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## EVALUATION OF THE INFLUENCE OF VARIOUS PARAMETERS ON A CLAY BARRIER RESATURATION IN ISOTHERMAL CONDITIONS

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**Key words:** radwaste, waste repository, clay barrier, resaturation, 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.

The barrier behaviour depends on the thermal-hydro-mechanical interactions with the canister and the host rock. However 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. The study is focused on the hydraulic behaviour of the barrier without phase change and with air at a constant pressure. A 2D-plane computation is done with the code CASTEM2000. A cylindrical geometry, composed of a barrier layer surrounded by a site layer, is represented.

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 CASTEM2000 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. The parametric study concerns the influence on the resaturation time of the clay material, the boundary conditions on the external site limit, the air pressure and the taking into account of the gravity. The results are the pressure and the saturation versus time.

## 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 [1] [2].

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 described here concern the first isothermal hydraulic step. A comparison between computations carried out with the computer code CASTEM2000 developed by the CEA Saclay and with the code CESAR developed by the LCPC is presented.

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 initially unsaturated whereas the site is saturated and submitted to the hydrostatic pressure. 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. The parametric study concerns the influence on the resaturation time of the clay material, the boundary conditions on the external site limit, the air pressure and the taking into account of the gravity. The results are the pressure and the saturation versus time.

## 2 Description of the problem

This paper presents a set of computations carried out with the fluid part of the computer code CASTEM2000 [3] developed by the CEA Saclay. The numerical model used [4] [5] for this study deals with the multiphase flows in porous media and was set up from [6] [7] [8]. 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. A comparison with results issued from the code CESAR from the LCPC is also realised.

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.

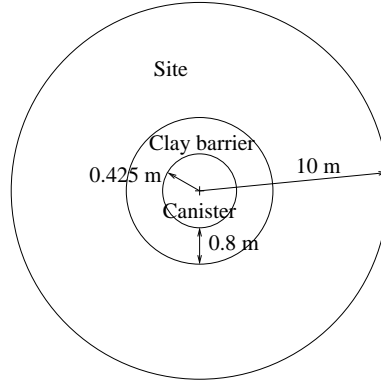


Figure 1: Geometry

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 a constant 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.

In the barrier, the air is at the atmospheric pressure. In the host rock, if we suppose the presence of a small quantity of air in the water, the air pressure would be the hydrostatic pressure. The modeling should represent this pressure difference for air. But with the Richard's equation, the model considers only a constant pressure identical for the site and the barrier. In order to test the influence of the air pressure, calculations were performed with the air pressure either at the atmospheric pressure or at the hydrostatic pressure in both sides.

One computation was carried out to check that the influence of the gravity was negligible. The other computations do not take into account gravity.

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 (Figure 2)

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

- the liquid relative permeability curve (Figure 3)

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

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

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

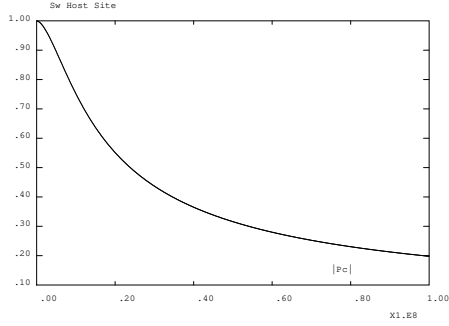


Figure 2: Capillary pressure curve of the host site

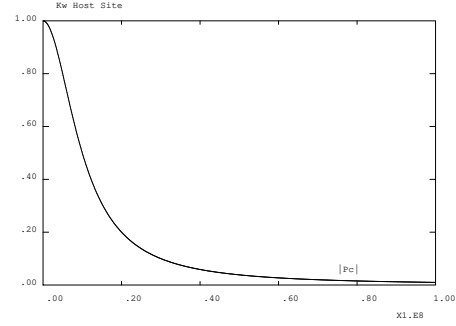


Figure 3: Liquid relative permeability curve of the host site

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 (Figures 4 and 5)

$$UPC \quad S_w(P_c) = \left[ 1 + \left( \frac{|P_c|}{17MPa} \right)^{\frac{1}{1-0,27}} \right]^{-0,27}$$

$$CEA \quad S_w(P_c) = \left[ 1 + \left( \frac{|P_c|}{1,5MPa} \right)^{\frac{1}{1-0,06}} \right]^{-0,06}$$

- the liquid relative permeability curve (Figure 6)

$$k_{rw}(P_c) = \left[ 1 + \left( \frac{|P_c|}{3MPa} \right)^{\frac{1}{1-0,5}} \right]^{-0,5}$$

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

The characteristics of the clay Serrata are:

- the capillary pressure curve (Figure 7)

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

- the liquid relative permeability curve (Figure 8)

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

- the liquid saturated permeability  $6 \cdot 10^{-14} \text{ m/s}$
- the porosity 30 %

- the storage coefficient  $1.55 \cdot 10^{-5} \text{ m}^{-1}$

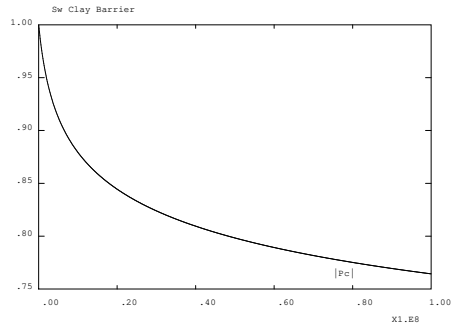


Figure 4: Capillary pressure curve of the clay FoCa defined by the UPC

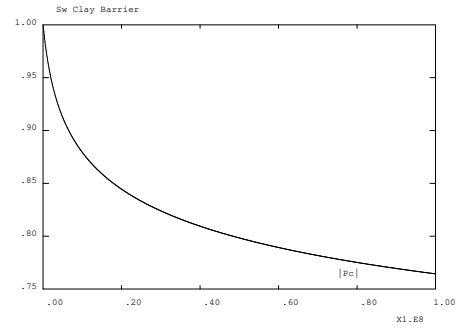


Figure 5: Capillary pressure curve of the clay FoCa defined by the CEA

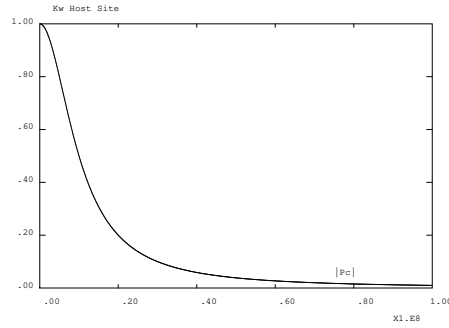


Figure 6: Liquid relative permeability curve of the clay FoCa

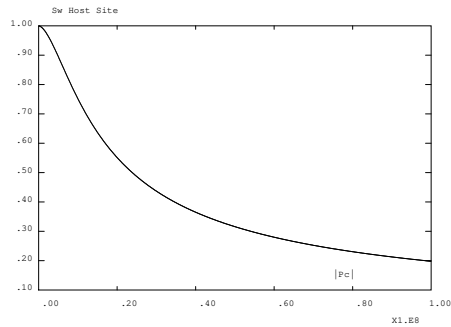


Figure 7: Capillary pressure curve of the clay Serrata

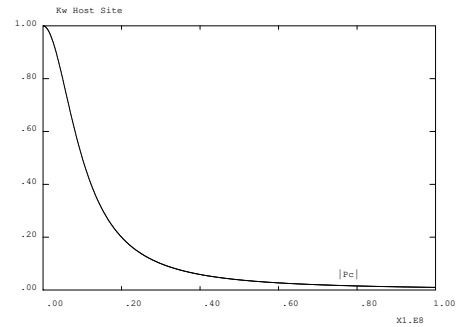


Figure 8: Liquid relative permeability curve of the clay Serrata

Three computations were performed with air at the hydrostatic pressure to understand the influence of the gravity and of the air pressure. Then a set of six computations with air at atmospheric pressure 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 Influence of gravity

In order to test the influence of gravity, a computation was carried out with gravity and the results were compared for a vertical and an horizontal lines. The air pressure was chosen at the hydrostatic pressure. The external boundary condition is an imposed pressure  $P_c = 0$ . The clay material is FoCa with the capillary pressure curve of the CEA. The resaturation times are presented for several saturation levels (Table 1).

Location of the line	Saturation level		
	95 %	99 %	99.9 %
horizontal	11 years 8 days	26 years 4 months 23 days	44 years 7 months
vertical	11 years 8 days	26 years 4 months 23 days	45 years 7 months

Table 1: Resaturation time for both line locations

One can remark that the gravity has not much influence on the resaturation time. The results are identical at the beginning of the computation. Gravity plays a role only when the barrier is almost resaturated. The figures 9 and 10 present the evolution of the pressure and the saturation versus time along the vertical and the horizontal lines with a logarithmic time scale.

The comparison is performed at six points aligned along a radius of the mesh. Three points are located in the clay and the others in the site.  $R_{in}$  indicates the internal radius of the layer,  $R_{middle}$  the middle of the layer and  $R_{out}$  the external radius of the layer.

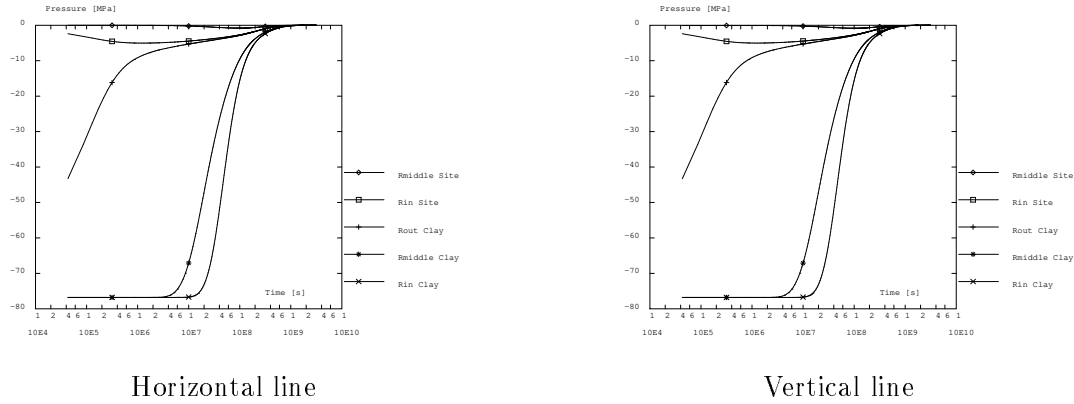


Figure 9: Pressure along an horizontal and a vertical lines

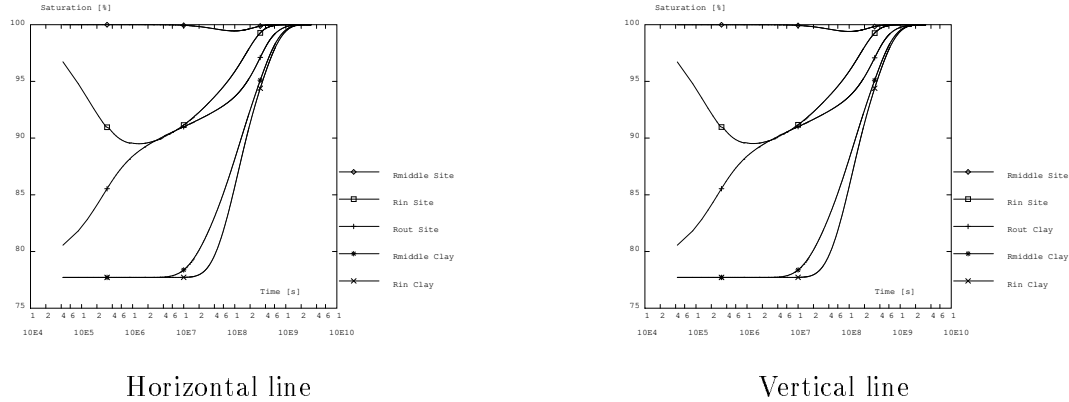


Figure 10: Saturation along an horizontal and a vertical lines

The pressure curves are identical for both lines. Gravity does not seem to influence the pressure raise. The saturation curves are almost identical for both lines. However, the resaturation is a bit lower at the end of the resaturation process (between  $10^9$  and  $3 \cdot 10^9$  s) when gravity is taken into consideration.

According to these results, gravity can be considered negligible for the resaturation time of the clay barrier. Indeed, gravity intervenes only when the saturation is complete or almost complete. Gravity will be neglected in the following computations.

We compared the results without gravity computed with the code CASTEM2000 with the results calculated from the same data with the code CESAR from the LCPC. The figures 11 and 12 show the resaturation process versus time with a linear time scale for both codes.

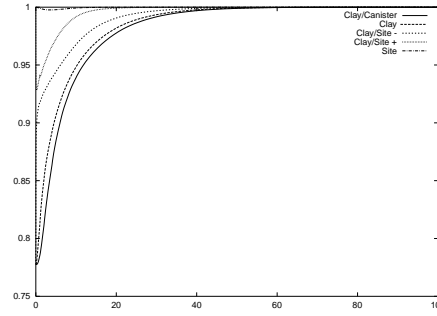
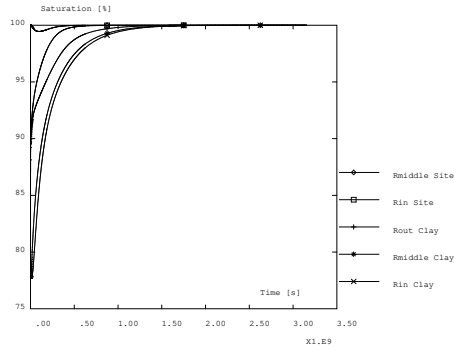


Figure 11: Computation with CASTEM2000

Figure 12: Computation with CESAR

The initial saturation levels are identical in the barrier for both codes (76 % next to the canister and in the middle of the buffer, 90 % almost instantaneously at the limit buffer-canister). Near the canister, a saturation level of 90 % is reached from 5 years with CASTEM2000 and from 6.5 years with CESAR. The kinetics of the resaturation process is slightly quicker with CASTEM than with CESAR. But the clay barrier is fully resaturated from 50 years with both codes.

The host rock desaturates more with the CASTEM2000 than with CESAR. At the limit buffer-site, the saturation level drops instantaneously until 90 % for CASTEM2000 and 93 % for CESAR. One can remark that both codes provide globally the same results from the point of view of the resaturation time.

## 4 Influence of air pressure

We test here the influence of the air pressure level taken in the Richard's equation model on the resaturation process computed with CASTEM2000. Computations were carried out with air at the hydrostatic pressure or at the atmospheric pressure. In the case of atmospheric pressure, the influence of the use of a storage coefficient in the host rock is also tested. The table 2 presents the resaturation time versus the saturation level of the barrier.

Air pressure	Saturation level		
	95 %	99 %	99.9 %
$P_a = 500 \text{ m}$	11 years 8 days	26 years 4 months 23 days	44 years 7 months
$P_a = 0$ Storage coefficient = 0	6 years 22 days	7 years 6 months	7 years 7 months
$P_a = 0$ Storage coefficient $\neq 0$	5 years 11 months	8 years 1 month	8 years 5 months

Table 2: Resaturation time versus the air pressure

We can note that the air pressure has a great influence on the resaturation time of the clay barrier. If we suppose that air is at the hydrostatic pressure, about 45 years are needed to resaturate the barrier. But if we suppose that the air is at the atmospheric pressure, the resaturation time is 5 times shorter: around 8 years. The figure 13 presents the pressure evolution versus time for the three cases.



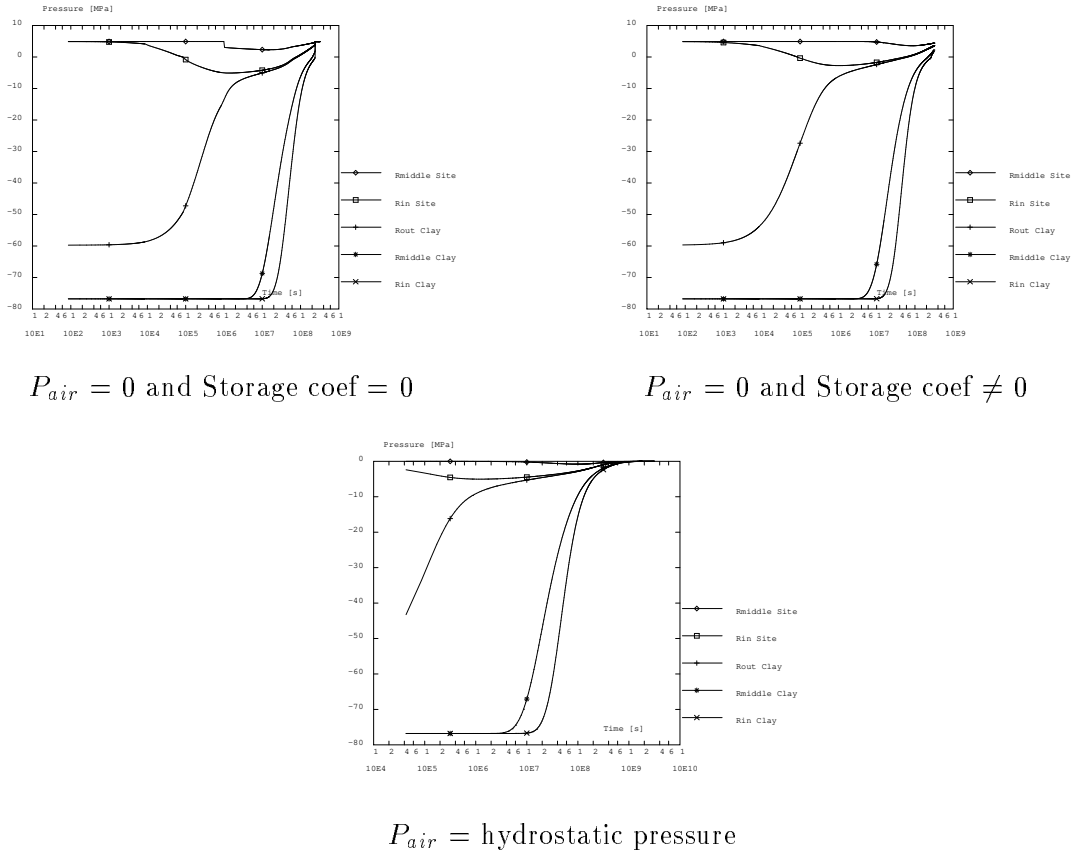


Figure 13: Water pressure versus the air pressure

We remark that the three pressure curves present different shapes. In the buffer, the pressure starts increasing from  $10^7$  s (less than 4 months) next to the canister and from  $3.10^6$  s (35 days) in the middle of the buffer for the three configurations.

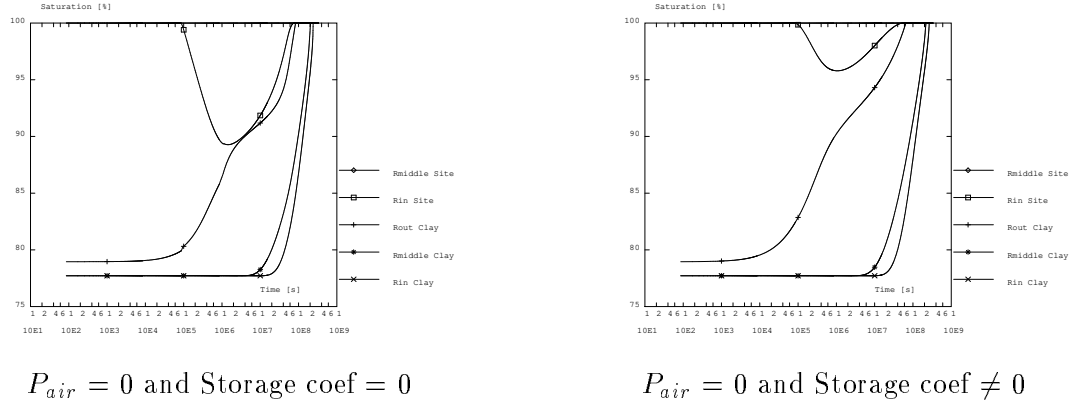
At the end of the calculation, the pressure increases regularly towards a zero value for " $P_{air} = \text{hydrostatic pressure}$ ". For " $P_{air} = 0$  and Storage coef = 0", the pressure increases suddenly as soon as the pressure becomes positive. Indeed, when the medium becomes saturated, the terms of  $\partial/\partial t$  become equal to zero in the Richard's equation and the pressure is immediately equal to the pressure imposed at the outer limit of the site.

For " $P_{air} = 0$  and Storage coef  $\neq 0$ ", we observe a slope change of the pressure curve but no jump, when the pressure becomes positive. During the passage from the unsaturated field to the saturated field, the capillary capacity used in the unsaturated field is replaced by the storage coefficient in the saturated field. So the pressure variation is always mitigated by a term in  $\partial/\partial t$ .

In the site, we observe an instantaneous decrease of the pressure next to the buffer for the three cases. This pressure fall is maximum at  $10^6$  s (12 days) for the three cases. The minimum value is -5 MPa for " $P_{air} = \text{hydrostatic pressure}$ " and " $P_{air} = 0$  and Storage coef = 0" and -2 MPa for " $P_{air} = 0$  and Storage coef  $\neq 0$ ". The storage coefficient seems to limit the host rock desaturation.

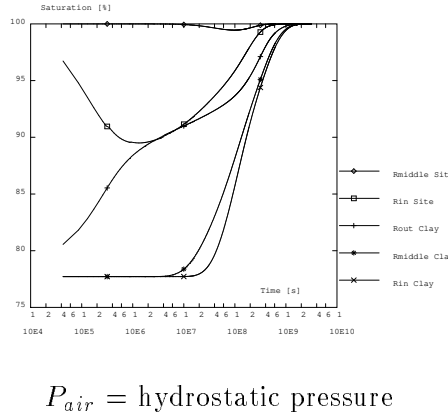
In the middle of the site, we note a small pressure decrease from  $10^7$  s (less than 4 months) for " $P_{air} = \text{hydrostatic pressure}$ " and " $P_{air} = 0$  and Storage coef  $\neq 0$ ". For " $P_{air} = 0$  and Storage coef = 0", the drop occurs sooner ( $10^6$  s = 12 days), simultaneously with pressure minimum in the buffer; the drop is sudden and higher. For both cases at " $P_{air} = 0$ ", the pressure remains positive what means

there is no host rock desaturation.



$P_{air} = 0$  and Storage coef = 0

$P_{air} = 0$  and Storage coef  $\neq 0$



$P_{air} = \text{hydrostatic pressure}$

Figure 14: Saturation versus the air pressure

The figure 14 shows the evolution of the saturation versus time for the three cases. The saturation curves are different for all the cases. In the barrier, the resaturation starts around  $1.5 \cdot 10^7$  s (6 months) near the canister limit and  $5 \cdot 10^6$  s (2 months) in the barrier middle for the three cases. The saturation stops from  $3 \cdot 10^8$  s (9.5 years) for both cases " $P_{air} = 0$ " and  $2 \cdot 10^9$  s (63 years) for " $P_{air} = \text{hydrostatic pressure}$ ".

In the vicinity of the site, the saturation starts immediately for all the cases. The resaturation is complete around  $2 \cdot 10^9$  s (63 years) for the hydrostatic pressure and around  $7 \cdot 10^7$  s (2 years 3 months) for the atmospheric pressure. The resaturation starts independently from the air pressure but the saturation process depends on it.

In the host rock, we observe an instantaneous desaturation near the buffer for " $P_{air} = \text{hydrostatic pressure}$ " and around  $8 \cdot 10^4$  s (1 day) for " $P_{air} = 0$ ". The minimum saturation level is 89 % at  $1.5 \cdot 10^6$  s (17 days) for " $P_{air} = \text{hydrostatic pressure}$ " and " $P_{air} = 0$  and Storage coef = 0" and 96 % at  $10^6$  s (12 days) for " $P_{air} = 0$  and Storage coef  $\neq 0$ ". The desaturation is maximum during the first month.

In the middle of the host rock, there is no desaturation for " $P_{air} = 0$ " and a slight desaturation for " $P_{air} = \text{hydrostatic pressure}$ ".

In conclusion, the air pressure hypothesis influences strongly the results. When " $P_{air} = 0$ ", the resaturation is faster. Without storage coefficient, we observe sudden pressure variations not very realistic. The use of the storage coefficient limits those variations and the host rock desaturation.

## 5 Influence of the clay material and of the boundary conditions

### 5.1 Analysis of the resaturation process versus time

The aim is to evaluate the resaturation time of the clay barrier according to clay material and the boundary conditions. The analysis is realised by comparing the evolution of the pressure (Figure 15) and the saturation (Figure 16) versus time with a logarithmic scale for six computations. The calculations are carried out until 20 years. The calculations do not account for gravity.

#### 5.1.1 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.

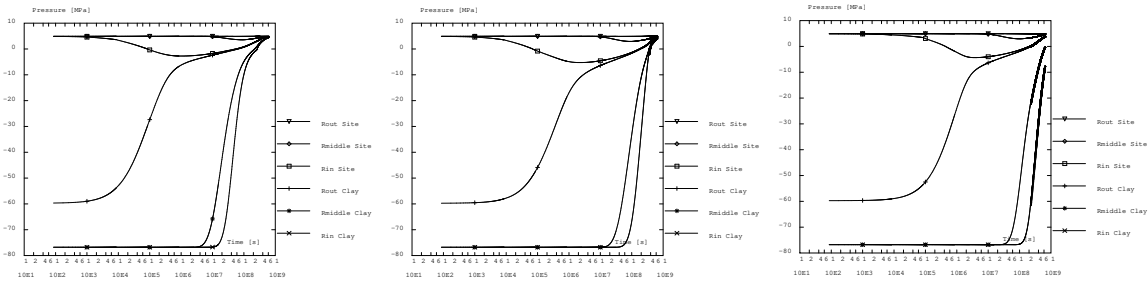
For the imposed flow, the pressure in the middle and at the outer limit of the site layer decreases respectively from 4 months and 15 months and then converges to a value smaller than the initial pressure. All the points of the site and of the buffer converge towards the same value: around 2 MPa for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

#### 5.1.2 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.

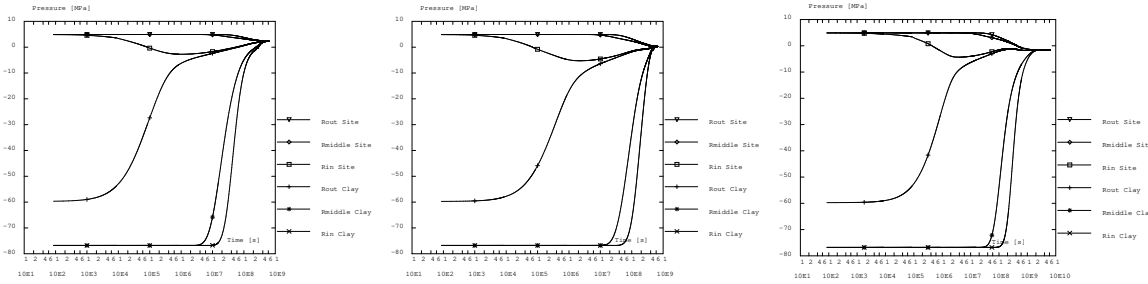
In the host rock, the middle of the site layer and the outer limit remain fully saturated, except in the case of the clay Serrata with no flow where they become unsaturated from 12 years.



Clay FoCa CEA  
Imposed pressure

Clay FoCa UPC  
Imposed pressure

Clay Serrata  
Imposed pressure

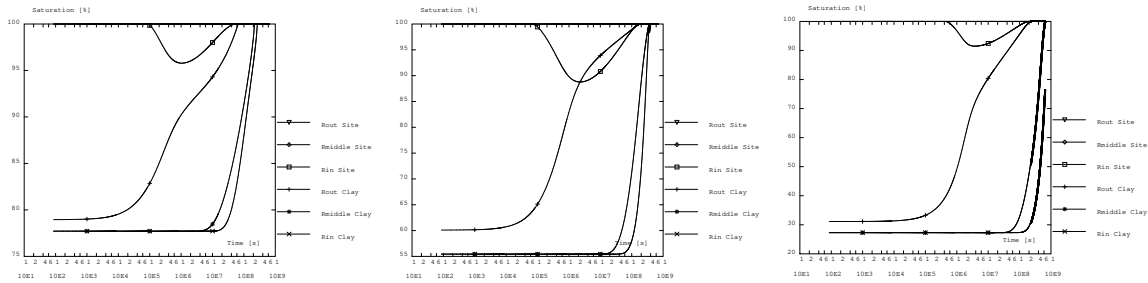


Clay FoCa CEA  
Imposed flow

Clay FoCa UPC  
Imposed flow

Clay Serrata  
Imposed flow

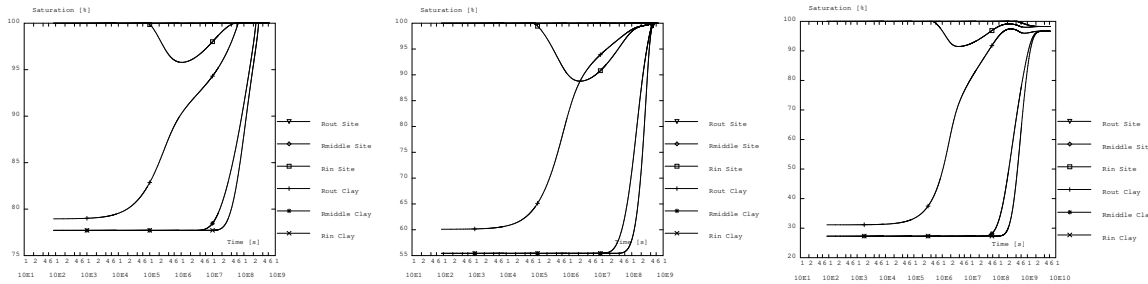
Figure 15: Pressure versus time



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 16: Saturation versus time

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.

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.

## 5.2 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 and the saturation 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.

The figures 17 and 18 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 the unsaturated buffer and the saturated host rock is correctly modelled.

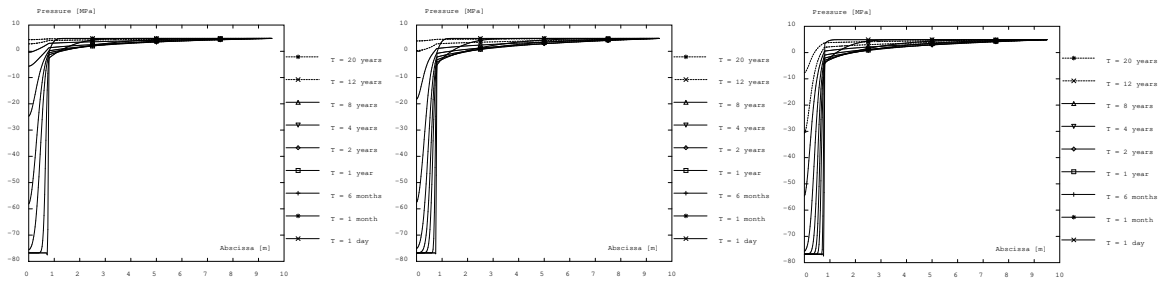
Progressively, the pressure and the saturation increase in the barrier until reaching the saturation level 100 % and the imposed pressure in the case of the pressure condition or the final pressure and final saturation level in the case of the flow condition.

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.

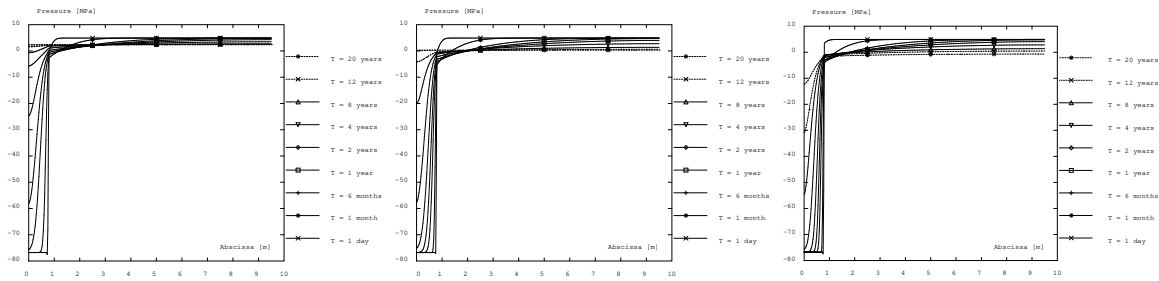
The figures 19 to 22 present the pressure and saturation for the clay FoCa CEA and for the two boundary conditions. They show that there is no difference during the first 3 years between the two boundary condition results either for the pressure, or for the saturation. Then the pressure increases more 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.



Clay FoCa CEA  
Imposed pressure

Clay FoCa UPC  
Imposed pressure

Clay Serrata  
Imposed pressure

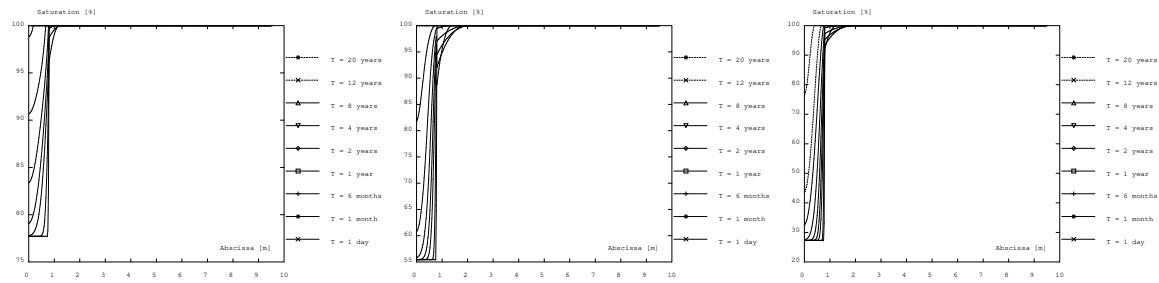


Clay FoCa CEA  
Imposed flow

Clay FoCa UPC  
Imposed flow

Clay Serrata  
Imposed flow

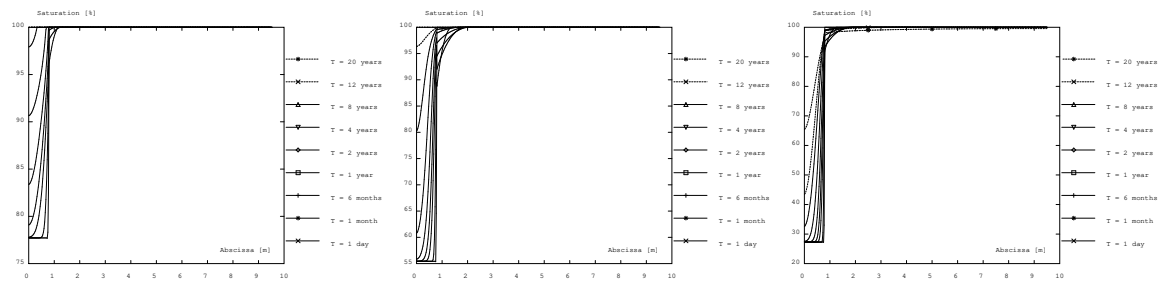
Figure 17: Pressure versus the distance



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 18: Saturation versus the distance

## 6 Conclusion

This study has presented computations performed with the code CASTEM2000 developed at the CEA. The numerical model consists in the resolution of the Richard's equation. In the frame of a benchmark, some of the results are compared with ones of the code CESAR from the LCPC. The purpose of the computations was to understand the influence of several parameters on the resaturation process of a clay barrier used in a long-term storage site.

We have shown that the gravity had not much influence whereas the air pressure changed completely the resaturation process. We also noted 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).

The future work will be devoted to a benchmark with the same codes about the modelling of the hydro-mechanical behaviour of the clay barrier resaturation.

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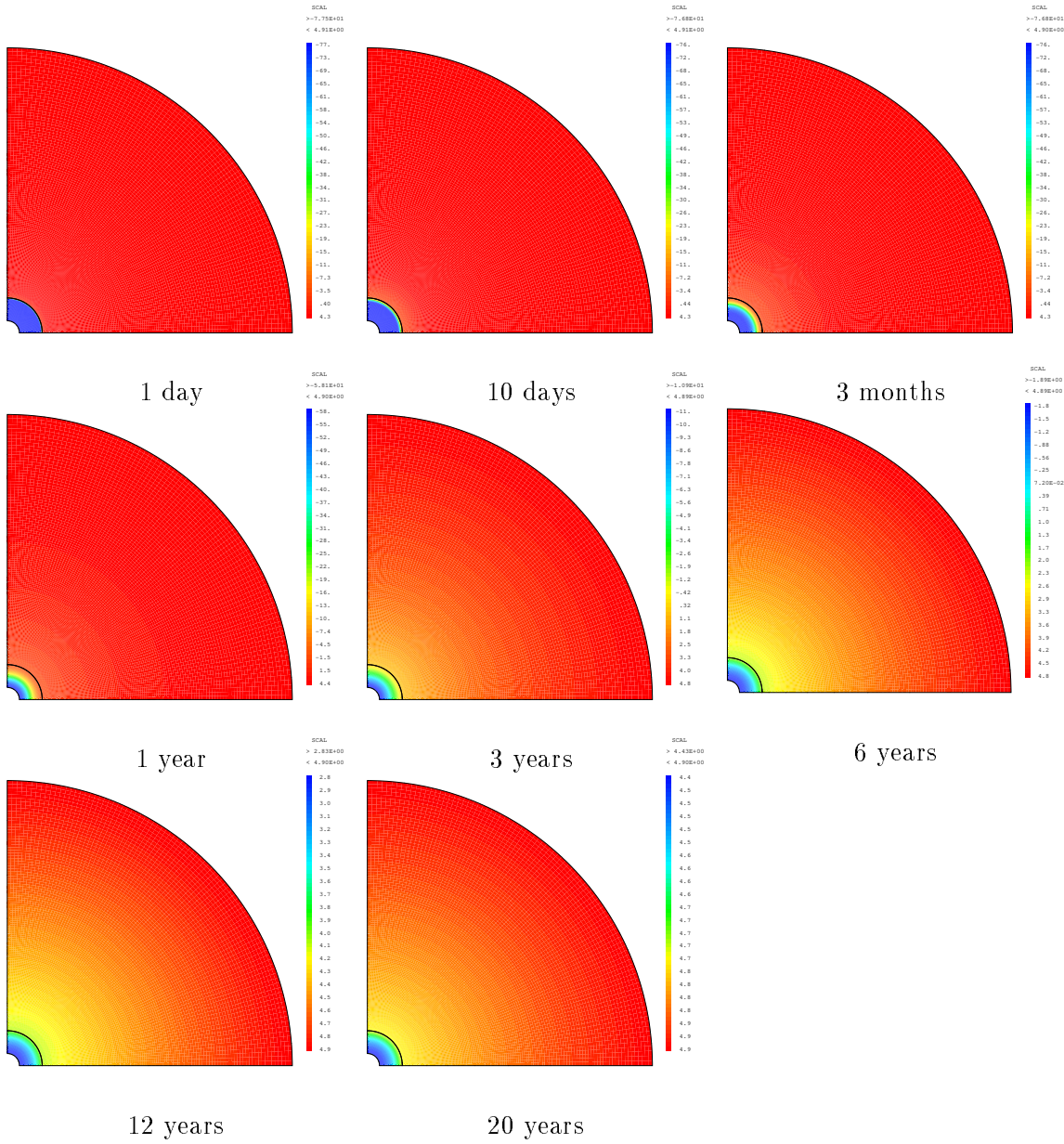


Figure 19: Pressure for the clay FoCa CEA with the imposed pressure

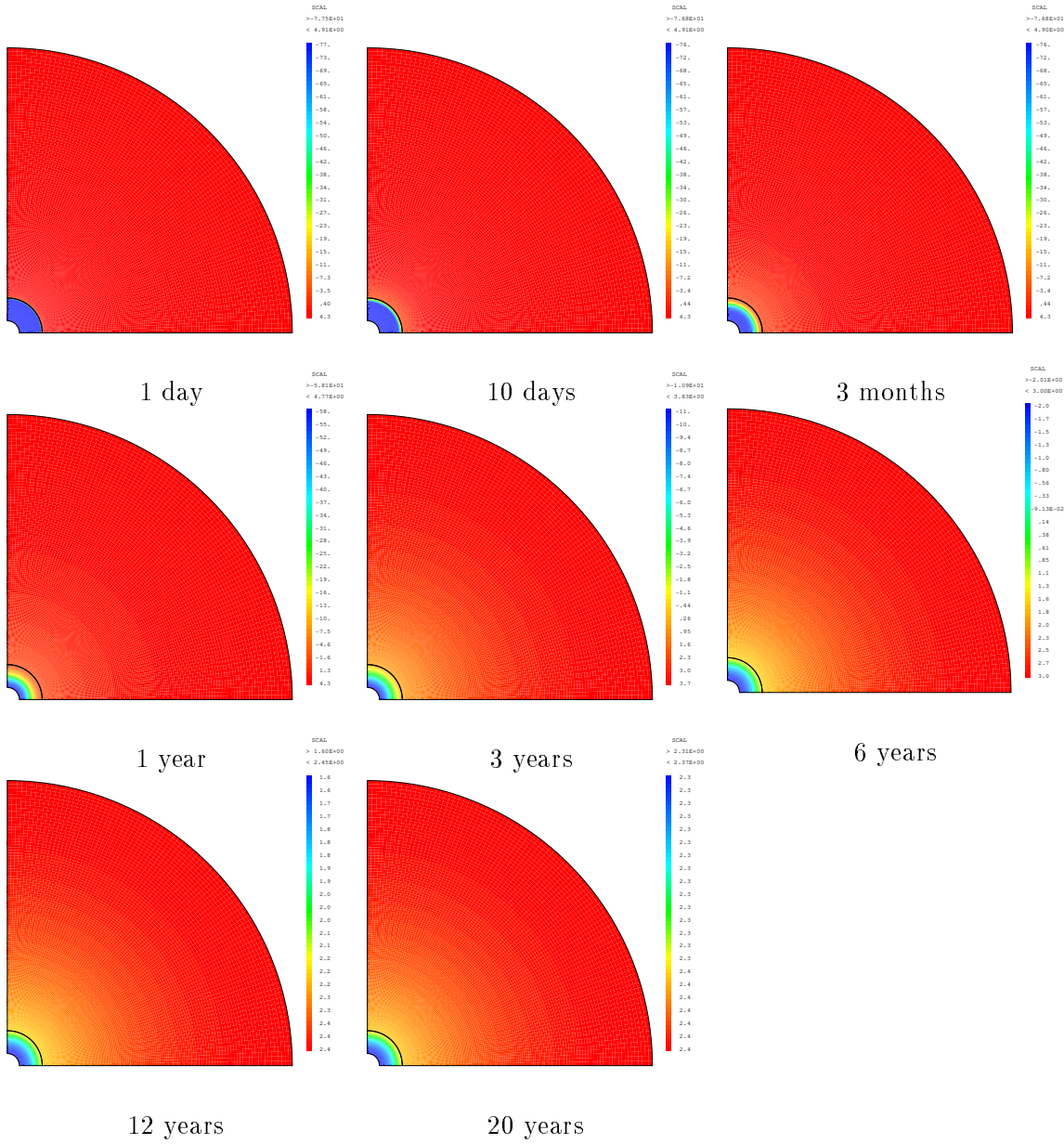


Figure 21: Pressure for the clay FoCa CEA with the imposed flow

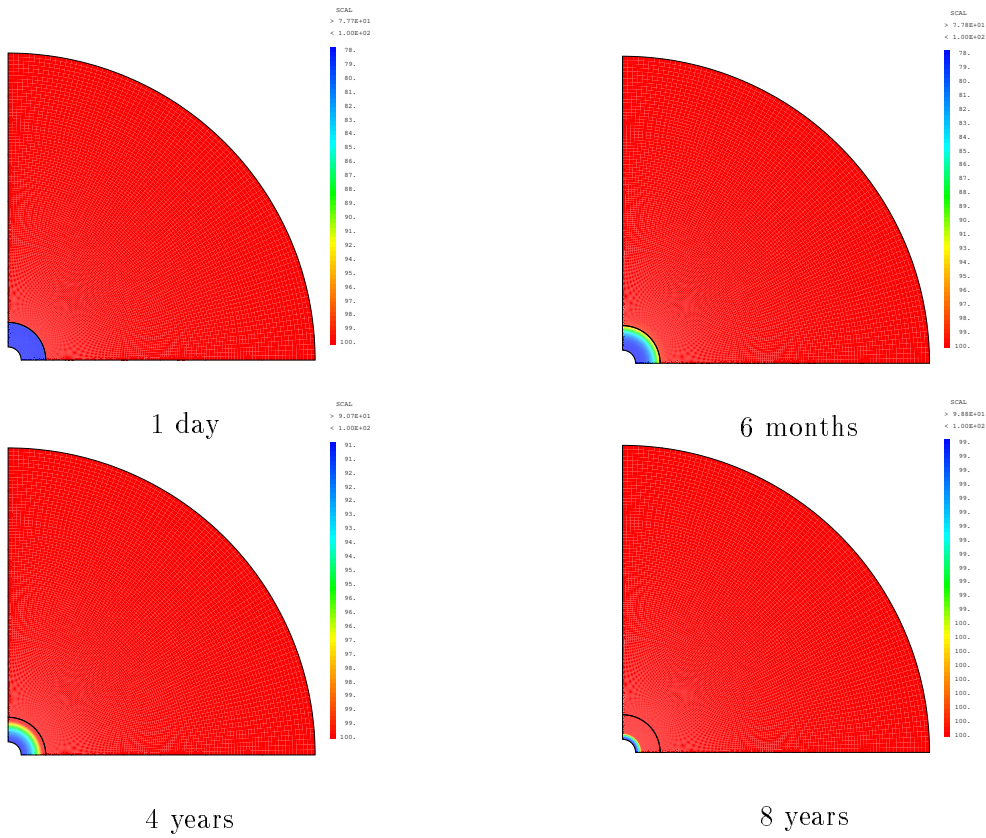


Figure 20: Saturation for the clay FoCa CEA with the imposed pressure

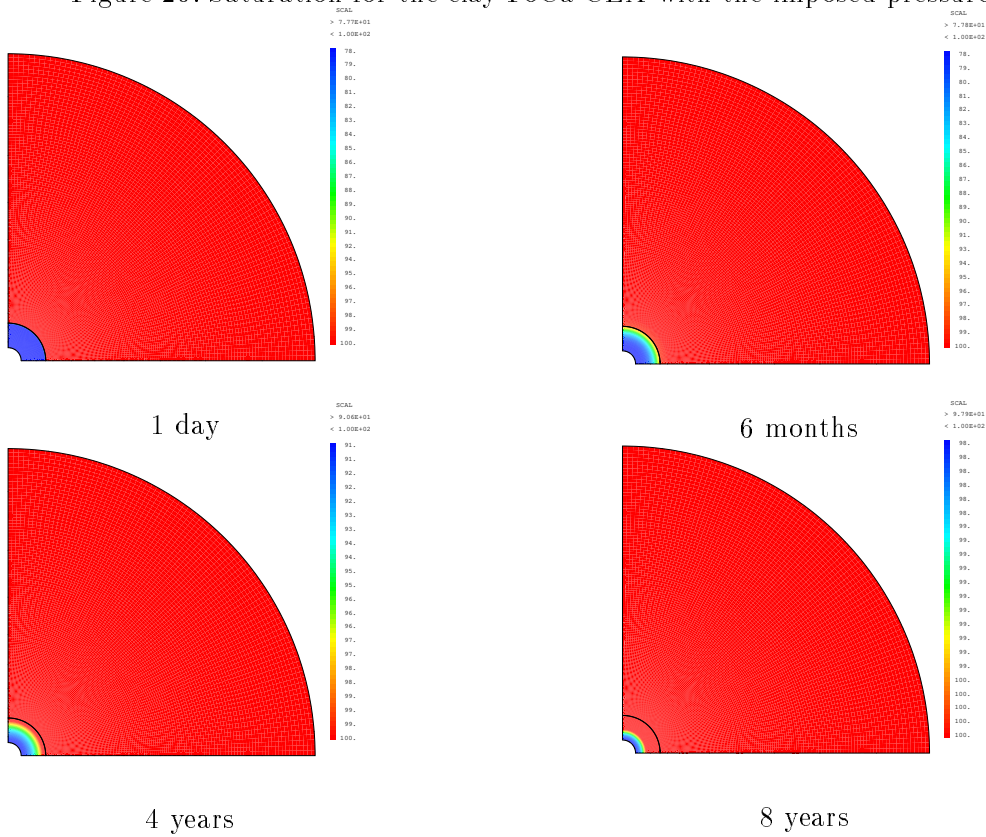


Figure 22: Saturation for the clay FoCa CEA with the imposed flow