Excavation Damaged Zones In Rock Salt Formations - 8172

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ABSTRACT

Salt formations have long been proposed as potential host rocks for nuclear waste disposal. After the operational phase of a repository the openings, e.g., boreholes, galleries, and chambers, have to be sealed in order to avoid the release of radionuclides into the biosphere. For optimising the sealing techniques knowledge about the excavation damaged zones (EDZ) around these openings is essential. In the frame of a project performed between 2004 and 2007, investigations of the EDZ evolution were performed in the Stassfurt halite of the Asse salt mine in northern Germany. Three test locations were prepared in the floor of an almost 20 year old gallery on the 800-m level of the Asse mine: (1) the drift floor as existing, (2) the new drift floor shortly after removing of a layer of about 1 m thickness of the floor with a continuous miner, (3) the new drift floor 2 years after cutting off the 1-m layer. Subject of investigation were the diffusive and advective gas transport and the advective brine transport very close to the opening. Spreading of the brine was tracked by geoelectric monitoring in order to gain information about permeability anisotropy. Results obtained showed that EDZ cut-off is a useful method to improve sealing effectiveness when constructing technical barriers.

INTRODUCTION

Salt formations are considered as potential host rocks for nuclear waste disposal. After the operational phase of a repository the openings, e.g., boreholes, galleries, and chambers have to be sealed in order to avoid the release of radionuclides into the biosphere. For optimising the sealing techniques knowledge about the excavation damaged zones (EDZ) around these openings is essential. Excavation disturbed zones in rock salt develop in the vicinity of openings during and after excavation, changing the original properties of the rock salt which is characterised by a very low porosity, low permeability and low water content. The highly inhomogeneous stress state around an opening leads to dilatancy, i.e., increase of porosity by microfracturing, and thus to a potential increase in permeability by several orders of magnitude.

For long term safety aspects of a repository and especially for the design and construction of sealing elements the knowledge of the gas and water migration in the excavation disturbed zone, its size and its development with time is essential. Furthermore it is of importance to investigate technical methods for reducing the EDZ.

At the Asse salt mine in the Stassfurt halite on the 800-m level the EDZ was investigated with the objective to investigate the diffusive and advective gas transport and the advective brine transport very close to the opening. Spreading of the brine was tracked by geoelectric monitoring in order to gain information about permeability anisotropy and porosity.

Three test locations on the floor of a 20 years old gallery were prepared:

1 the drift floor as existing
2 the new drift floor shortly after removing of a layer of about 1 m thickness of the floor with a continuous miner
3 the new drift floor one and a half years after cutting off the 1-m layer

LAYOUT OF THE TEST FIELD

Usually in-situ measurements on gas and water permeability are performed in boreholes which are sealed with packer systems. For investigations close to the opening the boreholes and packers have to be very short and sealing to the surface is not granted. During injection tests a significant portion of the injected fluid will migrate directly though the EDZ into the opening above the borehole, so that the rock portion affected by injection may be too small for representative results. A new method was therefore developed and tested for the first time in the frame of the BAMBUS II project [1].

A square plastic sheet with a side length of 1.8 m was embedded into a fresh layer of salt concrete and secured by screws. When the salt concrete was cured, a tight sealing of the surface was achieved. After installation of the sheet and curing of the salt concrete, five boreholes (BRL1 - BRL5) were drilled into the salt below the sheet (see Figure 1). Each of the five boreholes was equipped with a plug at the borehole bottom which provides a 60-mm long test interval. The top of the different test intervals was 40 to 900 mm below the surface of the salt floor, respectively. Two injection/ventilation tubes ran from the open gallery into this interval. The borehole void above the plug was sealed with resin. Four additional boreholes (EL1 – EL4) for installation of electrode chains were drilled and instrumented with 13 electrodes each. 16 surface electrodes were installed between the salt and the salt concrete layer to complete the geoelectric array. Electrode spacing was 0.1 m.

Each of the three test locations was equipped with one of these systems. The borehole and electrode arrangement as well as a cross section through a measurement borehole are shown in Figure 1.

INVESTGATION METHODS

The investigations performed comprise measurements of gas diffusivity and gas permeability as well as brine injection tests with geoelectric tracking of the brine.

Gas Diffusivity

Right after installation of the test location the residual volume of each borehole was purged and flooded at atmospheric pressure with a gas mixture of 2 vol% of helium, neon, krypton, iso-butane, and sulphur hexafluoride each (tracer gases) within the matrix of 90 vol% nitrogen. After 2 days the gas in the residual volume was extracted and the composition with regard to the tracer components was determined by a gas chromatograph. Additionally, oxygen was determined in order get information about the tightness of the system. After the first extraction the residual volume was purged and flooded with the gas mixture again, but the second extraction and analysis was performed after 10 to 41 days. The whole procedure was repeated with a third and forth extraction and analysis after 50 to 169 days.

The results of the concentration of the tracer components were compared to calculation results with different diffusivities obtained with the finite element code ANSYS in order to determine the in situ diffusivity values.

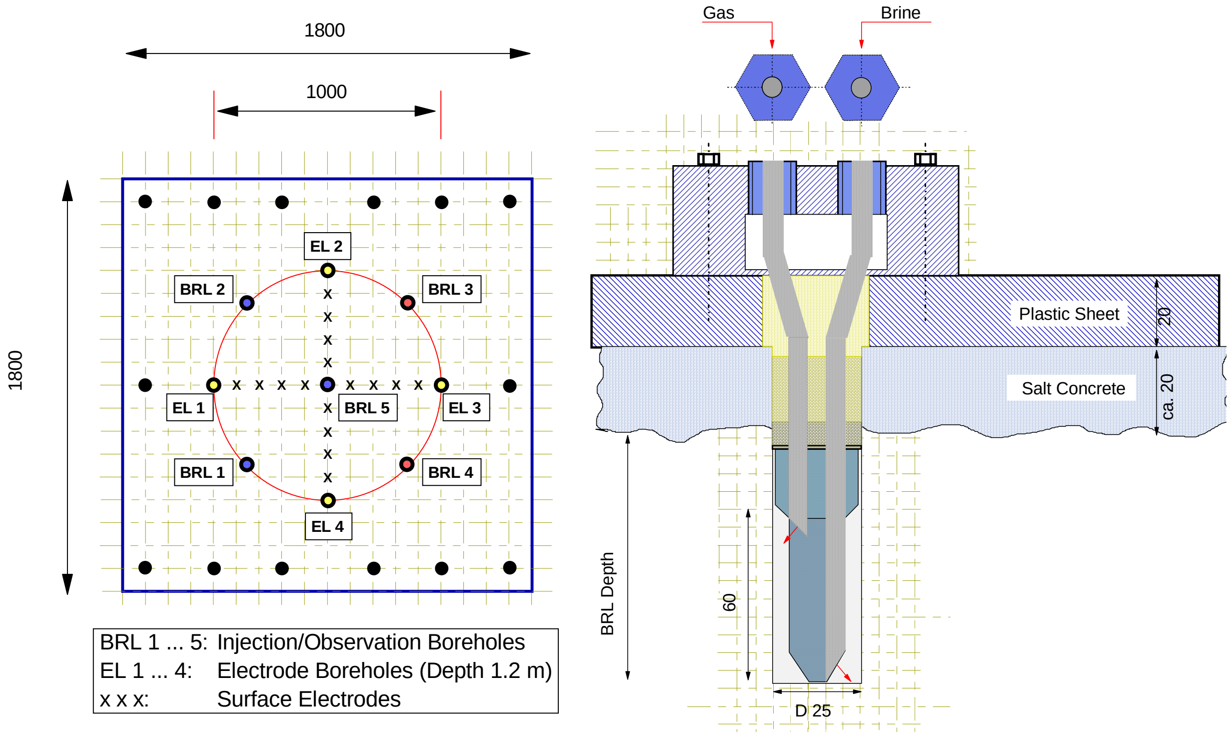

Fig. 1. Plastic sheet embedded in salt concrete on the drift floor with the boreholes for gas or brine injection (BRL1 - BRL5), the boreholes for the electrode chains (EL1 - EL4), and the surface electrodes (left) and cross section through a measurement borehole (right) (dimensions in mm).

Gas Permeability

Gas injection testing was performed in each of the five boreholes BRL1 – BRL5 of the different test locations. Nitrogen was injected at a rate of 200 ml/min up to a maximum overpressure of 1 MPa, or to a steady stress state if this was reached at a lower borehole pressure. The pressure evolution in all boreholes was recorded during the injection and the subsequent shut-in phase.

The gas injection system comprised a PC-based data acquisition system with pressure transducers and a programmable flow controller/flowmeter. The pressure transducers were connected to the injection/observation boreholes; each one of the boreholes could function as injection borehole by connecting a nitrogen tank via the flow controller/flowmeter. Injection rates of 20 ml/min up to 2000 ml/min and pressures up to 5 MPa were possible.

The recorded data were evaluated in terms of permeability using the computer code Weltest 200. It provides means to calculate the analytic solution to the diffusion equation or to numerically model pressure distribution in one- or two-dimensional models, and to iteratively minimize the deviation between the measured and calculated pressure data. For measurements with gas, the real pressure had to be transformed into the so-called pseudo-pressure $m(p)$ due to the highly pressure-dependent material properties of gas:

$$m(p) = 2\int_{p_i}^{p} \frac{p}{\mu(p)z(p)} dp \qquad \text{(Eq. 1)}$$

With the initial pressure p_i, the viscosity $\mu(p)$, and the z-factor $z(p)$.

The parameters affecting the calculated pressure development are the rock permeability, the rock porosity, the wellbore storage coefficient, and the skin factor. The skin factor accounts for an increased or decreased permeability of a zone close to the borehole wall, which can be due to the drilling procedure. No hints to such effects had been found in the relatively small permeability boreholes during earlier measurements; moreover, the whole rock close to the excavation was disturbed, so that no additional disturbance by drilling was regarded.

The calculated pressure curves are rather insensitive to changes in porosity. Therefore, the porosity was held constant at 0.2 %. This is a likely value for the deeper boreholes, while the porosity around the boreholes very close to the drift surface would be higher, but increasing the porosity by a factor of ten has no significant influence on the best fit permeability. Wellbore storage is important during the injection phase and controls the peak pressure reached during injection. The pressure curve form, especially during the shut-in phase, is controlled by the permeability.

Gas injection tests were performed at different times before and after the diffusivity measurements, but prior to brine injection testing.

Liquid Injection Tests

For brine injection only the central borehole of each test arrangement was used. During several injection campaigns saturated salt brine was injected to saturate the pore space near the injection hole. The brine used for injection was a saturated IP9 solution in order to minimize chemical interaction with the rock salt.

The liquid injection system was developed and successfully used in the frame of an earlier project [2]. Brine could be pumped into the test interval of the injection borehole via a filter and a flowmeter. Both the injection and the return tube were equipped with pressure transducers. The return tube was needed to let the gas out of the test interval. The amount of brine injected was measured by the flowmeter; additionally, the brine tank was put on scales providing backup information. The pump and flowmeter were laid out for injection rates between 200 and 1800 ml/min; the maximum injection pressure was 10 MPa. A water tank could be connected instead of the brine tank in order to be able to rinse the system.

Geoelectric Tomography

The electric conductivity of porous rocks is determined by the pore liquid. Thus, geoelectric measurements for determination of electric resistivity and its changes are adequate for monitoring changes in the water content of such rocks. For rock salt, a broad database on the relation between resistivity and water content is available [3, 4].

The geoelectric measurements were performed as dipole-dipole measurements: Two electrodes were used for injecting a low-frequency alternating current into the formation, while the resulting potential difference between pairs of other electrodes was measured, giving an apparent resistivity for each single measurement. The injection and measurement dipoles were located in the same or in different boreholes and on the surface profiles. By varying both the injection dipole and the measurement dipole, a large number of single measurements were obtained.

The resulting data of the two vertical planes including the central liquid injection borehole (i.e., the plane including EL1, EL3, and BRL5 and the surface electrodes in between as well as the plane including EL2, EL4, and BRL5 and the corresponding surface electrodes; see Figure 1) were used as input for inverse finite element modelling using the computer code SensInv2D [5].

From the vector of apparent resistivities the resistivity distribution in the considered plane was calculated as best fit between measured data and calculated response. The optimization method applied was the MSIRT (multiplicative simultaneous iterative reconstruction technique [6]).
The measuring system was an automatic geoelectric apparatus for direct-current measurement which was capable of controlling up to 240 electrodes [7].

RESULTS

The results concerning gas diffusivity, gas and brine permeability, and brine distribution in the host rock after liquid injection are presented in the following sections.

Gas Diffusivity

The gas diffusivity in the 20 years old floor close to the surface was in the range of $3 \cdot 10^{-8}$ m^2 s^{-1} and decreased to the range of $8 \cdot 10^{-9}$ m^2 s^{-1} at a distance of 90 cm to the surface. The drift floor after removal of a layer of 1 m thickness showed a gas diffusivity in the range of $6 \cdot 10^{-9}$ m^2 s^{-1} close to the surface and decreased to the range of $0.5 \cdot 10^{-9}$ m^2 s^{-1} at a distance of 70 cm. 19 months later, the measurements at the third location showed a somewhat increased diffusivity with coefficients between $2 \cdot 10^{-9}$ $m^2 s^{-1}$ and $7 \cdot 10^{-9}$ $m^2 s^{-1}$.

This result can be interpreted as the beginning of the forming of a new EDZ, although the diffusion coefficients are still considerably below the ones measured in the 20 year old floor. The gas permeability measurements (see below) show the same tendendy.

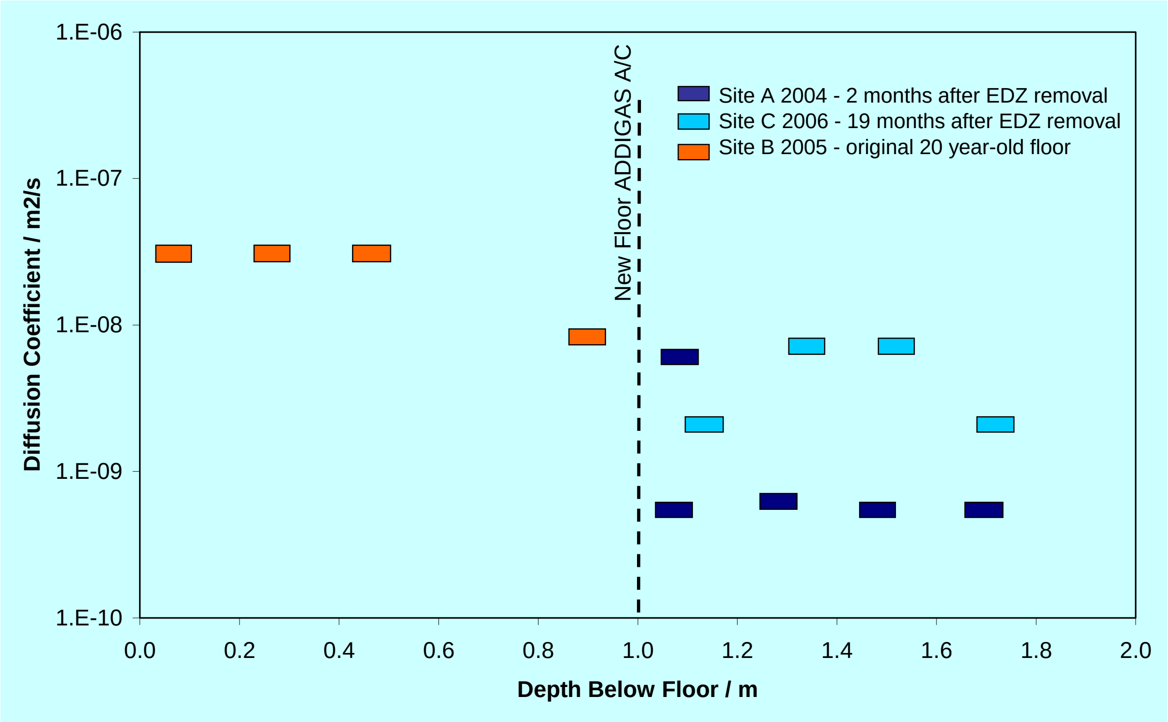

Fig. 2. Diffusion coefficients measurements of the component Helium.

Gas Permeability

Gas injection tests in the 20 years old floor yielded permeabilities up to the range of 10^{-15} m^2 a few centimetres below the surface, which decreases to about 10^{-17} m^2 at a depth of 0.7 m. This is in agreement with earlier measurements in the frame of the BAMBUS II project [1].

In contrast to these relatively high permeabilities found below the original floor, the measurements at the location where 1 m of salt below the floor had been removed yielded permeability values of 10^{-18} m^2 directly below the mine floor, which decreases below 10^{-19} m^2 already at 0.3 m depth. This result agrees again with earlier BAMBUS II measurements, but with packer tests performed at depths of 1 m and more below the floor. The measurements at this location were performed first two months after EDZ removal. Repeating the measurements 14 months later showed only slight increases in permeability, which is consistent with the diffusion measurement results. Figure 3 illustrates the permeability measurement results.

After removal of the EDZ, namely a package of 1 m below the drift floor, the original permeability is more or less kept for several months. This shows that EDZ removal is an effective method to improve seal performance.

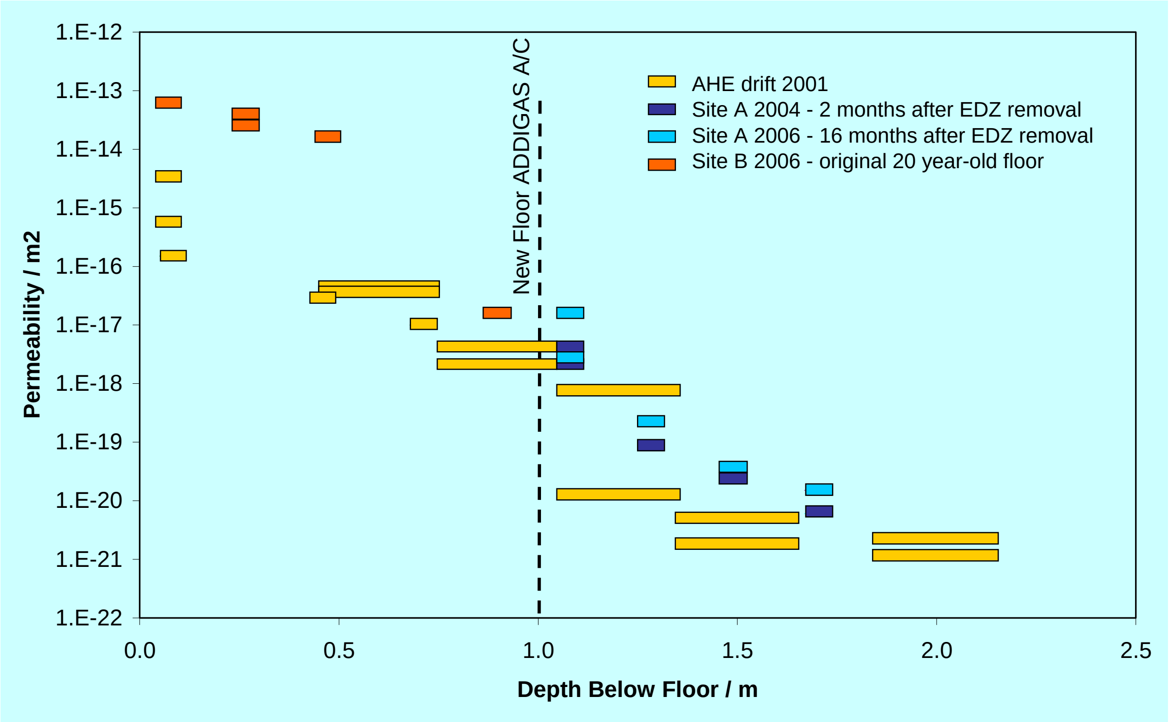

Fig. 3. Permeability distribution below the floor of the AHE drift (BAMBUS II) and at the ADDIGAS test site.

Liquid Injection and Geoelectric Tomography

A liquid injection test performed in the frame of BAMBUS II [1] showed that all the brine (in total 8.8 l) injected into the central borehole of 10 cm depth remained in the upper 30 cm layer below the floor. This is illustrated by the Figure 4 which shows the resistivity distribution in the rock before and after the brine injection: The geoelectric measurement performed prior to brine injection shows a very smooth tomogram with resistivities of 10000 to 60000 Ωm and higher resistivities towards the sides and the lower border of the investigation area as effects of the model borders. The values are in the range of typical rock salt. After the brine injection a pronounced decrease of resistivity can be detected, but it is restricted to the uppermost 30 cm below the floor.

The resistivity of the moist zone ranges down to 200 Ωm which corresponds to a water content around 1 vol%. Assuming a radial spread of the brine in a layer of 30 cm and a uniform water content of 1 vol%, the radius of the moist zone would be 1 m, which is, again, in good agreement with observations during injection (the side length of the sheet is 1.8 m, and the first centimetres of salt beyond the sheet became wet).

Since only partial saturation was reached during the brine injection test, the porosity of the uppermost decimetres of the salt has to be considerably higher than 1 %.

At test location B, below the twenty year old floor, a second brine injection test was performed. A total of 2.8 l of brine were injected in two campaigns (injection pressures between 0.18 and 0.45 MPa). In this case, the test interval depth was 24 – 30 cm below the floor. Again, the brine tended to remain in the injection depth, instead of spreading downward or upward. This shows that EDZ permeability is highly anisotropic not only due to its dependence on distance to the opening, but also due to orientation of fractures – as implied by laboratory results from various investigators.

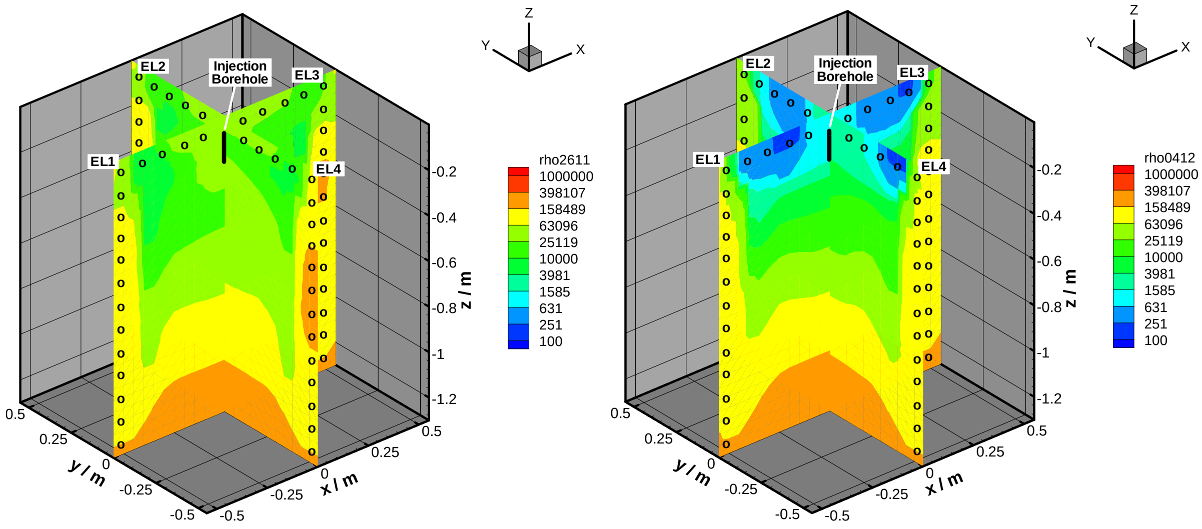

Fig. 4. Resistivity tomograms of the near-surface testing arrangement obtained before (left) and after (right) a brine injection campaign (scale in Ωm).

CONCLUSIONS

From the various investigations performed in rock salt below a 20 years old drift floor and below the floor after removal of the EDZ the following conclusions can be drawn:

1. Both the permeability and the diffusivity of the salt below the floor are considerably higher if the EDZ is not removed.
2. After removal of the EDZ the hydraulic properties of the salt below do not change significantly within months, meaning EDZ removal is effective for improving seal performance.
3. EDZ permeability is highly anisotropic, not only due to its dependence on distance to the opening, but also due to orientation of fractures.
4. The employed methods of gas and brine injection and geoelectric tomography are suitable for obtaining relevant EDZ data.

ACKNOWLEDGEMENTS

The presented work was founded by the German Bundesministerium für Wirtschaft und Arbeit (BMWi) under the contract No. 02 E 9824 (ADDIGAS). The work performed in the frame of the BAMBUS II project was co-funded by the German Bundesministerium für Wirtschaft und Arbeit (BMWA) under contract No. 02E9118 and by the Commission of the European Communities (CEC) under contract No. FIKW-CT-2000-00051.
The authors would like to thank for this support.

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