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# Evaluation of the Importance of Thermo-Hydro-Mechanical Coupling on the Performance Assessment of a deep Underground Storage Design

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**ABSTRACT** : An evaluation of the importance of the thermo-hydro-mechanical couplings (THM) on the performance assessment of a deep underground storage design has been made as part of the international DECOVALEX III project. It is a numerical study that simulates a generic repository configuration in the near field in a granite medium. The thermo-hydro-mechanical evolution of the whole configuration is simulated over a period of 100 years. The model used to represent the unsaturated behaviour of the various porous media makes allowance for moisture transfers through the effect of thermal and water gradients. The paper presents a comparison of the temperature, water pressure and stress fields obtained by TM, TH, HM and THM coupled calculations. The results demonstrate that temperature is hardly affected by the couplings. In contrast the influence of the couplings on the mechanical stresses is considerable. This is attributed to the key role that water has on bentonite swelling or shrinkage effects that are dependent on its saturation level variations.

## 1 INTRODUCTION

Several countries are considering the possibility of storing high-level nuclear waste in hard rock formations, such as granite. Japan, for example, has developed a concept for storing waste in vertical boreholes, in very low permeability granite, with possible fractures in the vicinity of the repository. The performance assessment of such a concept calls for a detailed analysis to be made of the physical phenomena that are likely to result from the heat produced by the waste packages, at various scales and for various timescales. In this study attention is focused on thermal (T), hydraulic (H) and mechanical (M) phenomena. Mathematical models have been developed, verified and validated against analytical solutions, laboratory and field experiments in the framework of the DECOVALEX international project over the past ten years to predict these phenomena (Jing et al., 1995), (Stephansson et al., 2001). Generally these models have considered full coupling THM processes that which would prevail in and around the repository. These models are complex; they require considerable development effort and also extensive input data. The main objective of the DECOVALEX III Benchmark test 1 (Nguyen et al., 2003) is therefore to answer the basic question: how important is T-H-M coupling for the safety of a typical repository? This paper contributes to providing an answer to the question.

A numerical study has been performed on a typical three-dimensional pattern of a hypothetical repository in granite located at a depth of 1000 m to evaluate the importance of the various couplings. This hypothetical case is inspired from a Japanese concept. Since the engineered barrier plays a major role on the flows inside the repository, the study has focused on the near field response, over

the first hundred years, during which the thermal paroxysm is reached. Various cases are considered in the project, but attention here will be restricted to the case of an intact rock, with no pre-existing major fracture.

This paper presents the case studied, then recalls the equations that govern the THM processes, and compares the results obtained for the fully coupled case against those obtained when some coupling effects are ignored. The major conclusions for possible simplifications are given.

## 2 DESCRIPTION OF THE CASE STUDIED

The repository design consists mainly of parallel drifts, into which vertical boreholes are sunk for waste canister emplacement. In the interests of symmetry and periodicity, a single pattern shown on Figure 1 has been selected for the THM coupling evaluation.

To observe a significant rock de-saturation and re-saturation during the whole duration of the experiment, it was important to estimate the range of air flow rates and humidity that the ventilation system should provide.

### 2.1 Mesh, initial and boundary conditions

In the interests of symmetry, only a quarter of the domain being considered has been meshed. The total mesh is divided into four zones (Figure 2). From inside to outside, we distinguish the over-pack, the buffer, the backfill and the rock mass. It is made up of quadratic finite elements. The total number of nodes is 5876 and the total number of elements is 2392.

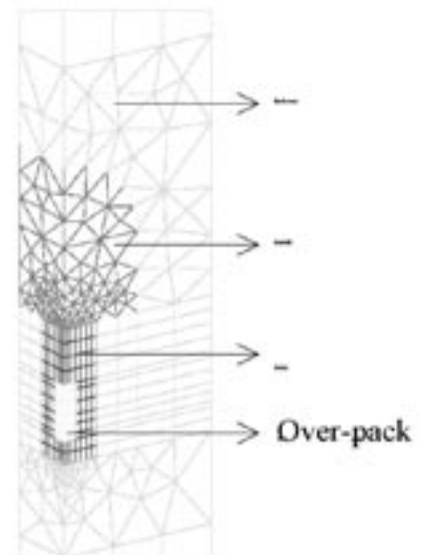
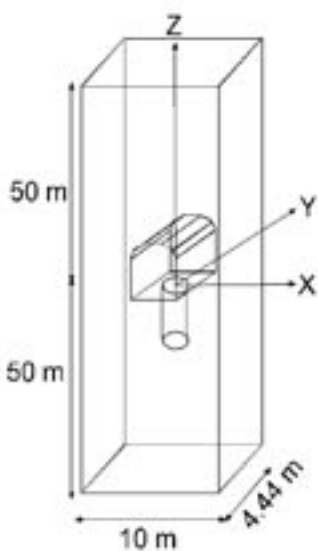


Figure 1: Domain selected for THM coupling evaluation and points of interest.

Figure 2: The various parts of the mesh (zoomed)

Prior to excavation, the rock mass is presumed to be in a saturated state, water pressure being equal to the hydrostatic pressure. The mechanical stress state corresponds to a vertical stress equal to  $\sigma_v = -25.6$  MPa, and horizontal stresses equal to  $1.5 \sigma_v$ . The initial temperature is  $45^\circ\text{C}$ .

Normal displacement of zero is prescribed at the lateral limits of the model. Vertical movement is prevented at the base of the model. At the top, the overburden load is maintained. The water and heat flows are equal to zero on the lateral limits of the model. On the top and bottom boundaries, the water pressure is set equal to the relevant hydrostatic pressure, and the temperature remains equal to 45°C.

In the simulations, the first sequence consists of setting the initial conditions in the rock mass before performing the excavation. Then the drift and the pitch are excavated, and a transient analysis is performed until some subsequent steady state is reached. The displacements obtained at the issue of this step are reset to zero, to start from the nominal geometry of the drift and pitch for waste emplacement.

Finally, the over-pack, the buffer and the backfill are simultaneously emplaced, and a transient response is calculated over a hundred-year period.

## 2.2 Material properties

The rock mass properties were taken from Canadian granite data (Nguyen et al., 2003). Typical values, determined from laboratory tests on intact samples, are:

Density (2300 kg/m<sup>3</sup>), Young's modulus (30000 MPa), Poisson's ratio (0.3), thermal expansion (8.21 10<sup>-6</sup> /°C), thermal conductivity (2.7 W/m/°C) and specific heat (833 J/kg/°C). Biot's coefficient for the rock mass has been hypothetically set at 1. Intrinsic permeability (K) may be one of three different values: 10<sup>-17</sup>, 10<sup>-18</sup> (reference case) and 10<sup>-19</sup> m<sup>2</sup>. Moreover, it varies with porosity (φ) according to the prescribed law:

$K(\varphi) = 2.186 \cdot 10^{-10} \varphi^3 - 5.185 \cdot 10^{-18}$ , where K is in m<sup>2</sup>.

The buffer (bentonite) and backfill (mixture of bentonite and aggregates) properties have been selected according to the Japanese concept, and calibrated from available laboratory test results (Jing et al., 1999). A Van Genuchten (1980) approximation has been used to set their capillary pressure curves and water relative permeability curves.

## 3 EQUATIONS GOVERNING THM PROCESSES

The fully coupled THM phenomena modelling is based on a simplification of the conservation law of the total mass of water, assuming that the vapour mass is negligible compared to liquid water mass, and that the vapour flow is mainly due to the temperature gradient, such that:

$$\underline{q}_v = - D_{T_v} \underline{\text{grad}} T \quad (1)$$

Where  $D_{T_v}$  is the coefficient of thermal diffusivity of water vapour. A generalized Darcy's law gives the flux of liquid water:

$$\underline{q} = \frac{K k_r}{\eta_l} \rho_l (-\underline{\text{grad}} p_l + \rho_l \underline{E}) \quad (2)$$

Where K is the intrinsic permeability,  $k_r$  the permeability relative to liquid water and  $\eta_l$  the dynamic viscosity of water.  $\underline{E}$  stands for body forces such as gravity.

The conservation of momentum is written classically as:

$$\underline{\text{div}} \underline{\underline{\sigma}} + \rho \underline{E} = 0 \quad (3)$$

Where  $\underline{\underline{\sigma}}$  stands for the total stress in the porous medium, and  $\rho$  its equivalent density, given by:

$$\rho = (1 - \varphi) \rho_s + \varphi S_1 \rho_l \quad (4)$$

In this equation,  $\rho_s$  denotes the density of the skeleton,  $\rho_l$  the liquid density, and  $S_l$  the liquid saturation. The material behaviour law is Biot's poroelastic type, such that:

$$d\underline{\underline{\sigma}} = \underline{\underline{C}} (\underline{\underline{\varepsilon}} - \alpha_s dT \underline{\underline{\delta}}) - b dp_l \quad (5)$$

Where  $\underline{\underline{C}}$  represents the drained elastic properties tensor,  $\alpha_s$  the skeleton thermal expansion coefficient,  $\underline{\underline{\delta}}$  the Kronecker symbol, and  $b$ , Biot's coefficient, which in the unsaturated case, is assumed to depend on the capillary pressure  $p_c$  ( $p_c = p_g - p_l$ ) (Lassabatère et al., 1998).

The degree of saturation is related to capillary pressure  $p_c$  through function:

$$S_l = S_l(p_c) \quad (6)$$

Which is assumed to be independent of the temperature, in view of the experimental results of the bentonite considered (Jing et al., 1999).

Finally, energy conservation is simply taken in the following simplified form:

$$\rho C \frac{\partial T}{\partial t} - \text{div} (K_T \cdot \underline{\underline{\text{grad}}} T) = q \quad (7)$$

Where  $\rho C$  stands for equivalent porous medium heat capacity,  $K_T$  is the heat conductivity and  $q$  represents a heat source.

### 3.1 Decoupling strategy

Three other analyses in addition to the THM analysis were performed: TH, TM, and HM.

In the TH analysis, it was assumed that skeleton porosity remains constant. Consequently, for the H

equations, rock permeability remains constant, the derivative  $\frac{\partial \varphi}{\partial t}$  is equal to zero in the water mass balance, and moreover, mechanical stresses have no effect on the water pressure field. For the T equations, thermal conductivity and heat capacity vary only with the saturation  $S_l$ .

In the TM analysis, it was assumed in the M equations that water pressure has no effect on the stresses, and that the bentonite has no swelling pressure effect. In the T equations, thermal conductivity and the heat capacity are constant.

In the HM analysis, the temperature is maintained constant, equal to 45°C and there is no thermal expansion effect. Porosity variations in particular are only due to the volume change of the skeleton and to variation in water pressure. Moreover, there is no thermal gradient-related water transfer, and water viscosity remains constant.

## 4 RESULTS

### 4.1 Some results for the THM fully coupled reference case ( $K = 10^{-18} \text{ m}^2$ )

Typical results for the effect of excavation on rock mass porosity, are illustrated in Figure 3, to underline the influence of porosity variations.

It can be seen on the right that the red zones correspond to increased porosity, due to the expansion of the rock towards the inside of the cavities, whereas the blue zones correspond to decreased porosity, the vertical load being supported by a narrower zone than prior to excavation.

Failure due to overloading in traction may occur, as can be observed on the maximum principal

effective stress, displayed on Figure 3. Here traction stresses are positive. The maximum reaches about 6.7 MPa, which should be compared with the tensile strength of the rock, measured in laboratory ( $R_t = 11 \text{ MPa}$ ).

The temperature field and the degree of saturation field after one year are shown in Figure 4. Note that the backfill re-saturates faster than the buffer, which may be partly due to the fact that the initial degree of saturation is higher in the backfill ( $S_i = 0.81$ ) than in the buffer ( $S_i = 0.62$ ), and that the buffer is closer to the heat source. After 40 years, the buffer and the backfill are fully re-saturated.

#### 4.2 Evaluation of the coupling effects

We propose a selection of some of the large number of results produced by the different analyses that correspond to two particular points in the buffer material (see Figure 1), where different behaviour patterns may be expected because of the different boundary and environmental conditions. These points are B4, at the contact point with the over-pack, which will be subjected to a high temperature, and B6, which lies at the interface between the buffer and the rock-mass. The results are presented in terms of temperature time-histories (Figures 5, 8), water pore pressure (Figures 6, 9), and horizontal stress  $\sigma_{xx}$  (Figures 7, 10). For each quantity, we compare the effect of the couplings for the lowest ( $K=10^{-19} \text{ m}^2$ ) and the highest ( $K=10^{-17} \text{ m}^2$ ) rock mass permeability.

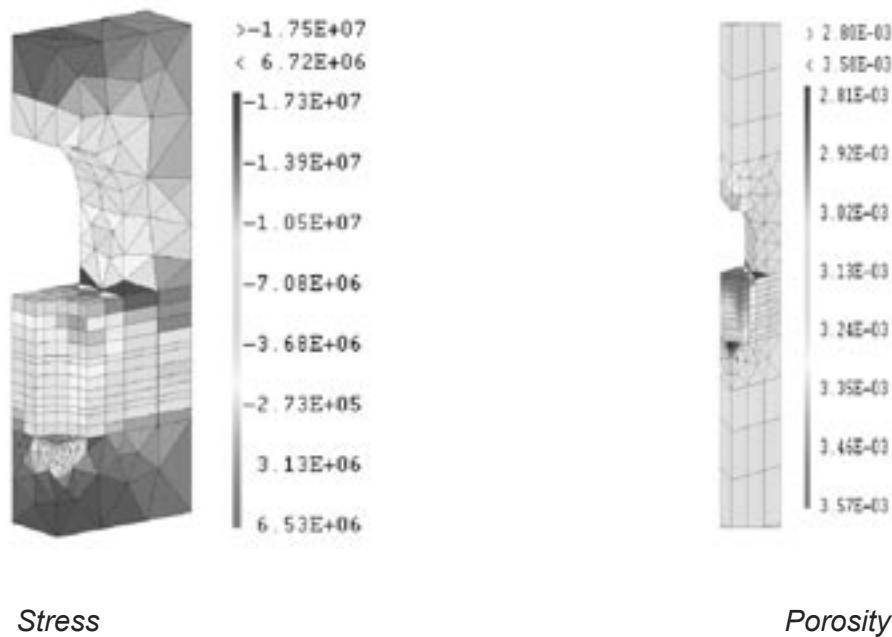


Figure 3: Porosity of the rock mass and maximum principal effective stresses after excavation (zoom around the cavities)

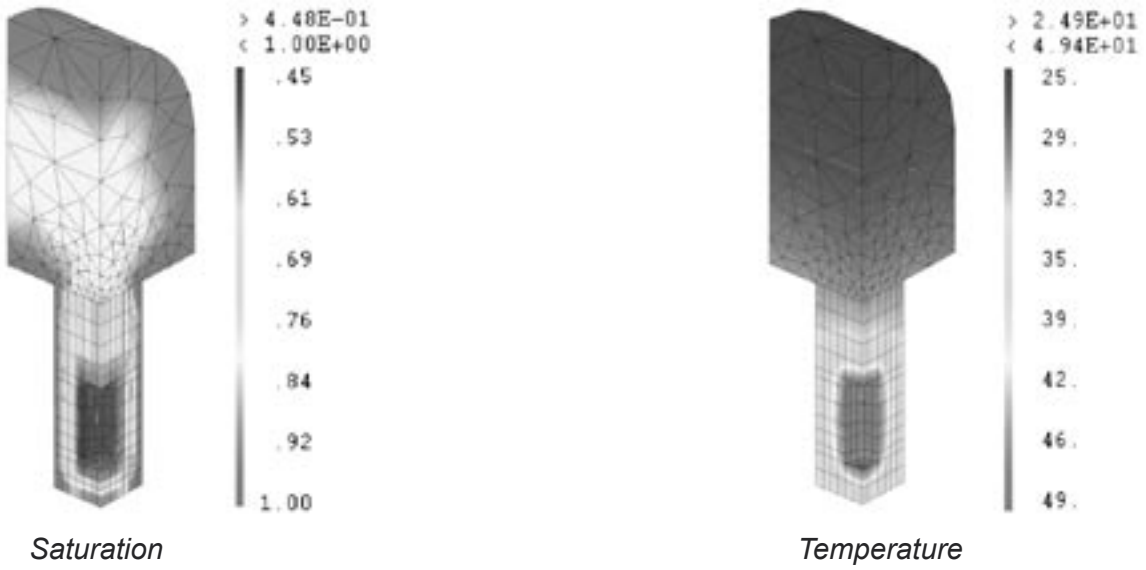


Figure 4: Iso-temperature and iso-saturation in the buffer and backfill after one year (reference case)

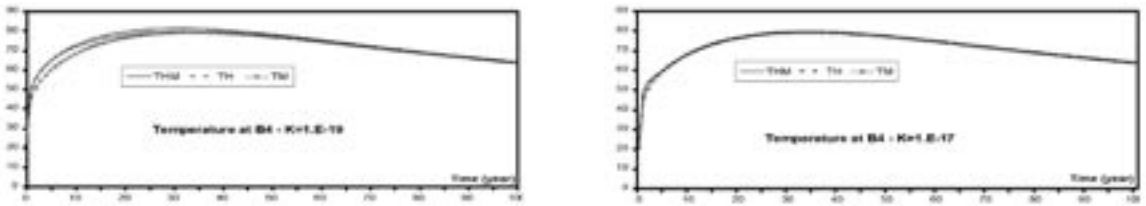


Figure 5: Temperature at point B4

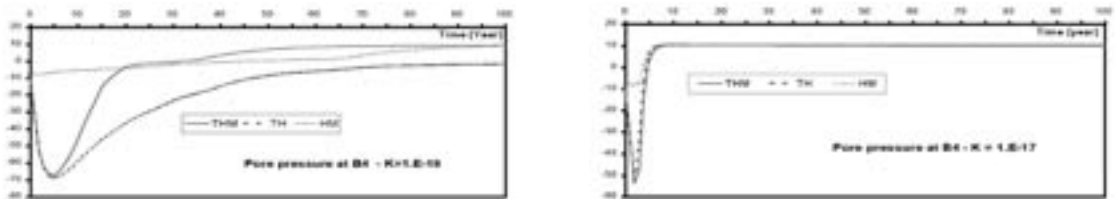


Figure 6: Pore pressure at point B4

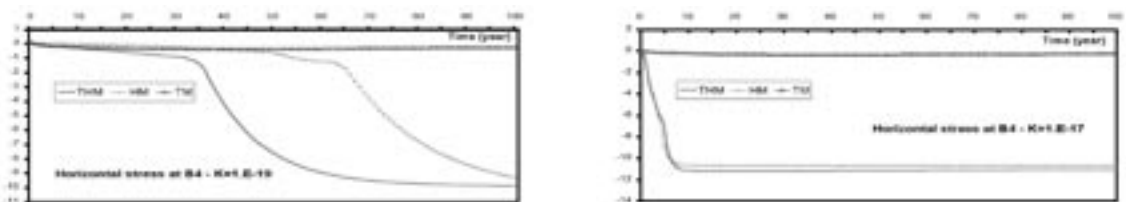


Figure 7: Horizontal total stress  $\sigma_{xx}$  at point B4

## 5 COMMENTS ON THE RESULTS

### 5.1 Results at point B4

Since point B4 in the buffer is at the interface with the over-pack, the temperature increase is higher and leads to localise drying of the buffer. Therefore, the effect of the couplings on temperature may be observed at the beginning and this effect is more pronounced for a low rock mass permeability. The  $K=10^{-19}\text{m}^2$  case in particular, the lower and upper curves of Figure 5 correspond to the TM case (constant degree of saturation) and to the TH case respectively (larger de-saturation) while the THM case is closer to the upper bound at the beginning due to drying and closer to the lower bound at the end, once re-saturated.

The drying effect is clearly visible on the pore pressure results shown in Figure 6. The corresponding suction is amplified when rock mass permeability is decreased, as is to be expected. Indeed, in the  $K=10^{-17}\text{m}^2$  case, the water exudes from the rock fairly fast, and the M couplings only have little effect. Where low rock mass permeability prevails, in the TH case, re-saturation is not achieved at B4 after 100 years (Figure 6). In this case the difference between the THM and TH cases illustrates the strong influence of the M couplings (porosity variation) on this re-saturation time.

The horizontal total stress  $\sigma_{xx}$  shows the effect of horizontal containment due to lateral symmetry boundary conditions: in particular in the  $K=10^{-17}\text{m}^2$  case, the difference between the THM case and the HM case is clearly related to the thermal stress given by the TM case (Figure 7).

### 5.2 Results at point B6

The results at point B6 show that the couplings have very little effect on temperature (Figure 8) for the range of permeabilities considered in the low permeability case, because point B6 is sufficiently far from the heat source.

Pore pressure differences are visible in Figure 9 in line with the permeability values: for higher permeability, the rock mass provides water fast enough to the buffer to prevent any drying. Conversely, for the low permeability case, a drop in pressure at the beginning is visible at both points, but less pronounced than at B4. Rebuilding of hydrostatic pressure starts at about 30 years for the THM case, and about 60 years for the HM calculation, while it is still unsaturated after 100 years in the TH case.

Horizontal total stress  $\sigma_{xx}$  evolutions, shown in Figure 10, are very similar to those obtained at point B4.

Millard et al. (2003) compared the results obtained by the six research teams involved in this benchmark test. The predictions of temperature, degree of saturation, pore pressure and total stresses are fairly close to each other. All the research teams assessed the couplings at the same importance. However, the predicted re-saturation time varies significantly between teams.

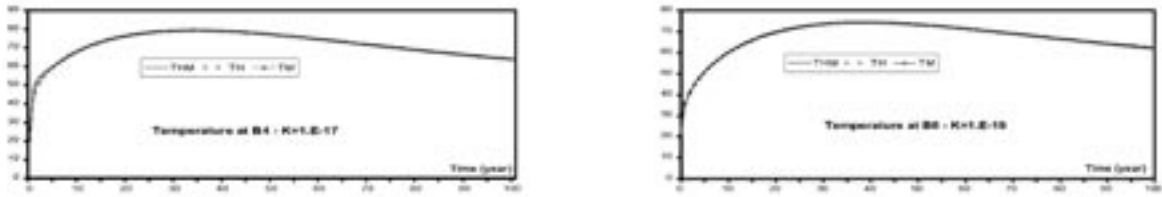


Figure 8: Temperature at points B6

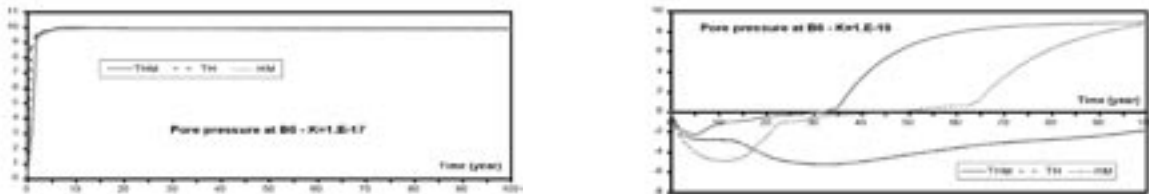


Figure 9: Pore pressure at point B6

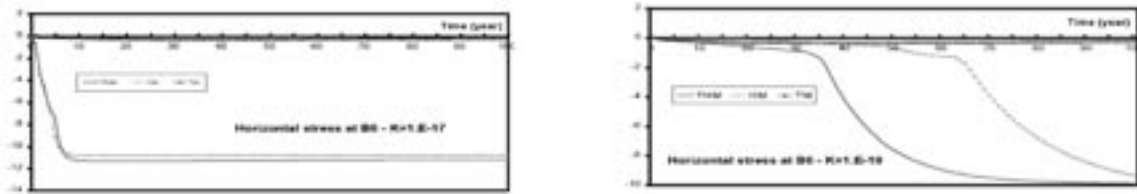


Figure 10: Horizontal total stress  $\sigma_{xx}$  at point B6

## 6 CONCLUSION

A study of a generic high-level nuclear waste storage has been performed to assess the importance of the various T-H-M couplings on near field behaviour. Some general trends on the influence of the various couplings can be derived from the results presented in this paper:

H and M have a limited effect on the T results during the re-saturation phase.

During re-saturation, the effect of water pore pressure on the stresses predominates over the effect of skeleton thermal expansion.

Porosity variations have a significant effect, in particular for low rock mass permeabilities.

These rough calculations confirm that initial rock mass permeability is a key parameter; it plays a major role in re-saturation time. The following remarks can be made about its influence:

The effects of the couplings on T, H and M are amplified by low rock mass permeability.

Suction close to the canisters may be important for low permeability.

It is important to account for all the THM couplings if we are to make more realistic predictions of the failure of the rock mass.

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