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**ASSESSMENT OF A CLAY BARRIER RESATURATION IN
ISOTHERMAL CONDITIONS**

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Keywords

radwaste, waste repository, clay barrier, re-saturation, hydraulic, Richard's equation

Abstract

Many projects of underground repositories for high level radioactive wastes involve an engineered clay barrier, placed between the waste canister and the surrounding rock. By hydrating progressively, the barrier swells, seals the gaps and provides a good global watertightness.

In a high level radioactive waste repository, the maximum admissible temperature for the barrier governs the space between canisters and consequently the cost of the civil engineering works. Thus a precise assessment of this criterion is compulsory.

Even though the barrier behaviour depends on the thermal-hydro-mechanical interactions with the canister and the host rock, the study is only focused on the hydraulic behaviour of the barrier without phase change in a first step.

A chamber containing one high level radioactive waste canister is simulated for the East of France repository site. A 2D-plane computation is done with the CASTEM2000 code. A cylindrical geometry, composed of a barrier layer surrounded by a site layer, is represented.

Two kinds of clay are studied for the barrier. The clay foreseen for the french repository sites is the FoCa clay. But in order to compare our

results with those of other european countries, we studied the spanish La Serrata clay too for the barrier. The East of France site is made of a clay, different from the barrier one.

To understand the influence of the boundary conditions on the barrier resaturation time, two sorts of boundary conditions are considered for the external site limit: an imposed water pressure or no water flow. On the internal barrier limit, we enforce a water flow equal to zero.

Initially, the site is saturated whereas the barrier is partially unsaturated. Neglecting the initial ventilation phase in the repository site, we suppose that the barrier is in thermal equilibrium with the surrounding site. Their average temperature is 50°C.

The models implemented in the CASTEM-2000 code are based on the mixed-hybrid finite element formulation. The numerical model used for this computation supposes that air remains at a constant pressure and water only exists in a liquid state.

This paper is devoted to the analysis of the barrier resaturation by the site water. A parametric study on the barrier material and the boundary conditions is realised. The results are the water pressure and the saturation versus time and along a radius.

1 Introduction

Many projects of high-level waste repositories

in geological media involve an engineered clay barrier, placed between the waste and the surrounding host rock. By hydrating progressively on contact with the interstitial water, the barrier swells, seals the gaps, and then provides a global mechanical stability of the waste-clay barrier-host rock system (Lassabatere, 1998) (Lassabatere, 1999).

In a high-level radioactive waste repository, the thermal waste creates a thermal field in the vicinity of the waste. The maximum admissible temperature for the barrier (beyond which physical, mechanical or chemical properties break down) dictates the distance between the canister cells and consequently the size of the repository. Thus a precise assessment of this criterion is a matter of great importance.

From a physical point of view, the evolution of the clay barrier is governed by thermics, hydraulics and soil mechanics, these three processes being coupled according to the following sequence: the waste creates a thermal field; interstitial water infiltrates the clay material; temperature modifies the fluid density and viscosity, vaporizes the liquid water; steam diffuses towards the cold area and condensates; the capillary pressure induces mechanical stresses which in turn modify the accessible porosity for the interstitial water.

In order to validate the computer codes and the models used to describe the clay barrier resaturation process, a benchmark has been undertaken between french codes. The validation was broken down into several progressive steps concerning successively the comparison of isothermal hydraulic models, thermal-hydraulic, hydro-mechanical and finally thermal-hydro-mechanical ones. The results presented here concern the first isothermal hydraulic step and are only relative to the computations carried out at the french CEA research center of Saclay with the computer code CASTEM2000.

A chamber containing one high-level radioactive waste canister is simulated for the East of France repository site. 2D-plane computations are performed with a model based on the Richards' equation. A cylindrical geometry, composed of a barrier layer surrounded by a site layer, is represented. The clay barrier is ini-

tially unsaturated whereas the site is saturated and submitted to the hydrostatic pressure.

Two kinds of clay are studied for the barrier. The clay foreseen for the french repository sites is the FoCa clay. Two different laws have been tested to model this clay. In order to compare our results with those of other european countries, we studied the spanish La Serrata clay too for the barrier. The East of France site is made of a clay, different from the barrier one.

To understand the influence of the boundary conditions on the barrier resaturation time, two sorts of boundary conditions are considered for the external site limit: an imposed water pressure or no water flow. On the internal barrier limit, we enforce a water flow equal to zero.

Initially, the site is saturated whereas the barrier is partially unsaturated. Neglecting the initial ventilation phase in the repository site, we suppose that the barrier is in thermal equilibrium with the surrounding site. Their average temperature is 50°C.

This paper is devoted to the analysis of the barrier resaturation by the site water. A parametric study on the barrier material and the boundary conditions is realised. The results are the pressure and the saturation versus time.

2 Description of the problem

This paper presents computations carried out with the fluid part of the computer code CASTEM2000 (CASTEM2000, 1997) developed by the CEA Saclay. The numerical model used (Benet, 1997) ((Le Potier, 1998) for this study deals with the multiphase flows in porous media and was set up from (De Marsily, 1981) (Bear, 1992) (Huyakorn, 1983). The model is based on the mixed-hybrid finite element formulation (Dabbene, 1998). It uses the Richards' equation which supposes that air remains at a constant pressure and water only exists in a liquid state.

The problem is represented geometrically by two concentric layers. The inner layer is the clay barrier whereas the outer layer is composed of a neighbouring part of the host site. The radwaste canister is not modeled because we consider that the barrier is in contact with

the canister and there is no hydraulic flow between both zones. The geometric description is given by the figure 1. We modeled a vertical section in 2D-plane.

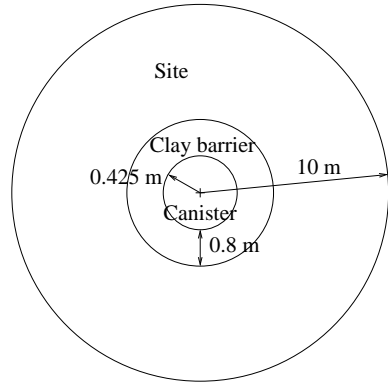


Figure 1 : Geometry

The initial conditions are:

- for the host site: temperature $T = 50^\circ\text{C}$ and 100% of relative moisture RM ,
- for the clay barrier: temperature $T = 50^\circ\text{C}$, 60% of relative moisture and air at the atmospheric pressure.

The capillary pressure P_c is given by:

$$P_c = P_w - P_a = \rho_w \frac{R T}{M_w} \ln RM$$

where P_w and P_a are the water and air pressure, $\rho_w = 1000 \text{ kg/m}^3$ the water density, $R = 8.373$ the constant of perfect gases and $M_w = 18 \text{ g/mol}$ the water mass.

The boundary conditions are:

- for the outer limit of the host site: either a water pressure equal to the hydrostatic pressure at the depth of 500 m, or no water flow,
- for the inner limit of the clay barrier: no flow between the canister and the barrier.

The host site is composed by the clay of the East of France site which is characterized by:

- the capillary pressure curve

$$S_w(P_c) = \left[1 + \left(\frac{|P_c|}{10 \text{ MPa}} \right)^{1.7} \right]^{-\left(1 - \frac{1}{1.7}\right)}$$

- the liquid relative permeability curve

$$k_{rw}(P_c) = \left[1 + \left(\frac{|P_c|}{10 \text{ MPa}} \right)^2 \right]^{-1}$$

- the liquid saturated permeability 10^{-12} m/s
- the porosity 5 %

- the storage coefficient $3.83 \cdot 10^{-6} \text{ m}^{-1}$

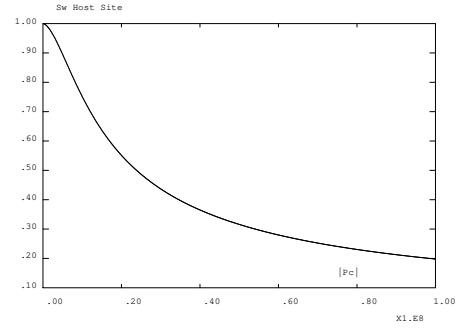


Figure 2: Capillary pressure curve of the host site

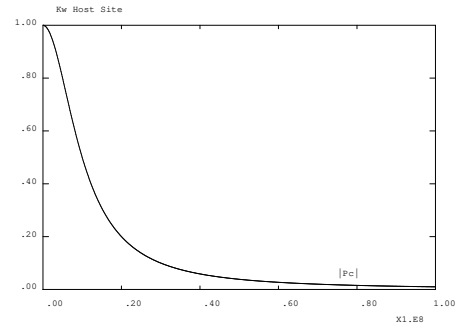


Figure 3: Liquid relative permeability curve of the host site

Two materials were considered for the clay barrier: the french clay FoCa and by the spanish clay Serrata. For the clay FoCa, the capillary pressure curve was determined by the Polytechnic University of Catalonia (UPC) and by the CEA. The characteristics of the clay FoCa are:

- the capillary pressure curve

$$UPC \quad S_w(P_c) = \left[1 + \left(\frac{|P_c|}{17 \text{ MPa}} \right)^{\frac{1}{1-0.27}} \right]^{-0.27}$$

$$CEA \quad S_w(P_c) = \left[1 + \left(\frac{|P_c|}{1.5 \text{ MPa}} \right)^{\frac{1}{1-0.06}} \right]^{-0.06}$$

- the liquid relative permeability curve

$$k_{rw}(P_c) = \left[1 + \left(\frac{|P_c|}{3 \text{ MPa}} \right)^{\frac{1}{1-0.5}} \right]^{-0.5}$$

- the liquid saturated permeability 10^{-13} m/s
- the porosity 30 %
- the storage coefficient $3.09 \cdot 10^{-5} \text{ m}^{-1}$

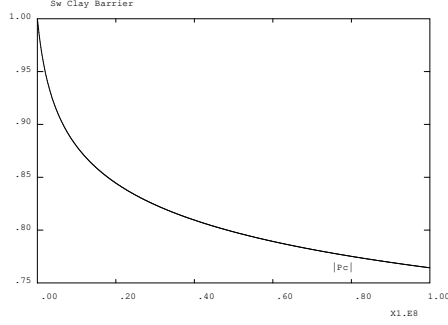


Figure 4: Capillary pressure curve of the clay FoCa defined by the UPC

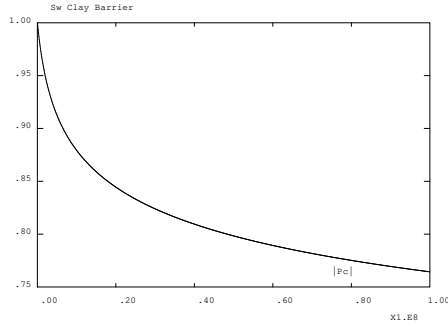


Figure 5: Capillary pressure curve of the clay FoCa defined by the CEA

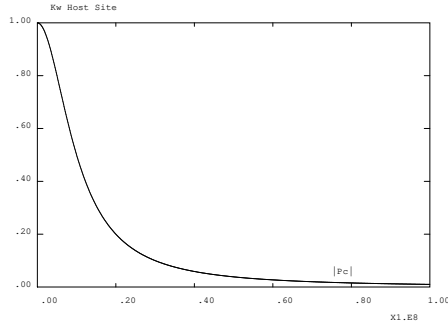


Figure 6: Liquid relative permeability curve of the clay FoCa

The characteristics of the clay Serrata are:

- the capillary pressure curve

$$S_w(P_c) = \left[1 + \left(\frac{|P_c|}{7MPa} \right)^{\frac{1}{1-0,35}} \right]^{-0,35}$$

- the liquid relative permeability curve

$$k_{rw}(P_c) = \left[1 + \left(\frac{|P_c|}{7MPa} \right)^{\frac{1}{1-0,35}} \right]^{-0,35*3}$$

- the liquid saturated permeability 6.10^{-14} m/s
- the porosity 30 %

- the storage coefficient $1.55.10^{-5} \text{ m}^{-1}$

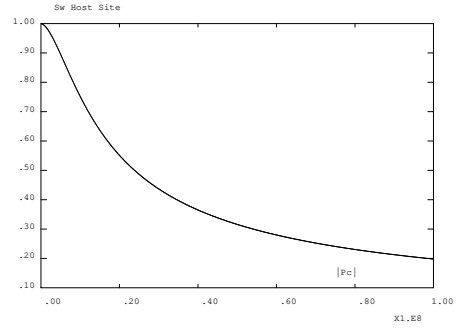


Figure 7: Capillary pressure curve of the clay Serrata

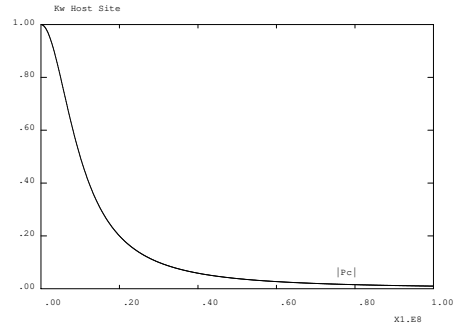


Figure 8: Liquid relative permeability curve of the clay Serrata

A set of six computations was carried out by combining the three clay barrier materials (FoCa CEA, FoCa UPC, Serrata) and the two boundary conditions at the outer limit of the host site (pressure or flow).

3 Analysis of the resaturation process versus time

The aim is to evaluate the resaturation time of the clay barrier for the six computations and to evaluate the effects of the material and boundary condition changes on the resaturation process. The analysis is realised by comparing the evolution of the pressure (Figure 9) and the saturation (Figure 10) versus time with a logarithmic scale for the six computations. The calculations are carried out until 20 years.

The comparison is performed at six points aligned along a radius of the mesh. As the computations do not account for gravity, the results are identical for all the radii. Three points are located in the clay and the others in the site. *Rin* indicates the internal radius of the layer, *Rmiddle* the middle of the layer and *Rout* the external radius of the layer.

3.1 Pressure

The initial pressure is 4.3 MPa in the host rock and -77 MPa in the clay barrier. The pressure starts increasing quite immediately in the clay buffer at the limit with the site and later in the rest of the barrier layer. In the middle of the buffer and at the limit with the canister, the pressure increases respectively from 1.5 month and 4 months for the FoCa CEA clay, 4 months and 15 months for the FoCa UPC clay, 9.5 months and 3 years for the Serrata clay. The beginning of the pressure increase is identical for both boundary conditions at the outer limit of the host site.

In the host rock, the pressure starts decreasing quite immediately at the limit with the clay barrier; it reaches a minimum of -3 MPa at 12 days for the FoCa CEA clay, -5 MPa at 25 days for the FoCa UPC clay, -5 MPa at 46 days for the Serrata clay. In the middle of the site layer, the pressure starts decreasing at 4 months for the three kinds of buffer. These results are identical for both boundary conditions.

For the imposed pressure boundary condition, the pressure remains constant at the outer limit of the site whereas the pressure decreases slightly with the zero flow condition. The pressure in the middle of the site layer reaches a minimum of 3 MPa for the FoCa CEA clay and around 2 MPa for the two other cases. Then the pressure increases again to match the imposed pressure.

At the end of the saturation process, all the points have the same pressure which is the pressure imposed at the outer site limit. This pressure is reached simultaneously in the whole mesh at a time depending on the clay material: around 20 years for the FoCa clay and 60 years for the Serrata clay.

For the imposed flow, the pressure in the middle and at the outer limit of the site layer decreases respectively from 4 months and 15 months and then converges to a value smaller than the initial pressure. All the points of the site and of the buffer converge towards the same value: around 2 MPa for the FoCa clay CEA, 0 MPa for the FoCa clay UPC and -2 MPa for the Serrata clay.

Generally, we observe that the clay material imposes the beginning and the end of the pressure increase in the clay barrier and the level of the pressure drop in the site. The beginning of the pressure decrease in the site seems to be independent from the clay material. The boundary condition at the outer limit of the site layer influences the final pressure in the whole model (barrier and host rock) but not the delay for the final pressure equilibrium.

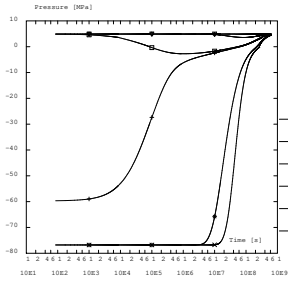
3.2 Saturation

The initial saturation level is 100 % in the host rock, 77 % in the clay FoCa CEA, 55 % in the clay FoCa UPC and 27 % in the clay Serrata. The saturation starts increasing quite immediately in the clay buffer at the limit with the site and later in the rest of the barrier layer. In the middle of the buffer and at the limit with the canister, the saturation starts raising at the same time as the pressure and is identical for both boundary conditions.

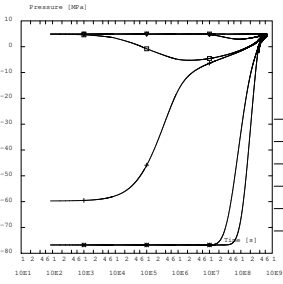
In the host rock, the middle of the site layer and the outer limit remain fully saturated, except in the case of the clay Serrata with no flow where they become unsaturated from 12 years.

At the limit with the clay barrier, the site starts desaturating from 28 hours for the clay FoCa CEA, 17 hours for the clay FoCa UPC and 4.6 days for the Serrata clay. The desaturation reaches a minimum before increasing again. This minimum is 96 % at 12 days for the FoCa CEA clay, 89 % at 25 days for the FoCa UPC clay and 91 % at 46 days for the Serrata clay. The beginning of the desaturation and the time corresponding to the minimum saturation level are identical for both boundary conditions.

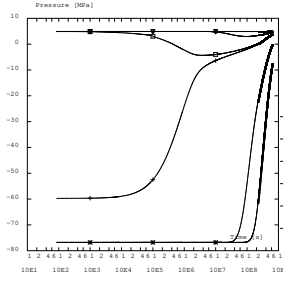
According to the clay material, the end of the saturation process is completely different. For the clay FoCa CEA, the host rock next to the buffer and the buffer next to the host rock become simultaneously saturated from 15 months; the middle of the buffer and the clay at the limit with the canister become saturated respectively from 7 years and 10 years.



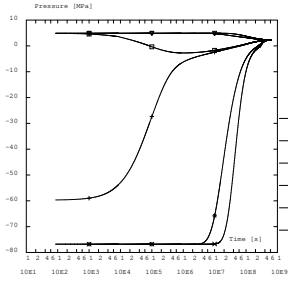
Clay FoCa CEA
Imposed pressure



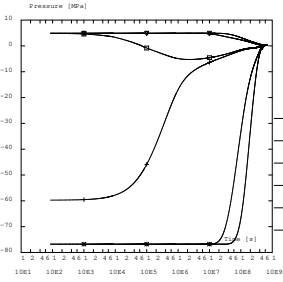
Clay FoCa UPC
Imposed pressure



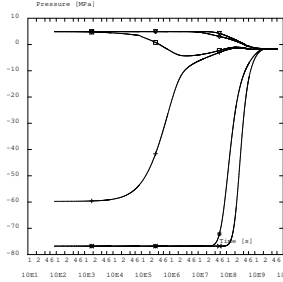
Clay Serrata
Imposed pressure



Clay FoCa CEA
Imposed flow

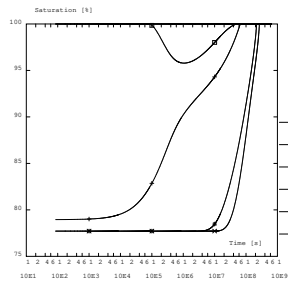


Clay FoCa UPC
Imposed flow

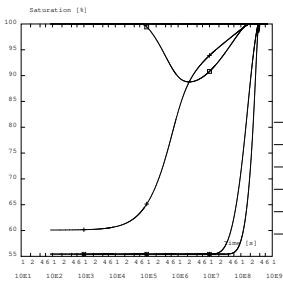


Clay Serrata
Imposed flow

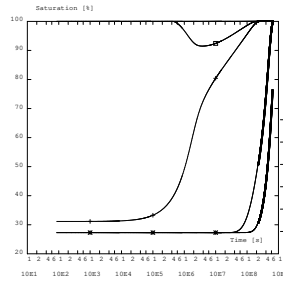
Figure 9: Pressure versus time



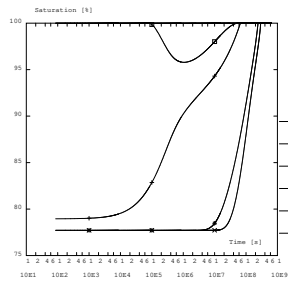
Clay FoCa CEA
Imposed pressure



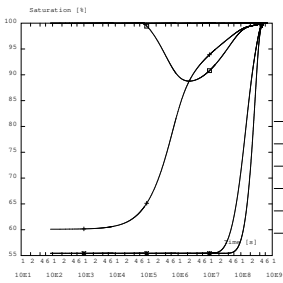
Clay FoCa UPC
Imposed pressure



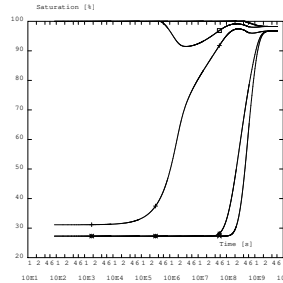
Clay Serrata
Imposed pressure



Clay FoCa CEA
Imposed flow



Clay FoCa UPC
Imposed flow



Clay Serrata
Imposed flow

Figure 10: Saturation versus time

The slope of the three buffer saturation curves is very steep until the end of the saturation process because the pressure at the final equilibrium is positive. The results are the same for the two boundary conditions.

For the clay FoCa UPC, the area at the border between the site and the barrier becomes saturated from 4.5 years whereas the rest of the buffer (middle of the layer and area next to the canister) remains unsaturated until 12.5 years in the case of the imposed pressure. On the contrary, the whole buffer and the site area in contact with the buffer resaturates at the same time (16 years) in the case of the imposed flow.

The slope of the saturation curves is steeper with the imposed pressure than with the imposed flow. Indeed the final pressure imposes a solution in the saturated domain in the imposed pressure case whereas the pressure with the imposed flow case is only slightly positive and thus very near to the limit of the unsaturated domain.

For the clay Serrata, the behaviour is very different according to the boundary conditions. When the pressure is imposed, both sides of the border site-barrier become saturated from 6 years; the middle and the center of the clay layer reach the 100 % saturation level from 19 years and 24 years respectively.

When a flow equal to zero is imposed, the final solution is unsaturated everywhere but the final saturation levels are different for both materials: 96 % in the barrier and 98 % in the site. The equilibrium is obtained from 80 years. However, if the areas far from the border site-barrier converge directly towards the final solution, the area next to the border oscillates around the solution before it stabilizes on it.

Generally speaking, we observe that, as for the pressure, the material governs the beginning of the barrier resaturation, the beginning of the site desaturation and the desaturation level at the interface with the barrier. The final resaturation time is globally imposed by the barrier material but it is influenced by the boundary conditions at the outer side limit. The boundary conditions only play a role at the end of the resaturation process where they

govern the shape of the curves and the final solution.

The clay FoCa CEA resaturates quicker than the clay FoCa UPC. The site is more desaturated and for a longer time by the clay FoCa UPC than by the clay FoCa CEA. The site remains always less desaturated than the barrier for the clay FoCa CEA. But, for the clay FoCa UPC, the site is more desaturated than the buffer during a certain time.

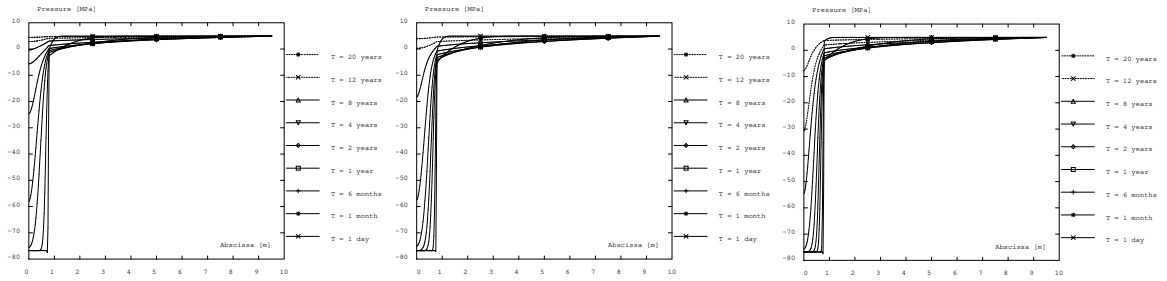
The final solution is in the saturated domain for both models of the clay FoCa and for both boundary conditions. However, the final pressure with the imposed flow condition is actually in the saturated domain for the clay FoCa CEA whereas it is near the transition with the unsaturated field for the clay FoCa UPC.

The resaturation time of the clay Serrata is much longer than the one of the clay FoCa, what can be explained by the initial saturation level of the barrier which is much lower than the one with the FoCa clay. The material Serrata induces a site desaturation level in the same range as the one of the clay FoCa. The final solution is in the unsaturated domain when the imposed flow boundary condition is zero; this solution conduces to a negative pressure and to saturation levels different in the site and the clay buffer.

4 Analysis of the resaturation process versus the distance

In order to understand better the resaturation process, a complementary analysis is realised. It consists in curves representing the pressure (Figure 11) and the saturation (Figure 12) for the six computations along a radial axis and in figures displaying a 2D section of barrier and the site for the FoCa CEA clay case only. These figures show the pressure (Figures 13 and 15) and the saturation (Figures 14 and 16) for both boundary conditions.

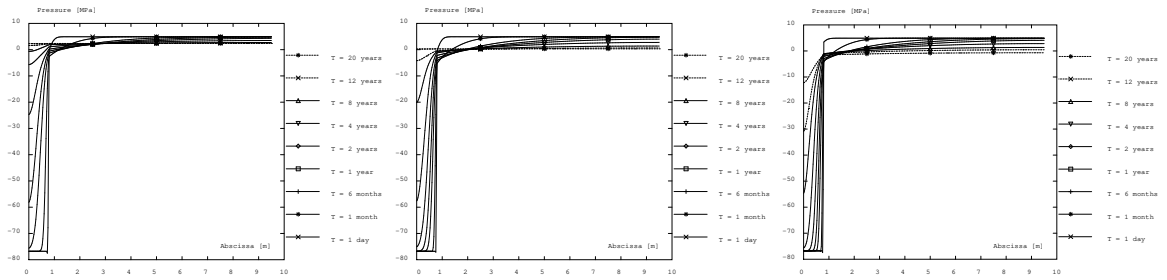
The figures 11 and 12 present the variation of the pressure or the saturation versus the distance to the canister wall at several instants: 1 day, 1 month, 6 months, 1 year, 2 years, 4 years, 8 years, 12 years and 20 years. The figures show that the initial transition between



Clay FoCa CEA
Imposed pressure

Clay FoCa UPC
Imposed pressure

Clay Serrata
Imposed pressure

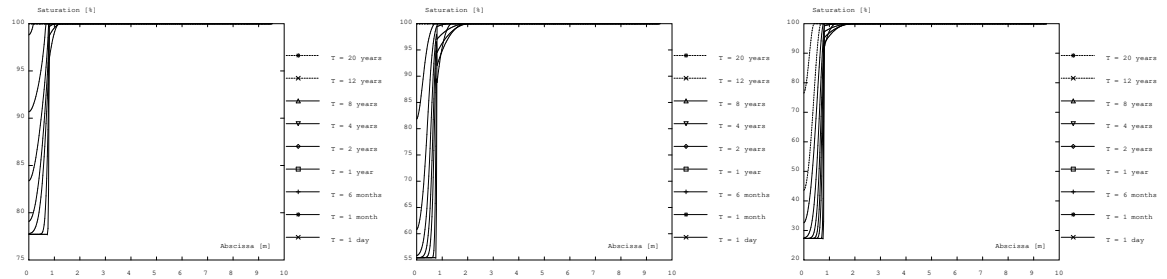


Clay FoCa CEA
Imposed flow

Clay FoCa UPC
Imposed flow

Clay Serrata
Imposed flow

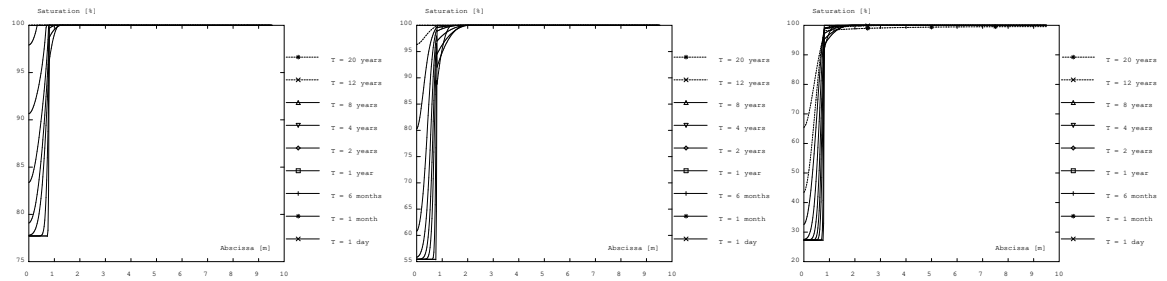
Figure 11: Pressure versus the distance



Clay FoCa CEA
Imposed pressure

Clay FoCa UPC
Imposed pressure

Clay Serrata
Imposed pressure



Clay FoCa CEA
Imposed flow

Clay FoCa UPC
Imposed flow

Clay Serrata
Imposed flow

Figure 12: Saturation versus the distance

the unsaturated buffer and the saturated host rock is correctly modelled.

Progressively, the pressure and the saturation increase in the barrier until reaching the saturation level 100 % and the imposed pressure in the case of the pressure condition or the final pressure and final saturation level in the case of the flow condition.

In the site, for the pressure boundary condition, the pressure decreases for approximately the first 6 months before it starts increasing again and reaches progressively the imposed pressure. As the pressure becomes negative near the barrier, the site desaturates locally at the beginning of the barrier resaturation process. The site is desaturated during the first year on a short distance (less than 1 m) for the clay FoCa CEA, during 2 years on a longer distance (1.5 m) for the clay FoCa UPC and the clay Serrata.

For the flow boundary condition, the pressure decreases very locally for the first month. The pressure is negative near the barrier and positive elsewhere. The maximum distance with a negative pressure is reached around 6 months - 1 year. Then we observe two areas: near the barrier, the pressure increases progressively while the pressure decreases in the rest of the site layer. The final pressure is identical in the whole site and is positive for the clay FoCa CEA, slightly positive for the clay FoCa UPC and slightly negative for the clay Serrata.

As for the imposed pressure, the site desaturates locally at the beginning of the barrier resaturation process but for a longer time. The site is desaturated during the first year on a short distance (less than 1 m) identical to the one of the imposed pressure condition for the clay FoCa CEA, during 4 years on around 1.5 m as for the imposed pressure for the clay FoCa UPC. For the clay Serrata, the site remains always desaturated and from 20 years the site is completely desaturated.

The figures 13 to 16 present the pressure and saturation for the clay FoCa CEA and for the two boundary conditions. They show that there is no difference during the first 4 years between the two boundary condition results either for the pressure, or for the saturation. Then

the pressure increases more with imposed pressure condition than with the no flow condition. At 8 years, the saturation level is slightly smaller for the imposed flow and the zone remaining desaturated is larger for the imposed flow than for the imposed pressure.

5 Conclusion

This study has presented a set of six computations performed with the code CASTEM2000 developed at the CEA. The numerical model consists in the resolution of the Richard's equation. The purpose of the computations was to compare the resaturation process of a clay barrier used in a long-term storage site for two barrier materials and two boundary conditions at the outer limit of the layer of modelled site.

We have shown that the barrier material governed the resaturation process from the beginning to the end and specially the resaturation time. The boundary conditions induced modifications only at the end of the resaturation process and imposed the final solution (saturated or unsaturated).

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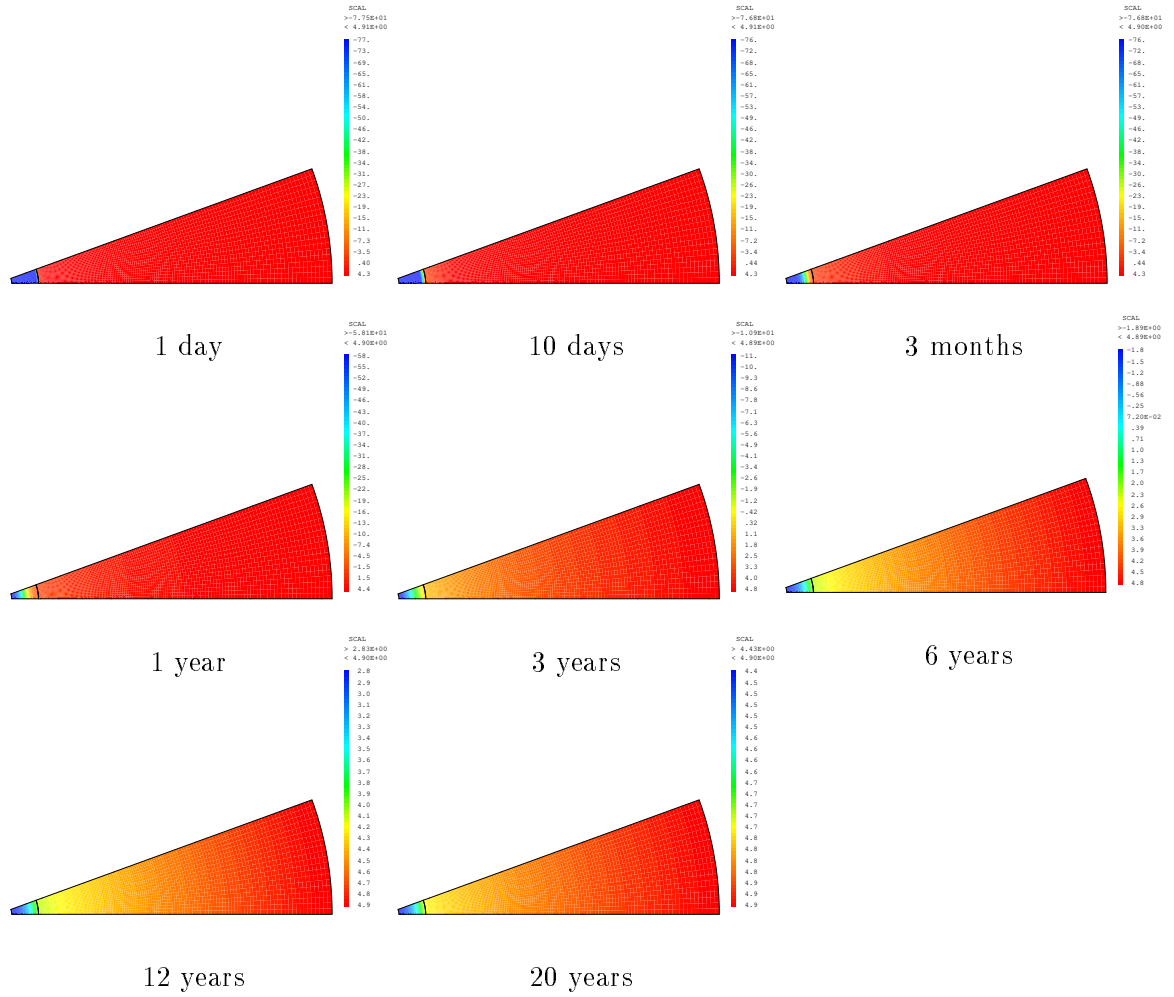


Figure 13: Pressure for the clay FoCa CEA with the imposed pressure

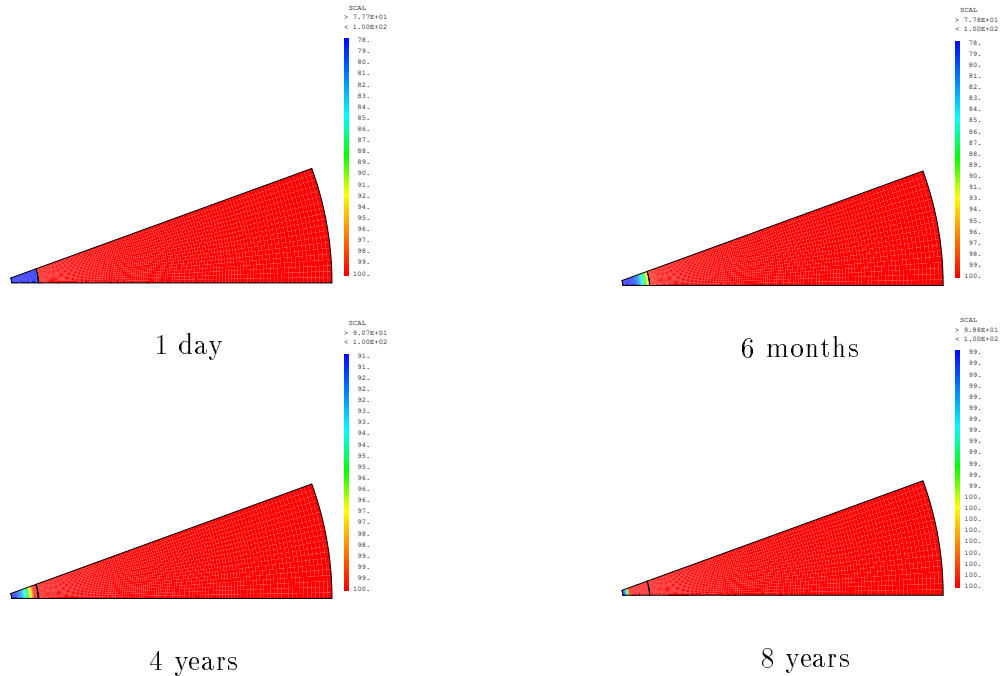


Figure 14: Saturation for the clay FoCa CEA with the imposed pressure

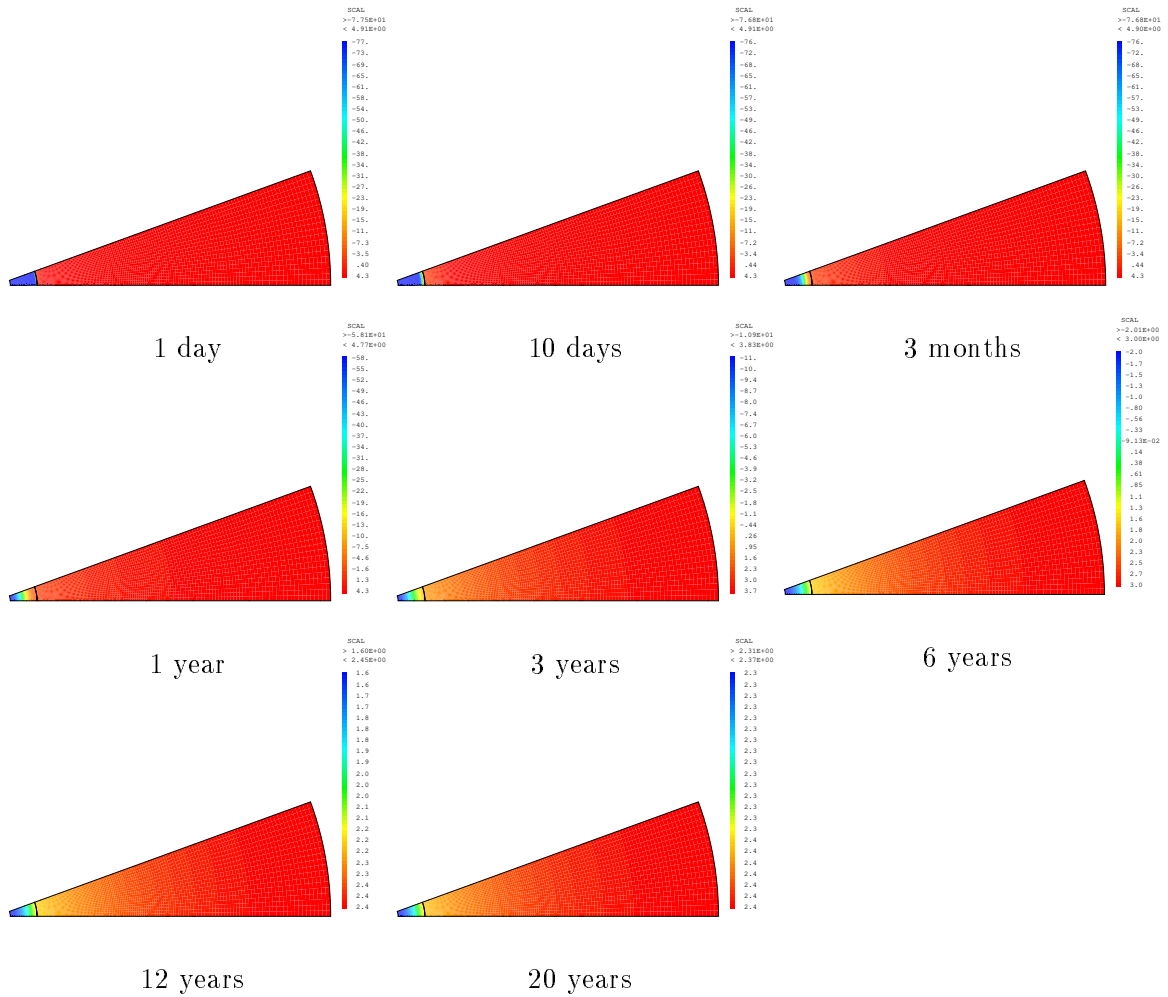


Figure 15: Pressure for the clay FoCa CEA with the imposed flow

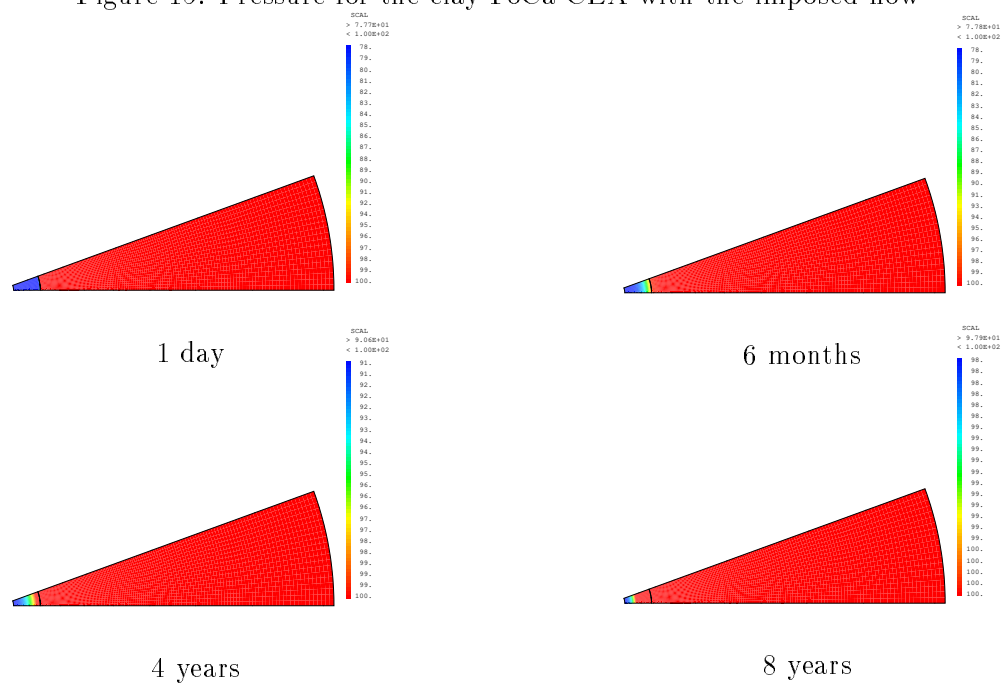


Figure 16: Saturation for the clay FoCa CEA with the imposed flow