	diameter 3 m centre 30.5 m from the cave axis
* Bentonite-sand barrier:	50 m from the cave axis
* Canister channels:	diameter 1.7 m slope 30° from horizontal plane radially outwards
* Canisters:	Three per channel combined length 16 m diameter 1.3 m
* Vertical pitch:	5.43 m (3 m rock orthogonally between channels)

The material data used are [2]:

* Rock:	Thermal conductivity 3.35 W/(m.K) specific heat 2.16 MJ/(m^3K) density 2700 kg/m^3
* Sand-water-filling:	Thermal conductivity 2.1 W/(m.K) specific heat 2.8 MJ/(m^3K) density 2190 kg/m^3

The heat generated by the fuel is modelled as a uniform power flow on the filling material located just outside the canister surfaces. The canisters themselves are not included in the model. The magnitude and time variation of the heat input are taken from [2].
The heat input corresponds to 8.55 tons of spent PWR fuel (specific power: 38.5 W/g, Burn-up: 38 GWd/tU and enrichment: 3.2 %) per channel.
The remaining boundary condition is a specified time-varying temperature at the sand-bentonite barrier, the temperature values being taken from [1]. 1)

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1) Note that this boundary condition is believed to give the correct "global" temperature (at that radius) for the cave, although the concept at that time, in [1], did not include the sand/water filling.

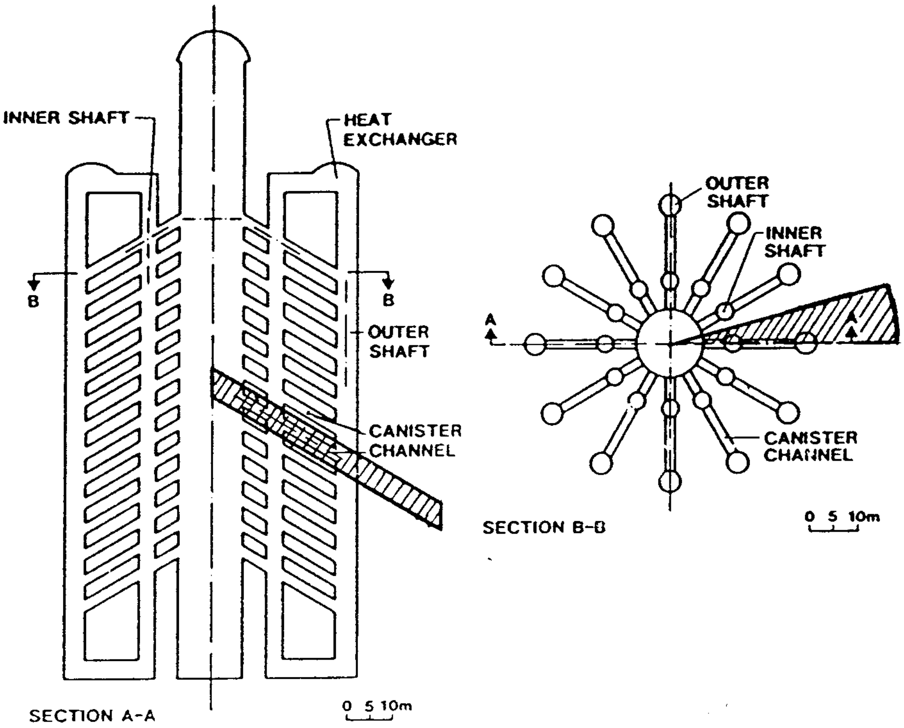


Figure 1. The location of the part modelled here

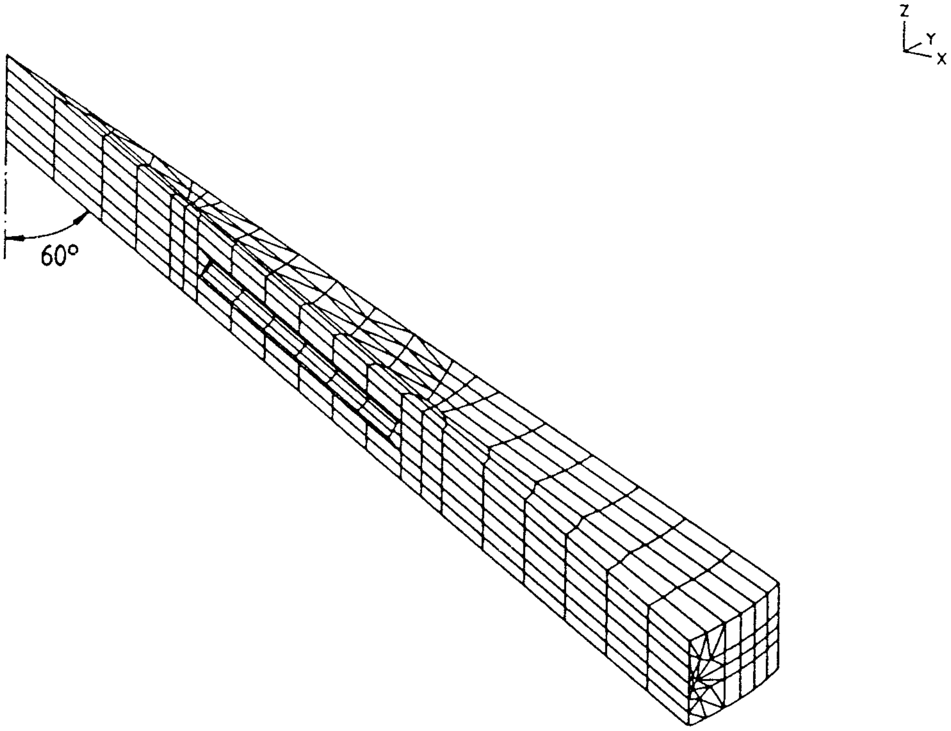
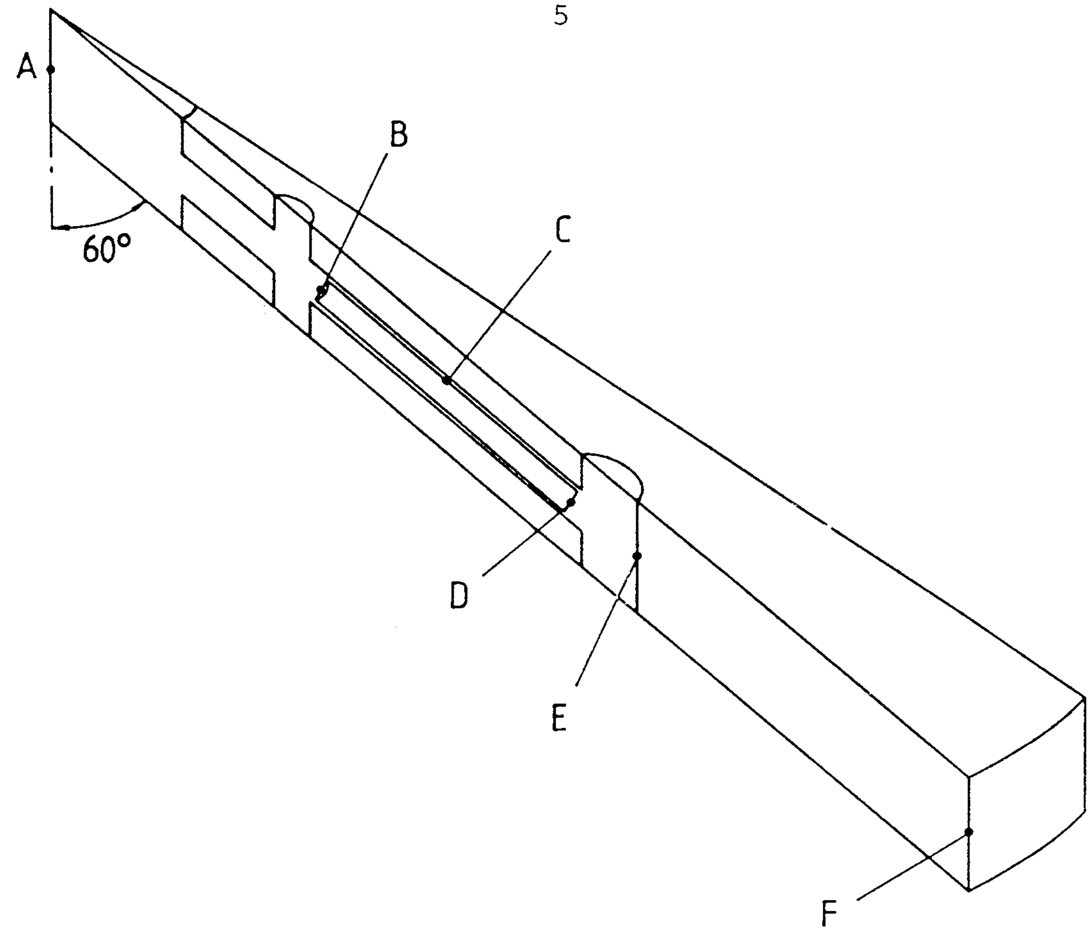


Figure 2. Three-dimensional finite element model used in the present study. The figure is plotted using the so-called "hidden lines" concept. Note the 30° slope of the model from the horizontal plane. The outer radius of the FE-model corresponds to the bentonite barrier in [1]

CALCULATED RESULTS

The temperatures near the canisters are studied in particular. At the time 0 (zero), spent fuel (40 years old) is placed in the storage. The initial temperature in the rock mass is 10°C. During 100 years, the storage channels are kept at low temperatures by air ventilation with heat exchangers, the value 40°C is used here. Then the storage is sealed, and the heat can be transported by conduction only. Figure 3 shows the calculated time-varying temperatures at some locations in the model. The time at the loading of the storage is set to zero. The maximum temperature is obtained at point B in Figure 3 50 years after the storage has been sealed.

Figure 4 shows the calculated isotherms on the boundary surface of the FE-model 50 years after the sealing of the cave.



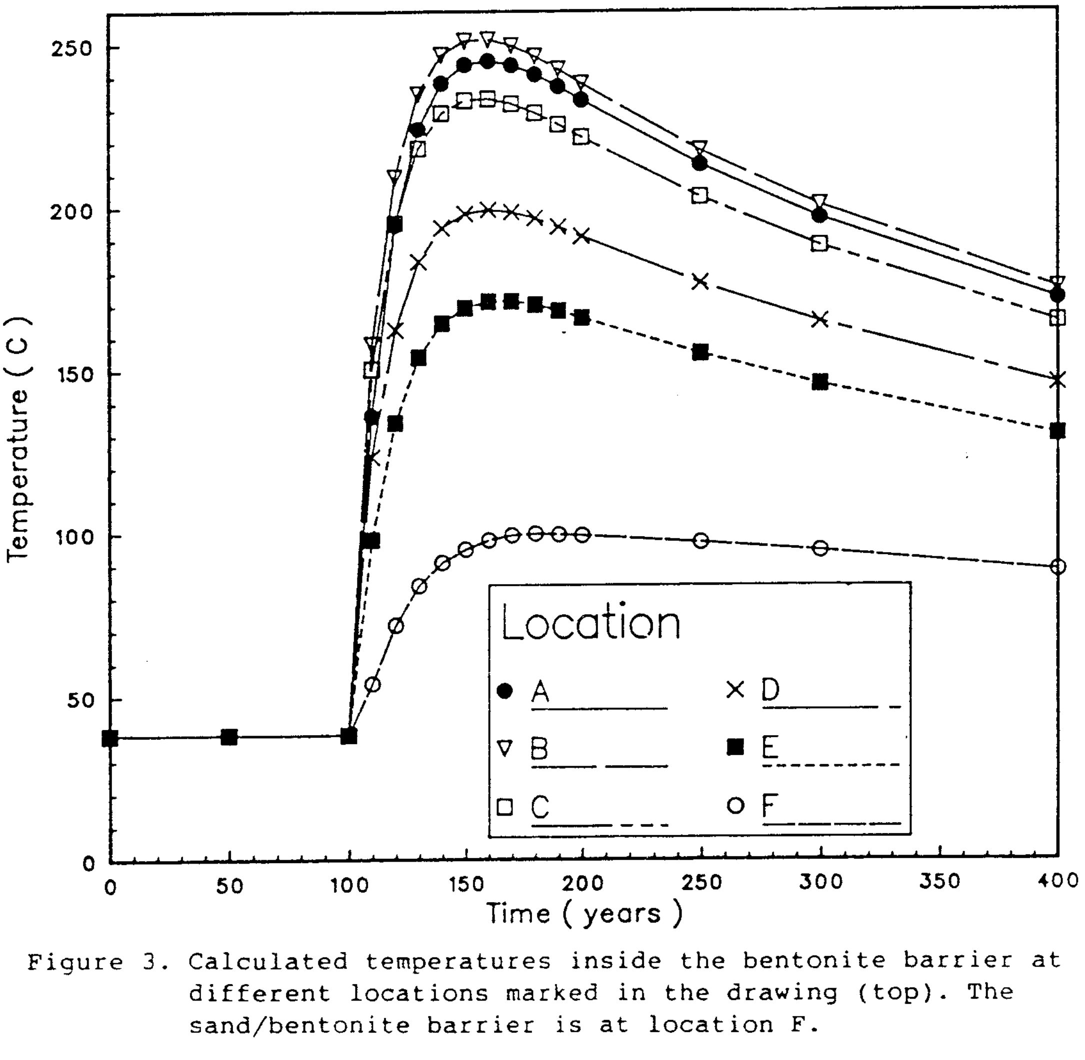


Figure 3. Calculated temperatures inside the bentonite barrier at different locations marked in the drawing (top). The sand/bentonite barrier is at location F.

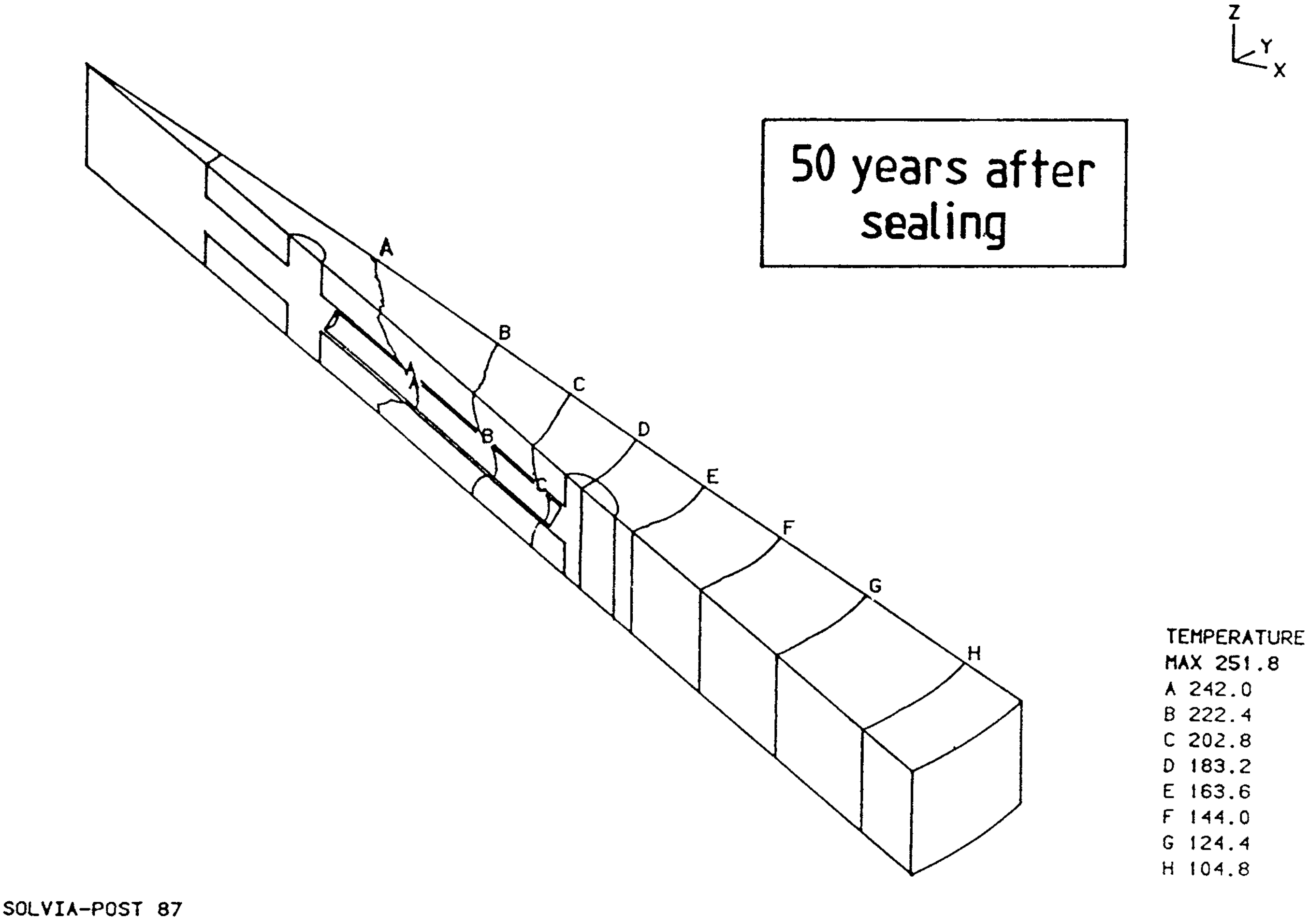


Figure 4. Calculated isotherms on the model boundaries. Time=50 years after sealing of WP-Cave

DISCUSSION

The computed maximum temperature 250°C is probably too high to be accepted, the real temperatures will be even higher at the canister surfaces.
Within the limits given by the sand/bentonite barrier, the best method to reduce the temperature would be to move the canisters further outwards towards the barrier. Moving the ventilation shafts outwards, say about 10 m, would probably reduce the temperature by about 50°C. The further out, the better.

One may note, that the maximum "bulk" temperature reached near the outer shafts (about 180°C, level D in Figure 4) is independent of how the fuel inside is arranged. It is analoguous to water flow in hydrology, where hydraulic head is analoguous to temperature, hydraulic conductivity <--> thermal conductivity and water flow <--> heat flow.
It is obvious, that the resulting water flow magnitude (hydraulic gradient) from sources inside is independent of where the sources are located, and thus also the hydraulic head (pressure).

Thus it is not possible to reduce the "bulk" temperature just outside the canister channels without lowering the heat input and/or increase the rock volume in which the canisters are placed, that is, place them further apart.

The calculated temperature field has a high estimated precision, probably better than 5 degrees at all points. This error estimation was made in a previous report [3] where a similar geometry was studied with the same FE-code and with the same elements and a similar element mesh.

The maximum temperature calculated here is believed to be 20-30°C too high depending mainly on two sources:

1) The assumption of infinite level stacking adds heat from the distant nonexisting levels. A comparison between two simple one-dimensional analytical models, one with cylindrical and the other with spherical symmetry, suggests that this error is about 20°C.

2) The canisters are not included in the model, leaving a cavity which gives the model a too low thermal conductance near the canisters. The inclusion of the canisters would require that the heat transfer properties in the boundary between the canister and the sand/water mixture was modelled.
This error is noticeable only near the canisters, but is believed to be largest for the highest temperatures, near location B in figure 3, where the heat has "the longest way" out to the barrier. It is difficult to estimate the magnitude of this error, and it depends also on the heat transfer between the canisters and the filling.

The model used is materially linear, so the temperature (minus the surrounding temperature) is proportional to:

1) dissipated canister power,
2) the inverse vertical distance between channel levels

Moreover, Figure 4 shows that the heat flow outwards and the temperature are nearly uniform a couple of meters outside the canisters. The heat flow density and the temperature vary thus only with the radius from about 32 m and outwards.

It is then possible to vary the model in any way that preserves the one-dimensional cylindrical symmetry, and solve a one-dimensional Poisson equation and boundary conditions for cylindrical coordinates (see next page).
A suitable time is chosen, when maximum temperature in the whole model is assumed, making it possible to neglect the time dependency.
The use of this one-dimensional heat flow model is believed to be a very good approximation, with an error of only a few °C.

The table below shows the reduction obtained (with the one-dimensional analytical model) after some different modifications of the geometry and amount of power:

Modification of the model	At location B in Figure 3 estimated temperature [°C] Maximum	Reduction
2 canisters per channel (the innermost removed)	155	-95
level thickness increased by 50% (to 8.15 m vertical pitch)	170	-80
Canisters moved outwards 10 m (along with the shafts)	180	-70
Canisters moved outwards 15 m (along with the shafts)	155	-95
Canisters moved outwards 25 m (along with the shafts, the barrier moved further out)	115	-135

As discussed above, these estimations are also, like the computed results (just outside the canister surfaces), probably 20-30°C too high due to model imperfections.

ONE-DIMENSIONAL CYLINDRICAL MODEL

Cylindrical symmetry is used. The problem is treated as quasi-stationary, which is possible because the temperature field is near steady-state at maximum. Thus, heat capacity effects are neglected.
The results in Figure 3 shows, that the maximum temperature is reached about 20-30 years later at the outer barrier than at location B.
For the model, the FE-values at an intermediate time are used, when the "average" capacity effect is near zero.
This is believed to give good results at the canisters.

The equation to solve is the Poisson equation with cylindrical symmetry, thus properties depend only on the radius ρ:

DE: $$\nabla^2 T = \frac{1}{\rho}\frac{d}{d\rho}\left[\rho\cdot\frac{dT}{d\rho}\right] = -\frac{g(\rho)}{\lambda}, \quad g(\rho) = \begin{cases} C/\rho, & \rho_i \leqslant \rho \leqslant \rho_o \\ 0 & \text{otherwise} \end{cases} \qquad (1);$$

BC1: $$\frac{dT}{d\rho}(\rho_i) = 0 \qquad (2);$$

BC2: $$T(\rho_b) \equiv T_b = T_e + (T_{b0}-T_e)\cdot(K/K_0) + \varepsilon\cdot K\cdot \ln(\rho_{b0}/\rho_b) \qquad (3)$$

Legend:

ρ = radius in metres from central shaft axis [m],
$T(\rho)$ = temperature at radius ρ [°C],
$g(\rho)$ = heat generation per unit volume [W/m^3],
λ = thermal conductivity [W/(m·K)],
the value 3.35 (rock) is used here
ρ_i = radius at inner end of canisters [m],
T_i = temperature ---"--- --"-- --"-- [°C],
ρ_o = radius at outer end of canisters [m],
T_o = temperature ---"--- --"-- --"-- [°C],
ρ_b = radius at the sand/bentonite barrier [m],
T_b = temperature ---"--- --"-- --"-- --"-- [°C],
T_e = environment temperature [°C],
C = $Q\cdot N/(2\pi\cdot h)$ [W/m], where
  Q = generated power per channel [W],
  N = number of channels per level,
  h = channel level pitch [m],
K = C/λ [°C]
ε = gradient factor = 1 for a pure cylindrical field,
0.85 is used here for spherical correction.

Entitites indexed with '0' refer to the values used in the FE-study.

The expression for the power density $g(\rho)$ (in W/m^3) can be explained by studying the top view in Figure 1 (right).
For the one-dimensional model, the canister power per unit radius ρ is constant for $\rho_i \leqslant \rho \leqslant \rho_o$, and the area of a cylinder surface is proportional to ρ. Thus the power density becomes inversely proportional to the radius ρ in that interval. This can be verified by a dimensional study.

The first boundary condition BC1 formulates the source-free region inside the canisters, where the heat flow is zero ($dT/d\rho=0$).

The second boundary condition BC2 at the sand/bentonite barrier is adjusted for different heat inputs and cave geometries. Counted from the environmental temperature T_e, the barrier temperature T_b (and the whole field) is proportional to the factor K above. T_e is assumed to be equal to the initial temperature (10°C in the study in [1]).
A correction factor ε has also been included to account for different barrier radii (3).

The solution is found to be (calculated in sequence):

$$T(\rho) = \begin{cases} T_b + K\cdot\ln(\rho_b/\rho), & \rho_o \leqslant \rho \leqslant \rho_b; \\ T(\rho_o) + K/(\rho_o-\rho_i)\cdot\left[(\rho_o-\rho) - \rho_i\cdot\ln(\rho_o/\rho)\right], & \rho_i \leqslant \rho \leqslant \rho_o; \\ T(\rho_i) \equiv T_i; & \rho \leqslant \rho_i \end{cases} \quad (4)$$

The maximum temperature T_i explicitly:

$$T_i = T_e + K\cdot\left[(T_{b0}-T_e)/K_0 + \varepsilon\cdot\ln(\rho_{b0}/\rho_b) + 1 + \ln(\rho_b/\rho_o) - \rho_i\cdot\ln(\rho_o/\rho_i)/(\rho_o-\rho_i)\right] \quad (5)$$

The formula is consistent if the barrier is unchanged, being very accurate for different parameter values. Its overall accuracy is believed to be very good, though giving 20-30°C too high values as discussed above.

This formula gives very good correlation with the FEM results using the same parameters at time=150 years (see also Figure 3):

At location B: FEM-result 251°C, one-dim result 251°C;
---"---- C: ---"---- 233°C, ---"--- --"--- 235°C.
---"---- D: ---"---- 199°C, ---"--- --"--- 198°C.

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GAS AND WATER TRANSPORT FROM THE WP-CAVE REPOSITORY

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SUMMARY

Gas and water transport from the WP-Cave repository has been calculated. The gas production has been estimated to be in the interval 3 500 to 74 000 Nm^3/y. The water flow during the initial period will occur with a maximum overpressure in the interior of the repository of 0.75 MPa. The gas flow requires an initial high overpressure. The gas flow through the bentonite-sand barrier starts only if the overpressure is greater than the critical pressure. The critical pressure for a mixture bentonite-sand 50/50 is about 0.5 - 1.5 MPA. An alternative design is discussed, the use of a mixture bentonite-sand with a lower content of bentonite (e.g. 10/90). In this case the critical pressure is lower and the pressure needed to maintain a given flow is lower as well.

INTRODUCTION

When the repository is filled with the canisters containing radioactive wastes, the air circulation may be maintained during a certain time to transport away the heat generated in the canisters. Before the repository is sealed, the open volumes will be filled with finely crushed rock. The open volumes are filled with crushed rock in order to reduce the volume of the water in the interior parts. Thereafter the repository will be filled with water in a controlled manner. The repository will be surrounded by a bentonite—sand barrier everywhere. The composition of the mixture bentonite—sand may be different in the different parts of this barrier. The composition in the cone at the top will be 50/50 (bentonite/sand), in the cylindrical part it will be 20/80 and in the cone at the bottom it will be 10/90.

In the initial period the oxygen dissolved in the water in the repository will cause aerobic corrosion of the canisters and other iron objects. When the oxygen is consumed, the corrosion process will become anaerobic, with production of hydrogen.

The calculations will be made for the reference case:

- WP—Cave 1500
- Forced water filling and filling with crushed rock
- Bentonite—sand layer in the bottom (double cone)

DESCRIPTION OF THE PROCESS.

The production of hydrogen in the reference case starts when the repository is filled with water and after the dissolved oxygen has been consumed by the aerobic corrosion. The production rate of hydrogen is in the interval 3 500 to 74 000 Nm^3/y. A part of the hydrogen gas will be dissolved in the water in the repository. When the solubility limit is reached, hydrogen gas will form. This gas will occupy a certain volume in the interior of the repository. The volume of gas produced will be determined by the gas production and the pressure in the repository. The increment of the volume occupied by the gas must be compensated by an equivalent volume of water, which is expelled from the repository through the bentonite—sand barrier.

The gas will flow to the upper parts of the repository. First it will collect at the top of the vertical central tunnel. When the pressure of this "bubble" is large enough to expel the water from the fractures in the rock, the hydrogen gas will flow to the top of the repository. On the inside of the bentonite—sand barrier, at the top, a new "bubble" will form. Gas will start to flow through the bentonite—sand barrier when the pressure is larger than the critical pressure needed to start the gas flow through this barrier. The gas will flow through that part of the bentonite—sand barrier which is above the water table level. These processes are schematically shown in Figure 1.

CALCULATIONS

WATER FLOW FROM THE WP-CAVE REPOSITORY

If gas production starts when the repository is filled with water, water is expelled from the repository through the bentonite-sand barrier. The water flow rate is equivalent to the gas production rate at the conditions which exist in the repository. The temperature is about 50 C and the pressure is between 2.0 and 5.0 MPa at the top and bottom respectively. The water flowrates through the bentonite-sand barrier for a gradient of 1 m/m (overpressure of 0.05 MPa) are presented in Table 1.

Table 1 Water flow during the initial period for a hydraulic gradient of 1 m/m.

Part of the repository	Area m^2	Hydraulic conductivity, m/s	Water flow rate m^3/y
1	19 000	$1 \cdot 10^{-12}$ - $1 \cdot 10^{-11}$	0.6 - 6.0
2	56 000	$3 \cdot 10^{-11}$ - $1 \cdot 10^{-10}$	53 - 177
3	19 000	$1 \cdot 10^{-10}$ - $3 \cdot 10^{-10}$	60 - 180
Total water flow			114 - 360

For a gradient of 1 m/m the water flow varies in the interval 110 – 360 m^3/y. The water flow depends mainly on the hydraulic conductivities in parts 2 and 3 of the cone (Cylindrical part and lower cone). The flowrate is directly proportional to the hydraulic gradient in the bentonite-sand barrier. The hydraulic conductivity of the rock is assumed to be much higher than in the bentonite-sand mixture.

This water flow is caused by a gas production rate of 110 – 360 m^3/y at the conditions which exist in the repository. For an overpressure in the repository equal to 0.05 MPa (hydraulic gradient of 1 m/m), the pressure at the top of the bentonite-sand barrier will be 2.05 MPa, if the top is located 200 m below the water table. The pressure at the bottom will be about 5.0 MPa. The temperature in the repository may be assumed to be about 50 C (this water flow is expected to occur in the first 100 years).

The equivalent gas production would have to be 3 800 – 12 000 Nm^3/y to expel the water at the rate given above. These figures are greater than the expected value for the gas production due to anaerobic corrosion. The gas production rate is estimated to be 3 500 Nm^3/y for a corrosion rate of 44 μm/y. The overpressure would stabilize at a lower overpressure than 0.05 MPa. The water level in the repository would decrease as the gas cushion increases. At some point the pressure in the gas would increase enough to start gas flow through the bentonite–sand barrier.

The above production of hydrogen was calculated assuming a surface area of corroding iron of 19 000 m^2. If the walls in the repository are covered with iron sheets, the surface area which may be corroded will be 117 000 m^2. The hydrogen production rate will be about 21 500 Nm^3/y for a corrosion rate of 44 μm/y. The overpressure inside the repository, in the initial period when water is expelled from the repository, will then be about 0.25 MPa.

Due to the high temperature in the repository (180 °C) the corrosion rate may be strongly increased. If the corrosion rate is assumed to be 150 μm/y, the hydrogen production rate will be 74 000 Nm^3/y for a surface area of 117 000 m^2. In this case the overpresure inside the repository will be 0.75 MPa in the initial period.

GAS TRANSPORT THROUGH THE BENTONITE–SAND BARRIER.

The water saturated bentonite–sand barrier does not permit the gas to flow through it if the pressure is lower than the critical pressure. In this case gas may be transported only by diffusion in the water phase in the backfill.

The gas flow starts when the critical pressure for gas flow is reached. Then, some channels in the bentonite–sand barrier are emptied of the water and they are opened to the gas flow. The gas permeability may become very high and a large gas flowrate may be obtained. The pressure in the interior may decrease below the critical pressure and the channels are closed. A cyclic pressure swing process may conceivably develop. Because different channels have somewhat different opening pressures a more probable mechanism is that somemore channels are opened when the pressure is increased and that some channels are closed when the pressure decreses. Instead of the cyclic pressure swing between extreme values a more even pressure may develop in this case.

The critical pressure for a mixture bentonite–sand 50/50 is between 0.5 and 1.5 MPa (Swelling pressure for this mixture is 1.0 – 2.0 MPa). This high overpressure in the repository will expel a large volume of water. The water level would lie 50 – 150 m under the top of the repository. In practice, this level will vary between 50 m under the top and the upper border of the cylindrical part of the bentonite–sand barrier. This part of the barrier will contain a mixture of 20/80 bentonite/sand. In this mixture the critical pressure is lower, about 0.1 – 0.3 MPa.

This high pressure in the interior of the repository may cause problems. Before the critical pressure is reached, a large volume of water may be expelled from the repository through the bentonite–sand barrier. When channels are opened gas escapes and the gas pressure is reduced. Water then may flow back into the repository. This could conceivably generate a cyclic water flow with an increase of the contamination release from the repository to the rock outside the bentonite–sand barrier as a consequence. If the pressure stabilizes as discussed above no cyclic water flow will take place.

To decrease the size of the gas bubble a bentonite–sand mixture with a lower bentonite content could be used. In this case the critical pressure will be lower and smaller volumes of water will be expelled from the repository. For a mixture bentonite–sand 10/90, the critical pressure is about 0.05 – 0.10 MPa. This means that at the start of gas flow the water level is about 5 – 10 m below the top of the bentonite–sand barrier. The available area for the gas flow is also smaller (about

500– 1000 m^2).

If the gas permeability is large enough to permit the gas to escape from the repository through this free area, the pressure will decrease in the interior of the repository. The water level will stabilize at a higher level and the area for gas flow will decrease. A steady state may be reached for the gas flow. Another case may develop where the channels which are open to the gas flow are closed when the pressure drops and the pressure must increase again to the critical pressure to let the gas escape. This will be determined by the relationship between the critical pressure, the gas permeability and the water level. These effects have not been explored sufficiently yet but Table 2 shows the stable water levels for various combination of gas production rates and permeabilities. The gas flow is varied in the interval 2 000 to 74 000 Nm^3/y. The value 12 000 Nm^3/y corresponds to a corrosion rate of 150 $\mu m/y$ acting on a surface of iron of 19 000 m^2. The last values (21 500 and 74 000 Nm^3/y) correspond to a surface of iron of 117 000 m^2 and corrosion rates of 44 and 150 $\mu m/y$ respectively

Table 2 Hydraulic gradient for a given gas flow with a given gas permeability.

Gas Flow Nm^3/y	Gas Permeability m^2	Hydraulic gradient m/m	Water level relative to the top m
2 000	$1 \cdot 10^{-16}$	0.16	- 0.80
5 000	$1 \cdot 10^{-16}$	0.32	- 1.60
12 000	$1 \cdot 10^{-16}$	0.56	- 2.80
21 500	$1 \cdot 10^{-16}$	0.79	- 3.95
74 000	$1 \cdot 10^{-16}$	1.50	- 7.50
2 000	$1 \cdot 10^{-17}$	0.75	- 3.8
5 000	$1 \cdot 10^{-17}$	1.25	- 6.2
12 000	$1 \cdot 10^{-17}$	1.90	- 9.5
21 500	$1 \cdot 10^{-17}$	2.44	- 12.2
74 000	$1 \cdot 10^{-17}$	4.08	- 20.4

DISCUSSION

One of the critical issues is if there may develop a pulsating flow of gas from the repository. If this is possible, a situation may conceivably develop where water is alternatively expelled and then flows back into the repository again. The water may carry nuclides with it. We think, however, that such a situation may not develop because there will be inhomogeneities in the bentonite–sand mixture so that there is not one single opening and one single closing pressure. We think it is probable that there will be a multitude of channels with different opening and closing pressures. If this is the case, a slight increase in pressure will open one more channel etc., and a steady flowrate will be maintained. Experiments on a larger scale would show if the later situation may develop.

Determinations of critical pressure for gas flow for different compositions of the bentonite–sand mixture should be made. In these measurements different density would be used (different packing)

The use of a 50/50 mixture of bentonite–sand at the top of the repository leads to a very high gas cushion (greater than 50 m) and an overpressure of more than 0.5 MPa at the top of the repository. We cannot at present see what consequences this may have on the function of the repository. This must be further explored. An alternative is to use a 10/90 or 20/80 mixture in the top to decrease the size of the bubble.

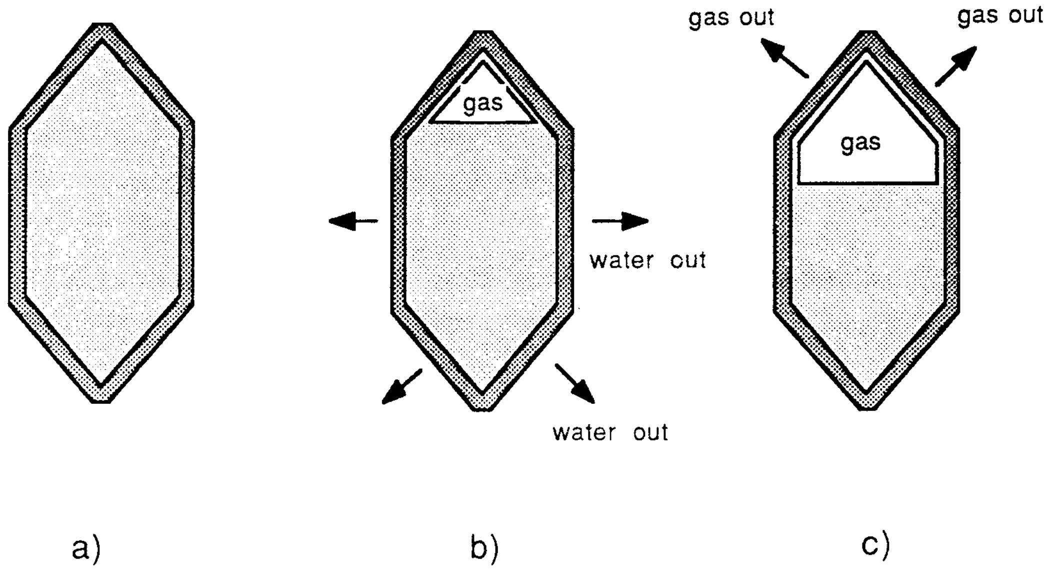

Figure 1 Evolution of water and gas flow in the repository

a) Repository is filled with water

b) Overpressure is less than the critical pressure for gas flow. Water is expelled

c) The critical pressure for gas flow has been reached. Gas escapes.

APPENDIX

Parts in the repository

P1	Upper cone of Bentonite–sand
P2	Cylindrical part of the Bentonite–sand layer
P3	Lower cone of Bentonite–sand

AVERAGE SURFACE AREA OF THE BENTONITE–SAND LAYER

A1	19 000 m^2
A2	56 000 m^2
A3	19 000 m^2

BENTONITE–SAND MIXTURES

A1	50/50 Bentonite/sand
A2	20/80 Bentonite/sand
A3	10/90 Bentonite/sand

HYDRAULIC CONDUCTIVITY

K1	(50/50)	$1 \cdot 10^{-12}$	–	$1 \cdot 10^{-11}$	m/s
K2	(20/80)	$3 \cdot 10^{-11}$	–	$1 \cdot 10^{-10}$	m/s
K3	(10/90)	$1 \cdot 10^{-10}$	–	$3 \cdot 10^{-10}$	m/s

GAS TRANSPORT

Critical pressure: Different mixtures.

50/50 Bentonite/sand	0.5 – 1.5 MPa
20/30 Bentonite/sand	0.1 – 0.3 MPa.

APPENDIX

REFERENCES USED FOR HYDRAULIC CONDUCTIVITY DATA

1. R. Pusch, SFR–85–08

Table 2 100 % GEKO/QI bentonite - Forsmark water

Density t/m^3	Gradient m/m	Hydraulic Conductivity m/s
1.8	100	$9 \cdot 10^{-12}$
1.6	50	$6 \cdot 10^{-11}$
1.6	100	$9 \cdot 10^{-11}$

Table 3 For mixtures 10/90 (GEKO/QI bentonite/sand).

Density t/m^3	Gradient m/m	Hydraulic conductivity m/s
2.35	1000	$1 \cdot 10^{-10}$
2.25	1000	$1 \cdot 10^{-10}$
2.20	1000	$3 \cdot 10^{-10}$

Table 4 Large samples (diameter=0.78 m, heigth=0.30 m)
Forsmark water.

Material	Density t/m^3	gradient m/m	Hydraulic Conductivity m/s
100% GEKO/QI	1.68	30	$4 \cdot 10^{-11}$
100% GEKO/QI	1.60	30	$2 \cdot 10^{-10}$
10/90	2.28	0.08	$1 \cdot 10^{-9}$

Data for gas transport.

Critical pressure for gas flow through a bentonite-sand barrier (10/90) is 0.05 - 0.1 MPa

Gas flow in a 10/90 mixture bentonite-sand expels about 0.1 - 0.2 % of the water in it.

Comments:

- An increase in the hydraulic gradient may increase the hydraulic conductivity
- An increase in the temperature increases the hydraulic conductivity

2. R. Pusch, Personal communication, jan-87

Data for gas transport.

For a mixture 50/50 (bentonite/sand):
Critical pressure 0.5 - 1.5 MPa.

3 R. Pusch, L. Ranhagen, K. Nilsson, SFR 84-05

Table 5 Mixtures 10/90 and 30/70 (GEKO/QI bentonite/sand).
Allard' water.

Mixture	Density t/m^3	Gradient m/m	Hydraulic conductivity m/s
10/90	2.35	40	$1 \cdot 10^{-10}$
10/90	2.25	40	$1 \cdot 10^{-10}$
10/90	2.20	40	$3 \cdot 10^{-10}$
30/70	1.95	200	$1 \cdot 10^{-11}$

Data for gas transport.

For pressure lower than the critical pressure the gas permeability for the gas is very low:

Mixture	Density	Permeability, m^2	
	ton/m^3	P < Critical pres.	P > Critical pres.
10/90	1.55	$2 \cdot 10^{-21}$ - $2 \cdot 10^{-20}$	$1 \cdot 10^{-17}$
10/90	1.63	$1 \cdot 10^{-21}$ - $1 \cdot 10^{-17}$	$1 \cdot 10^{-17}$
10/90	2.33	-	$5 \cdot 10^{-16}$
50/50	1.88	$4 \cdot 10^{-22}$ - $4 \cdot 10^{-21}$	-

4. R. Pusch, M. Cederström, SFR 84-04

Mixture 30/70 (GEKO/QI bentonite/sand):

Density = > 1.95 t/m^3

K = < $1 \cdot 10^{-10}$ m/s

SKB-WP-CAVE PROJECT - PHASE II

TRANSPORT OF ESCAPING NUCLIDES FROM THE WP-CAVE REPOSITORY TO THE BIOSPHERE.

INFLUENCE OF THE HYDRAULIC CAGE

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KAT-88/28

ABSTRACT

Transport of radionuclides escaping from the WP-Cave repository to the biosphere is calculated. The effect of the hydraulic cage is taken into account. It is found that the hydraulic cage may play an important role if the transport distance to the biosphere is short. For longer distances the effect of the hydraulic cage is smaller.

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SUMMARY

The effect of the hydraulic cage on the escape of radionuclides from the WP-Cave repository to the biosphere is studied. The purpose of the hydraulic cage is to divert the groundwater flow away from the repository. In a previous report /Moreno et al., 1988/ the transport of actinides from the WP-Cave repository were calculated for a transport length of 100 m ignoring the hydraulic cage.

It is assumed that the water flow between the cave and the cage is 10 % of the undisturbed flow. Two cases are analysed: a) some channels are not intersected by the hydraulic cage and b) all the channels are intersected by the hydraulic cage.

The release rates of three actinides (^{238}U, ^{239}Pu, and ^{242}Pu) are calculated for an input which decays with their respective half-lives. The actinides' releases are calculated for the different cases with a distance of 25 m and 50 m respectively between cave and cage.

The results show that the maximum release rate of ^{238}U is not modified by the hydraulic cage, due to the very large half-life and small sorption coefficient. For the other radionuclides the transport distance and the water flow influences the maximum release rate.

The hydraulic cage may play an important role if the transport distance between the WP-Cave repository and the effluent to the biosphere is small. For long distances the effect of the hydraulic cage is less important.

The hydraulic cage will intersect more channels than the bare repository. It will also change the flow pattern considerably to a distance of at least the diameter of the cage and thus also in this way connect more channels including fast channels near the surface where there is a higher conductivity and probably more fast channels. For those nuclides for which the retardation and decay in the far field is important, the presence of more fast channels may,

to some extent, compensate the decreased release from the near field due to the smaller flowrate of the water passing around the cave. With our present very limited knowledge of the nature and frequency of channels it is not possible to make much firmer statements.

In this report it is concluded that the hydraulic cage may under some circumstances have some beneficial effects but may also have some detrimental effects. Much work will be needed, especially as regards to gathering data on channeling and understanding the nature of flow in fractured channeled rock, in order to be able to quantify the effects of a hydraulic cage.

1 BACKGROUND AND INTRODUCTION

The WP-Cave is an egg-shaped underground repository surrounded by two engineered barriers: a 5 m thick sand-bentonite layer and a hydraulic cage. The purpose of the hydraulic cage is to divert the groundwater flow away from the repository so that it will not penetrate through the repository. In time, radionuclides will eventually escape from the repository's storage canisters due to canister failure. These nuclides will, after dissolving into the water, migrate into the rock mass and sand-bentonite barrier surrounding the repository. Those radionuclides not retained by the sand-bentonite barrier will be transported to the biosphere by the water flowing in fractures in the rock.

The hydraulic cage will divert the water flow in the rock past the cage on the outside because the cage has a very much higher conductivity than the rock. In principle there would be no hydraulic gradient within the cage if it could be assured that the cage is perfect. As this is not possible with our present knowledge we will explore some cases where the function is not perfect.

In previous reports /Arve et al., 1988 and Moreno et al.,1988/ we calculated the transport of radionuclides escaping from the WP-Cave repository to the biosphere for a transport length of 100 m. In these studies the hydraulic cage was ignored. The water flow around the WP-Cave repository was assumed to be 0.3 l/m^3a. This value corresponds to the average water flow without a hydraulic cage over the depth where the cage will be located.

2 DESCRIPTION OF THE POSSIBLE FLOW PATTERNS

The hydraulic cage is to reduce the hydraulic gradient in the rock around the repository (see Figure 1). A value of 2 - 3 % of the hydraulic gradient without the hydraulic cage is found plausible in the SKN analysis of the cage for a homogeneous rock mass /Boliden WP-Contech AB, 1985/. In this study a value of 10 % has been adopted. In a porous medium, this means that the flow in the rock will be reduced 10 times everywhere. In this case the water flow would be 0.03 l/m^3a.

Water flow in fractured rock is known to occur in sparse channels in the fractures. It is not known at present if it is possible to intersect all channels with the bore holes of the cage. Channeling may therefore modify the effects of the hydraulic cage depending on if the boreholes in the cage intersect or do not intersect these channels. In this study the consequences of the escape of radionuclides are analyzed assuming a 90 % water diversion by the cage, and this is also assumed in the case of discrete channels.

The following two cases are discerned:

1) A fraction of the channels are not intersected by the hydraulic cage, and
2) All the channels are intersected by the hydraulic cage.

2.1 A FRACTION OF THE CHANNELS ARE NOT INTERSECTED BY THE HYDRAULIC CAGE

In this case, the channels which pass through the cage will have the same pressure difference as that over the cage itself. These channels will then act as if there had been no cage present. Thus the residence time of the water will not be influenced by the cage. In these channels the water can then be assumed to pick up radionuclides in the same way as in the case where there is no cage. The difference will be that only 10 % of the water will be contaminated. The interaction of the nuclides in these channels with the rock will also be the same as if no cage existed.

2.2 ALL THE CHANNELS ARE INTERSECTED BY THE HYDRAULIC CAGE

In this case, it is assumed that the water which penetrates into the cage spreads out in all the channels inside the cage. The water velocity decreases by a factor of 10. This will have two effects. The escape rate of the nuclides will decrease by a factor of about 3 (the square root dependence on the flowrate in the near field), and the residence time of the water in the channels in the rock will increase by a factor of 10 over the case when there is no cage. This will act in the same way as if the travel distance was to be increased by a factor of 10. The 50 m thick rock between the cave and the cage would have the same retardation effect as a 500 m travel distance outside the cage. This may for some nuclides make a large difference.

In case 2 there are two sub-cases which we must explore:

2a) The channels pass out through the cage without mixing with the water in the cage, and

2b) The water in the channels from the cage mixes fully with the water in the cage.

The difference between cases 2a and 2b is small if the water was to travel in similar pathways. Then the radionuclide retardation would be the same and the effluent rate of the nuclides would be the same. The difference would be that in case 2a the flowrate of contaminated water is ten times less than in case 2b but the concentration is ten times higher. There may, however, be a difference in flow paths in the two cases because the presence of the cage, which is larger than the cave itself, will connect more channels and the chances of intersecting fast channels increases.

There is a further effect of the presence of the hydraulic cage which must be taken into account. The hydraulic gradient over the cage itself will be zero ideally. With our assumptions of a decrease of the flowrate by a factor of ten, the gradient will be ten times less than without the cage, assuming all else to be unchanged. This means that the gradient just outside the cage will increase if the boundary conditions far away are unchanged. This is illustrated in Figure 2. The flowrate in the cage will be considerably more than two times larger than it would have been in the same rock volume without the cage. This will shorten the travel time of the water over the distance from the cage to the surface. If the travel distance is of the same magnitude as the size of the cage there may be considerable (perhaps two times or more) shortening of the residence time of the water.

3 ATTEMPT TO QUANTIFY THE DIFFERENCE IN RELEASE RATE IF THE HYDRAULIC CAGE IS THERE OR NOT

In the case when there is no cage the radionuclide release rate from the near field is denoted N_o. It is assumed that the distance between the cave and cage is 50 m and that the distance from the cage to the effluent point at the surface is 350 m. It is assumed that the travel time from the cage to the point of effluent is reduced by a factor of two when there is a cage by reasons given in connection with the discussion around Figure 2.

In case 1 when there is a cage the release rate from the cage is $N_o/10$.

In case 2 the release rate from the near field is decreased by a factor of 3 due to reasons given earlier. The travel distance of 50 m between cave and cage is as effective as 500 m in the case of no cage, because the velocity is 10 times lower. In the pathway from the cage to the effluent the velocity is 2 times higher and the effective distance is reduced to 350/2 = 175 m. The total effective travel distance would then be 500 + 175 = 675 m. This is close to a factor of 2 larger than in the case when there is no cage. If there were no differences between the far fields in these cases there would be a 3 times smaller release when there is a hydraulic cage.

4 RELEASE RATE TO BIOSPHERE FOR THE DIFFERENT CASES

The maximum release rates from the repository to the biosphere are calculated for the different cases discussed above. Three radionuclides were chosen for these calculations: ^{239}Pu, ^{242}Pu, and ^{238}U. ^{239}Pu has a short half-life (24,000 years) and a sorption coefficient of 5 m^3/kg. This radionuclide would significantly decay during the transport through larger distances. The half-life of ^{242}Pu is longer, thus the effect of the transport distance would be less. ^{238}U has a very long half-life and a sorption coefficient of 1.0 m^3/kg is used. This means that the effect of the distance would be negligible for a radionuclide with these characteristics.

The maximum release rates are calculated for the case without a hydraulic cage for distances up to 1600 m from the sand-bentonite barrier. They are calculated for a source with unit release rate at the initial time which decays according to the half-life of the respective radionuclide. The unit release is used for the release from the near-field for the case without a hydraulic cage. When the release from the near field is reduced by the cage, the source strength is reduced by the same factor.

The results are shown in Figure 3. These values are not directly comparable with the results obtained for transport in the far field when the transport through the sand-bentonite barrier is accounted for because the latter varies with time /Moreno et al., 1988/.

The results for the case without a hydraulic cage show that a distance of 100 m reduces the release of ^{239}Pu to a value of about 26 %. For ^{238}U the release reduction is negligible. The reduction of ^{242}Pu is intermediate. A distance of 800 m without a hydraulic cage reduces the release rate of ^{239}Pu by 3 - 4 orders of magnitude.

For the case with a hydraulic cage, the same two cases described above are calculated. Distances of 25 and 50 m between the cave and the cage are used. The total transport distance is varied up to 1600 m.

In case 1, the concentration in the channels is the same as that without a cage except only 10 % of the water is contaminated. This effect reduces the release from the near-field by 10 times. The release rate for case 1 is the same regardless of the distance between the near-field and the hydraulic cage.

In case 2, the water flow between the cave and the cage is reduced to 10%. This means that the release from the sand-bentonite barrier is reduced by a factor of about 3 /Neretnieks, 1979/. The water flow outside the cage is considered to be larger than without the hydraulic cage, for this reason the effective transport distance is reduced outside of the hydraulic cage by a factor of about 2.

Once the nuclides have been released from the cage, the influence of the transport on the far-field will be different for the different nuclides. The results for ^{238}U are similar in the 3 cases. They show an insignificant influence of the transport distance. This is due to that the half-life of ^{238}U is very long. In practice, the transport distance modifies the release of ^{238}U, due to that the inventory of the radionuclides is limited.

Figures 4 and 5 show the results for ^{239}Pu and ^{242}Pu, respectively. The maximum relative release rate is presented for total transport distances (the distance between the cave and the cage and the distance from the hydraulic cage to the biosphere). For case 1 the release rate is reduced by a factor 10. For case 2, the presence of the hydraulic cage reduces the release rate of both nuclides for short distances. For longer distances the effect of the cage is not important, this is due to that the cage increases the water flowrate in the nearest portion of the far-field but when the distance from the cage is increased the water velocity will be less influenced by the presence of the cage.

For the assumptions used in this report, the hydraulic cage would be important if the total distance between the cave and the biosphere was small (100 - 200 m). For larger distances (800 - 1600 m) the effect of the hydraulic cage is not significant.

5 DISCUSSION AND CONCLUSIONS

The hydraulic cage is larger than the cave and will intersect more channels. It will also change the flow pattern considerably to a distance of at least the diameter of the cage and thus also in this way connect more channels including fast channels near the surface where there is a higher conductivity and probably more fast channels. For those nuclides for which the retardation and decay in the far field is important, the presence of more fast channels may, in part, compensate the decreased release from the near field due to the reduction of the flowrate passing the cave. With our present very limited knowledge of the nature and frequency of channels it is not possible to make much firmer statements.

It is concluded that the hydraulic cage may under some circumstances have some beneficial effects but may also have some marginally detrimental effects in some cases. Much work will be needed, especially as regards to gathering data on channeling and understanding the nature of flow in fractured channeled rock, in order to be able to quantify the effects of a hydraulic cage.

The hydraulic cage plays an important role if the transport distance between the WP-Cave repository and the effluent to the biosphere is small. For large distances the effect of the hydraulic cage is less important.

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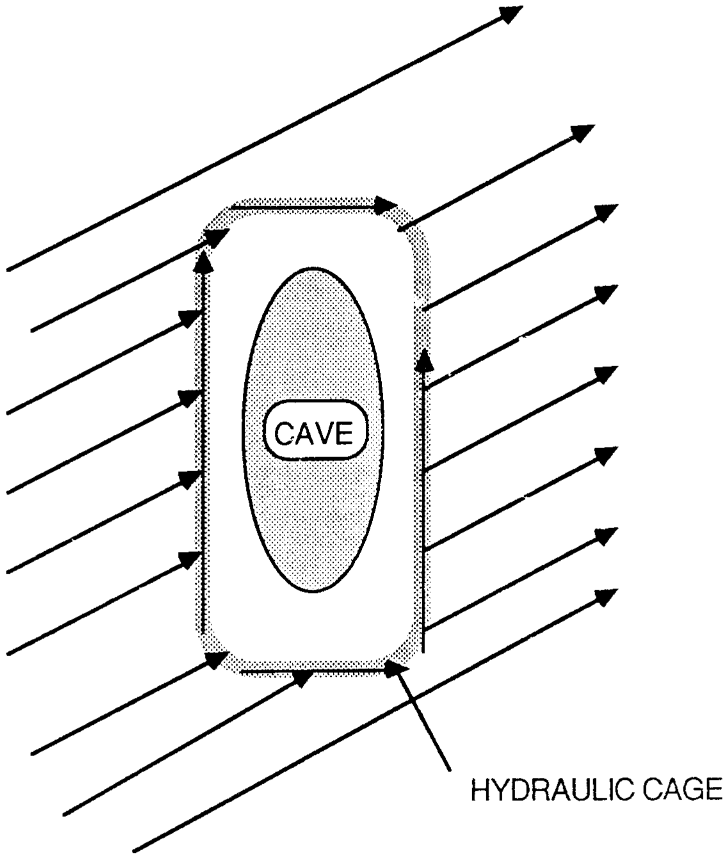

Figure 1. Illustration of how the hydraulic cage diverts the flow into and through the cage itself and not allowing any flow inside the cage.

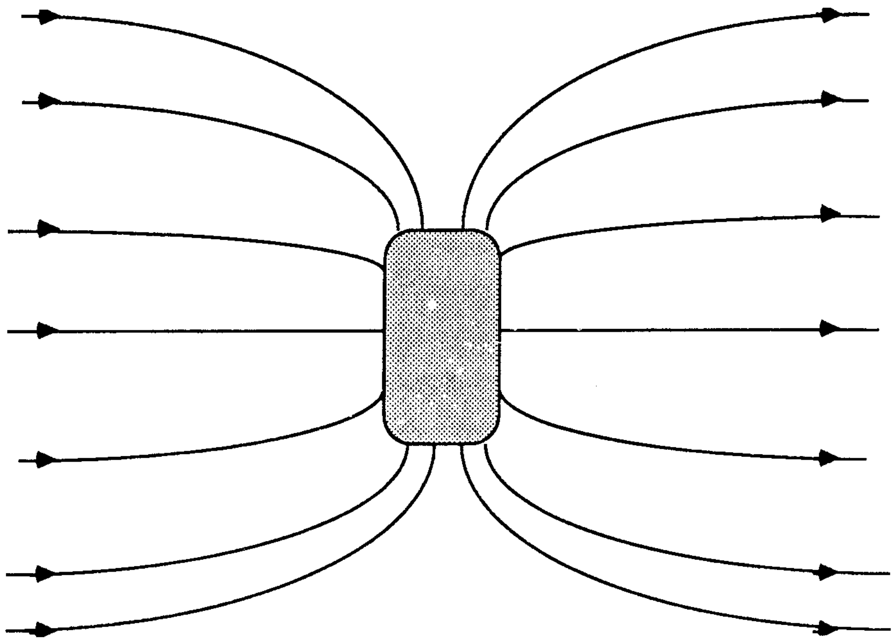

Figure 2. Illustration of the streamlines being drawn into the hydraulic cage thus increasing the flowrate and velocity near the cage.

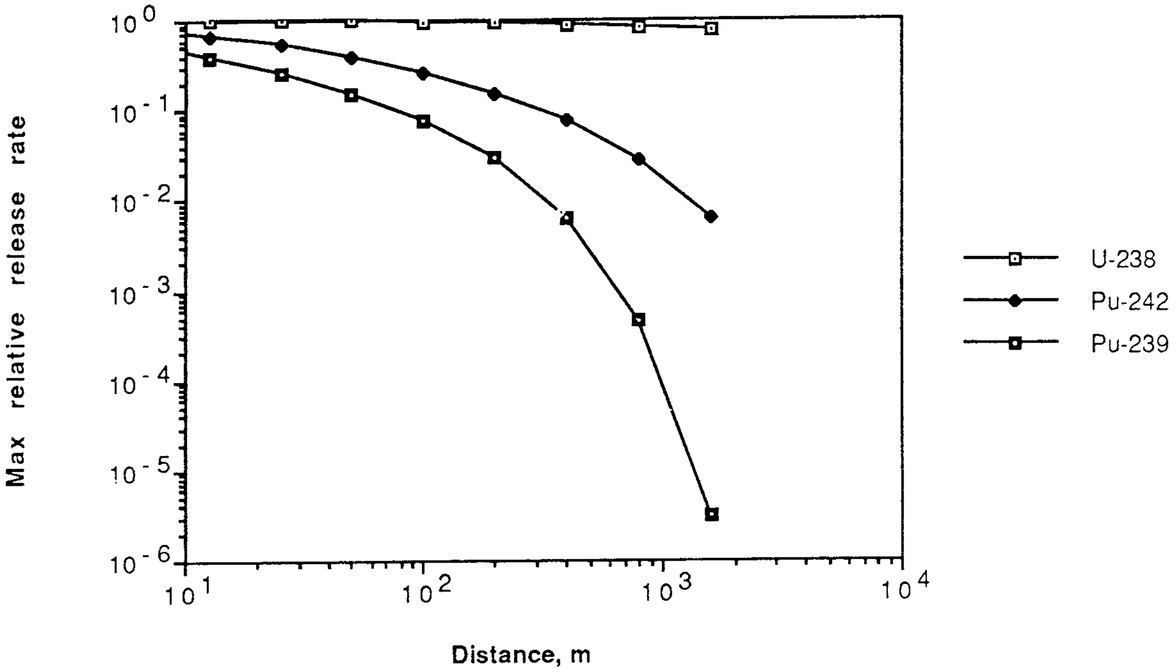

Figure 3. The maximum relative release rate for different radionuclides for the case without a hydrualic cage. The distance is measured from the sand-bentonite barrier.

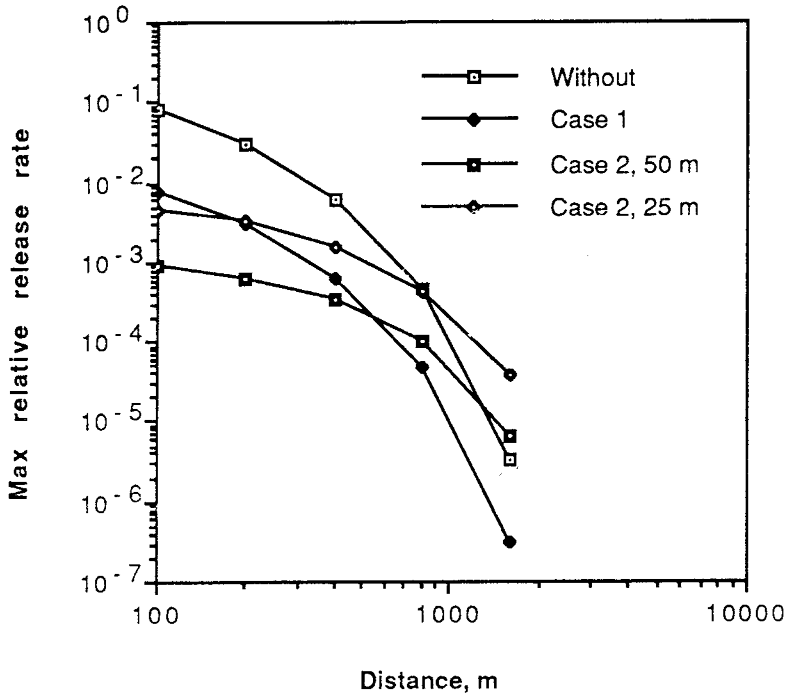

Figure 4. The maximum relative release rate to the biosphere for ^{239}Pu for the different cases, with and without a hydraulic cage. The distance is measured from the sand-bentonite barrier.

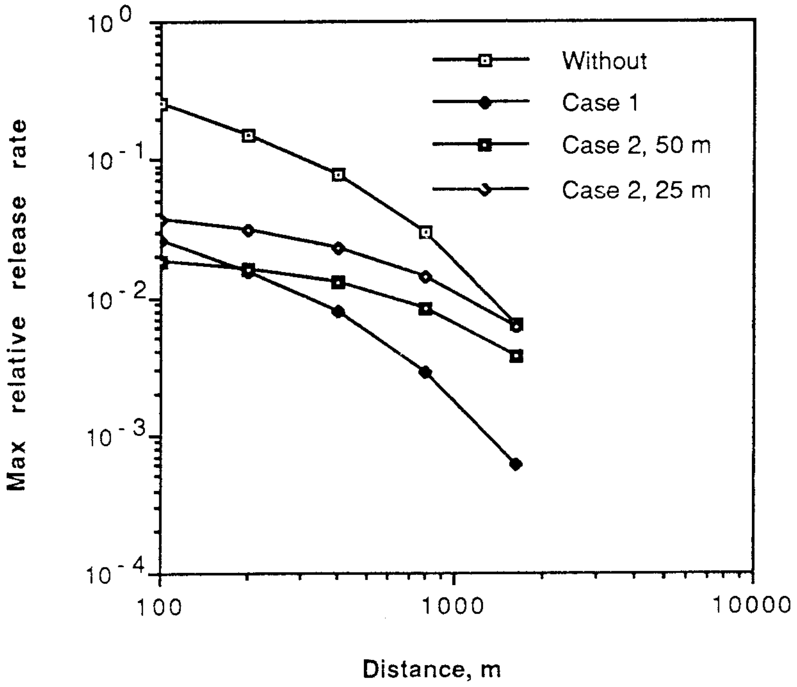

Figure 5. The maximum relative release rate to the biosphere for ^{242}Pu for the different cases, with and without hydraulic cage. The distance is measured from the sand-bentonite barrier.

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