Hydraulic fracturing at the European HDR/HFR test site Soultz-sous-Forêts (France) – a conceptual model

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Abstract

The HDR/HFR (Hot-Dry-Rock, Hot-Fractured-Rock) technique allows the extraction of heat from deep crystalline rock by circulating fluids through an underground heat exchanger which is formed by a hydraulically stimulated fracture system. During the last 10 years massive hydraulic fracturing tests have been performed successfully at the European test site Soultz. By injection of water at high rates and pressure, large fracture systems could be generated in the crystalline basement between 3 and 5 km depth. A clear understanding of the hydro-frac process is necessary for the development of more efficient stimulation techniques in order to achieve higher flow rates and larger fracture surfaces.

Thus, a conceptual model for hydraulic fracturing is proposed which has been developed based on hydraulic and seismic observations. It is assumed that the hydro-frac process creates tensile artificial fractures within or between natural faults and major fracture zones. The opening of artificial fractures during hydraulic stimulation leads to irreversible shearing along the natural faults. The stimulation experiments at Soultz revealed that a self-propping mechanism kept the fractures open. This observation is attributed to the shearing mechanism. Preliminary results from analytical and numerical model calculations confirm the validity of the conceptual model.

Keywords: HDR/HFR/EGS, hydraulic fracturing, stimulation, bilinear flow, modeling

Introduction

The European HDR/HFR test site is located in the Rhine graben near Soultz-sous-Forêts, northern Alsace, France. The overall aim of the European HDR programme is the realization of power production by extracting geothermal energy from hot deep crystalline rocks. Fluid will be circulated through a 3-borehole system (1 injection, 2 extraction boreholes) connected to each other by a large underground heat exchanger in 5 km depth. A scientific pilot plant for geothermal power production of about 6 MWe will be realized. The heat exchanger has to be created artificially by injection of fluid at high flow rates and pressure. These hydraulic fracturing tests (hydro-fracs) are a common method to increase permeability of a reservoir.

The conventional hydro-frac technique includes the injection of proppants to keep the artificially created fractures open [1]. For geothermal purposes the use of proppants is not recommended because of their limited penetration depth and their relatively high costs. Hydraulic fracturing tests using water without proppants require an irreversible shearing process for persistent fracture opening (self propping effect). Since 1993, several water-frac tests have been carried out successfully in the Soultz boreholes GPK1 and GPK2. Two hydraulically separated artificial fracture systems could be created in dephts of about 3500 m and 5000 m. In 1997, a four-month circulation test in the shallow reservoir was carried out sucessfully [2]. After deepening GPK2 down to a depth of 5 km in 1999, a deep reservoir was stimulated which is hydraulically separated from the shallow reservoir. A temperature of 200°C was reached. In 2002, a second 5 km deep well, GPK3, was completed and will be stimulated in 2003. The injectivity and productivity of the boreholes GPK1 and GPK2 could be enhanced by more than one order of magnitude [3] showing that the water-frac technology is suitable for the creation of large geothermal underground heat exchangers.

In order to achieve higher flow rates and larger fracture surfaces for future commercial geothermal power plants, an enhancement of the efficiency of hydraulic stimulation methods is essential. A clear understanding of the hydraulic fracturing process is necessary for the development of more efficient stimulation techniques. As contribution to the improvement of understanding, a new conceptual model for the hydro-frac process was proposed by *Jung* and *Weidler* [4]. The model has been developed based on hydraulic and seismic observations in Soultz (shallow reservoir). Preliminary results from analytical and numerical modeling addressing the validity of the conceptual model will be presented.

Hydraulic and seismic observations

The hydraulic test programm of the deep reservoir is running at present and revealed indications for a relatively tight and fault dominated reservoir system [3]. These observations are preliminary and we focussed this analysis on the shallow reservoir. The main results of hydraulic tests in the boreholes GPK1 and GPK2 between 1993 and 1996 are as follows:

The injection overpressure during water-frac experiments was found to reach maximum values of 12.5 MPa. This is in agreement with the minimum horizontal stress at Soultz [5] and indicates a pressure limitation due to normal opening of existing fractures or tensile fracture propagation.

Pressure build-up and decline curves recorded during frac and post-frac injection tests exhibit a transient pressure behaviour changing linearly with the fourth root of time (Fig. 1a) which is characteristic for bilinear flow [6]. The bilinear flow period comprises two simultaneous linear flows, one occurs within a fracture of finite conductivity, the other permeates into the formation, perpendicular to the fracture plane. Fig. 1a shows a bilinear flow period persisting for approximately one day.

All post-frac hydraulic tests with step-like flowrate history displayed a quadratic relationship between downhole overpressure and corresponding flowrate (Fig. 1b). This behaviour indicates the presence of turbulent flow [7].

The post-frac injectivity or productivity shows a linear relationship with increasing flowrate applied during water-frac stimulation (Fig. 2a).

Massive hydro-frac stimulation produces micro-seismic events. Their spatial distribution is assumed to represent the shape and size of the stimulated fracture system. Fig. 2(b) displays the top view of the recorded seismic cloud (after [8]). Some linear structures are obvious.

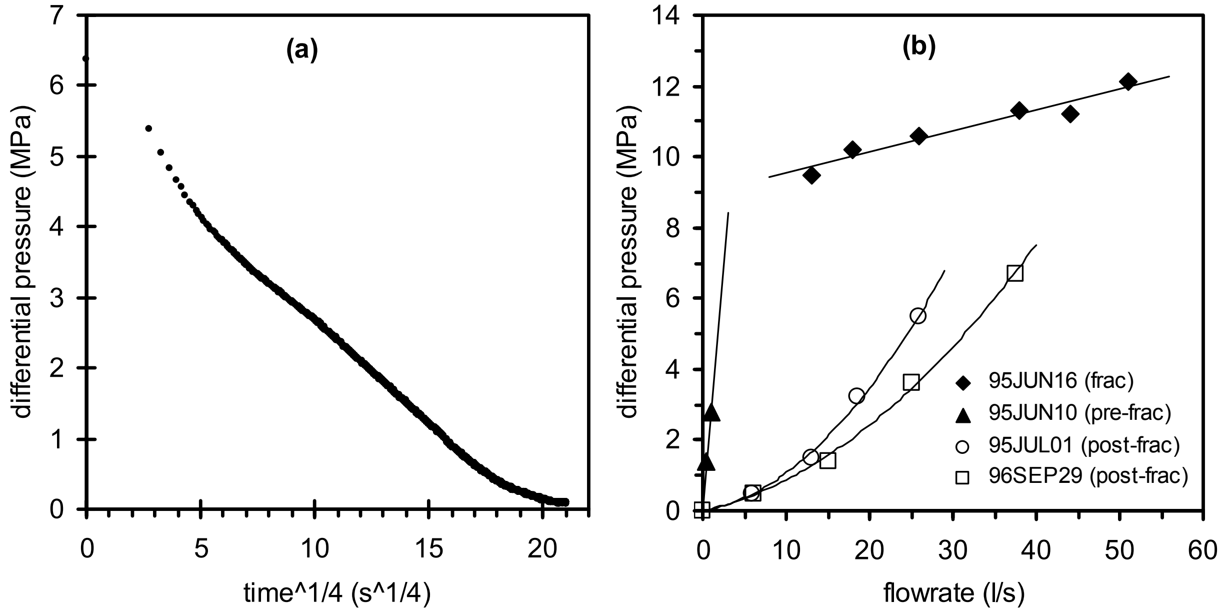

Fig. 1: (a) Pressure decline during a hydraulic post-frac injection test in the Soultz borehole GPK2 in 1996 (test 96SEP29, 0 $s^{1/4}$=shut-in). The decline curve shows a fourth root of time behaviour which indicates the presence of a distinct bilinear flow period. (b) Downhole overpressure during hydraulic tests vs. corresponding flowrates. Post-frac curves show a quadratic behaviour with increasing flowrate.

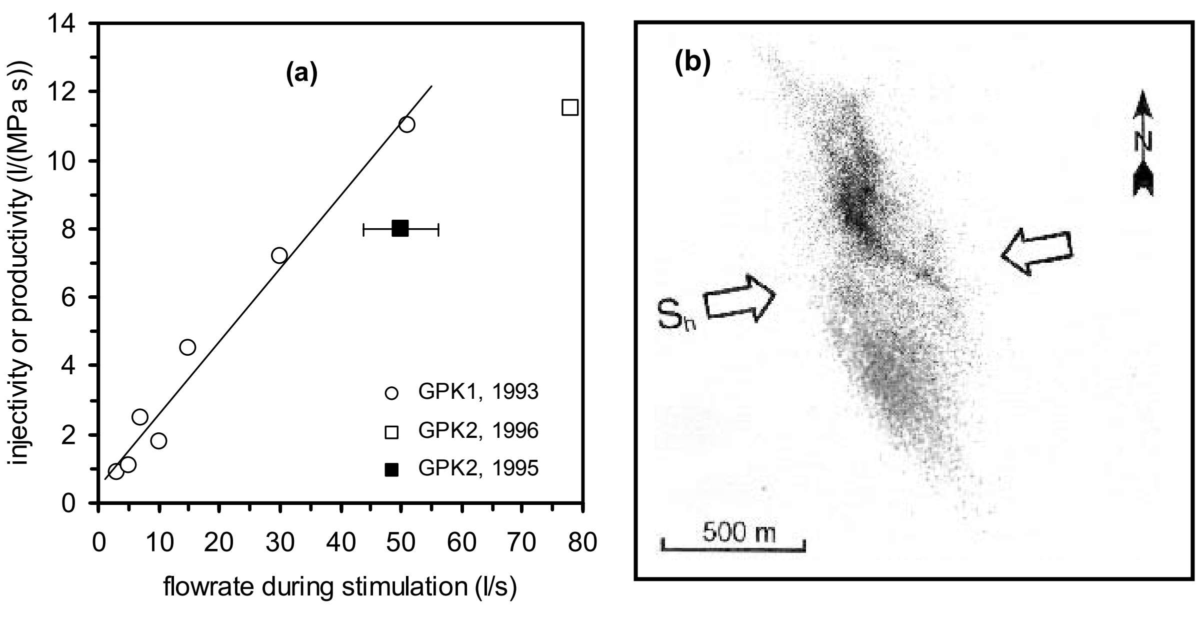

Fig. 2: (a) Post-frac injectivity or productivity is linearly related to the flowrate applied during hydro-frac stimulation. (b) Locations of micro-seismic events during hydro-frac experiments in the Soultz boreholes GPK1 and GPK2, orientation of minimum horizontal stress S_h. Linear structures are obvious in the seismic cloud [8].

A conceptual model for hydraulic fracturing

A clear understanding of the physical processes during hydraulic fracturing is essential for the development of more efficient stimulation techniques. A conceptual hydro-frac model was developed by *Jung* and *Weidler* [4] which is based on the hydraulic and seismic observations in the shallow reservoir. Fault or fracture zones of a scale of at least several 100 m to some km are believed to represent the important natural discontinuities in a crystalline basement. The conceptual model assumes that a tensile artificial fracture is created within or between these natural fault zones (Fig. 3). The observed increase of the borehole productivity and injectivity is attributed to this mechanism. The vertical growth of artificial fractures is stopped as soon as they intersect the natural discontinuities. The fracture heights may amount to some 10 m. The fracture length may reach several 100 m or even more than 1 km and is limited due to fluid losses into the fracture zone. The normal opening of artificial fractures leads to irreversible shearing along the natural discontinuities. The stimulation experiments at Soultz revealed that a self-propping mechanism kept the fractures open. This observation and also linear structures identified in the seismic cloud are attributed to this shearing mechanism.

The hydraulic observations can be explained as follows: The overpressure during the water-frac experiment is limited due to normal opening of existing fractures or tensile fracture propagation. The natural and artificial fractures together form a bilinear flow system as indicated by the arrows in Fig. 3. Due to the limited fracture height the flow velocity within the artificial fracture is high which leads to turbulent flow conditions. The linear increase of post-frac injectivity or productivity with increasing flowrate can be understood as result of the fracture propagation that is controlled by the fluid losses into the matrix. The propagation stops when the amount of fluid losses equals the injection flowrate. Thus, the fracture lengh *L* and the post-frac injectivity or productivity is proportional to the injection flowrate during the water-frac test.

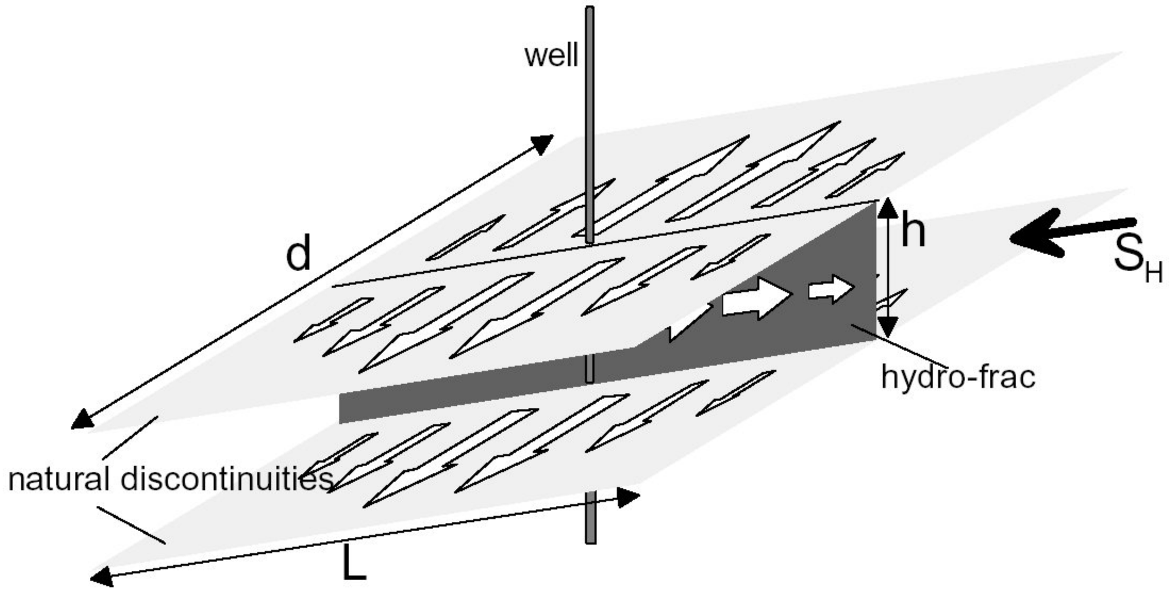

Fig. 3: Proposed conceptual model of hydraulic water-frac stimulation in a crystalline rock mass: During the hydro-frac process, a tensile artificial fracture is created within or between natural fracture zones. L *is the fracture lengh,* h *its height, and* d *is the penetration depth of the pressure front into the fault zone (from [4]).*

Estimation of bilinear flow parameters

After an analytical solution for bilinear flow developed by *Cinco-Ley* and *Samaniego-V.* [6], the differential pressure curve is given by

$$\Delta P = mt^{1/4} \quad \text{with} \quad m = \frac{34.97 q \mu B}{\left(T_f h\right)^{1/2}\left(T_z S_z \mu\right)^{1/4}} \qquad \text{(eq. 1)}$$

and with differential pressure ΔP [kPa], time t [hr], flowrate q [m³/d], dynamic fluid viscosity μ [Pa s], formation volume factor B [m³/m³], fracture transmissibility T_f [Dm], fracture height h [m], total transmissibility of the fault zone T_z [Dm], and total storage coefficient of the fault zone S_z [m/Pa]. Eq. 1 was developed for laminar flow behaviour, but the bilinear flow period seems to be preserved even under turbulent fracture flow conditions [7]. From eq. 1, the product $T_f h$ can be expressed by ($B = 1$)

$$T_f h = \frac{34.97^2 q^2 \mu^2}{m^2 \left(T_z S_z \mu\right)^{1/2}} \ . \qquad \text{(eq.2)}$$

The Reynolds number *Re* indicates the beginning of turbulent flow. For rough fracture surfaces, deviations from laminar Darcian flow may be found at Reynolds numbers as low as 100 [7]. From *Re*, a maximum fracture height *h* can be estimated as follows

$$\mathrm{Re} = \frac{q_c \rho}{h \mu} > 100 \Rightarrow h < \frac{q_c \rho}{100 \mu} \qquad \text{(eq. 3)}$$

with a flowrate of q_c at the onset of turbulence. Combining eqs. 2 and 3, a minimum transmissibility T_f can be calculated (rf. Table 1). The minimum effective fracture width is given by the cubic law [9]:

$$w_{eff} = \left(12 T_f\right)^{1/3} \ . \qquad \text{(eq. 4)}$$

The half lengh of the artificial fracture *L/2* can be determined from the duration of the bilinear flow period which ends at the time t_b [6]:

$$L/2 = \left(10\beta\right)^{1/4}\left(T_f h\right)^{1/2}\left(T_z S_z \mu\right)^{-1/4} t_b^{\ 1/4} \qquad \text{(eq. 5)}$$

with unit conversion constant β = 3.6e-09. The penetration distance of the pressure front into the surrounding fault zone, *d/2*, can be estimated from the hydraulic diffusivity *D* and may be expressed by

$$d/2 = \left(D t_b\right)^{1/2} \quad \text{with} \quad D = \frac{T_z}{S_z \mu} \ . \qquad \text{(eq. 6)}$$

The parameters for the bilinear flow system as described above (rf. Fig. 3) have been estimated based on data from the post-frac step injection test 96SEP29 (rf. Fig. 1) in the Soultz borehole GPK2 in 1996. Table 1 summarizes the adopted parameters and the results.

Input parameters		*from:*
Flowrate q	0.0375 m^3/s = 3240 m^3/d	test data
Dynamic fluid viscosity μ	3.e-04 Pa s	assumed
Total transmissibility of fault zone T_z	< 1.e-12 m^3 = 1 Dm	assumed
Total storage coefficient of fault zone S_z	< 1.e-09 m/Pa	assumed
Slope of the fourth root of time curve m	3.e05 Pa/$s^{1/4}$ = 2.3e03 kPa/$hr^{1/4}$	Figure 1a
Duration of bilinear flow period t_b	$t_b^{1/4}$ = 17 $s^{1/4}$ = 2.2 $hr^{1/4}$	Figure 1a
Flowrate at onset of turbulence q_c	0.005 m^3/s	[7]
Fluid density ρ	1000 kg/m^3	assumed
Parameters of bilinear flow system		
Product $T_f h$	> 3.9e-10 m^4	eq. 2
Fracture height h	< 170 m	eq. 3
Fracture transmissibility T_f	> 2.3e-12 m^3	eq. 2 and 3
Effective fracture width w_{eff}	> 0.3 mm	eq. 4
Fracture half length $L/2$	> 800 m	eq. 5
Penetration depth $d/2$	≈ 530 m	eq. 6

Table 1: Estimated parameters of the bilinear flow system.

The adopted values of transmissibility T_z and storage coefficient S_z represent reasonable maxima. Smaller values of T_z and S_z lead to a higher estimate of fracture transmissibility T_f and subsequently to higher values of fracture half length $L/2$ and smaller values of penetration depth $d/2$. The estimated values of $L/2$ and $d/2$ are in reasonable agreement with the size of the stimulated fracture system which is given by the spatial distribution of micro-seismic events recorded during water-frac stimulation.

Modeling results

Analytical and numerical model calculations addressing the validity of the above described conceptual model have been performed.

The post-frac step injection test 96SEP29 was analysed using KAPPA's pressure transient interpretation software Saphir Advanced. The selected analytical model comprises a well intercepted by a vertical finite-conductivity fracture in an isotropic, homogeneous reservoir with planar constant pressure boundary at a distance of some 100 m. The modeled transient behaviour of a vertically fractured well includes linear fracture flow followed by a bilinear flow period, formation linear flow, and finally a pseudoradial flow period. Bilinear flow is observed in finite-conductivity fractures and before fracture tip effects affect the well behaviour [6].

The observed downhole pressure during the step injection test and the fitted curve are displayed in Fig. 4. The model calculation yields a quite well fit of the observed pressure history. This indicates that the observed pressure curve which exhibits a distinct bilinear flow period can be reasonably explained by a well-fracture system as proposed in the conceptual model of hydraulic fracturing. Nevertheless, further calibrations of the model are necessary in order to determine the hydraulic fracture parameters.

Additionally, numerical finite-element modeling based on the above described conceptual model have been started using the FE-code RockFlow. In order to focus on the underlying physical processes, it is necessary to reduce the uncertainties by using simple model geometries. The finite-element model consists of an artificial fracture of reasonable dimensions (rf. Table 1) within a fault zone. The fault zone is given by a porous permeable matrix representing altered crystalline rock in the fault. The natural discontinuities are replaced by this matrix. Turbulent fracture flow is implemented by Forchheimer's approach. Preliminary results based on the flowrate history of the injection test 96SEP29 also suggest that the FE model is suitable to explain the observed pressure curves.

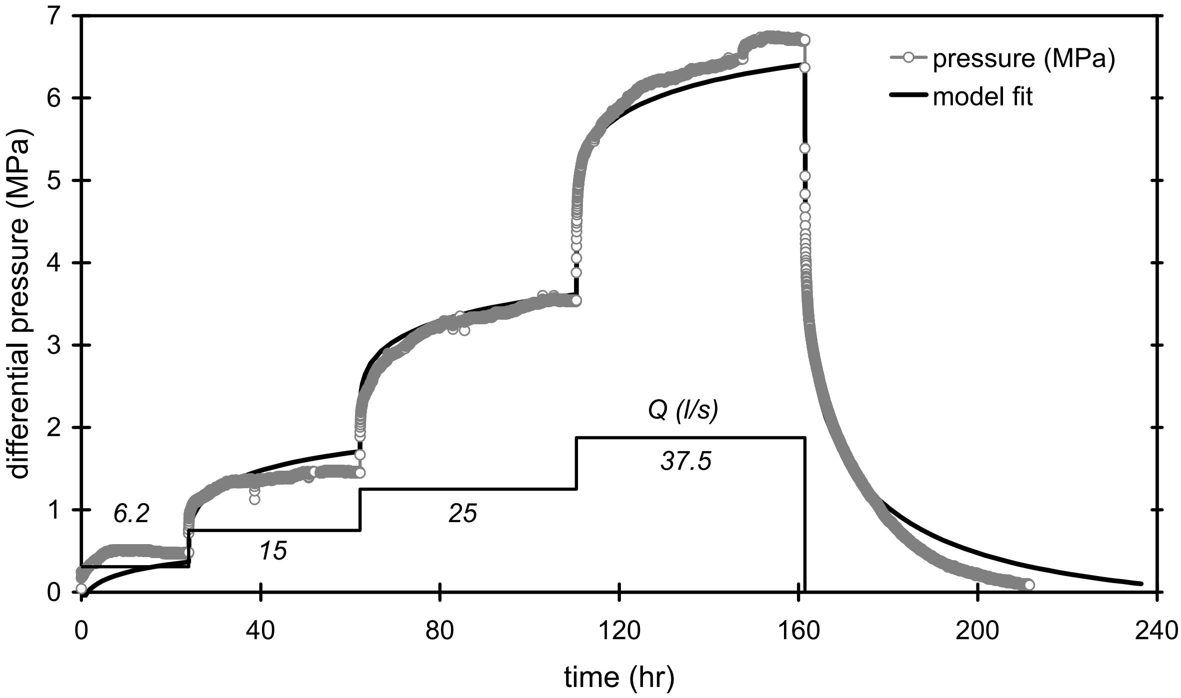

Fig. 4: Analysis of hydraulic post-frac test 96SEP29 in the Soultz well GPK2; downhole differential pressure in MPa (gauge depth 3200 m), and fitted pressure (vertically fractured well, KAPPA's Saphir Advanced) vs. time; injection rate Q in liters/sec vs. time.

Conclusions

The water-frac technology is a suitable method to create large scale underground heat exchangers for geothermal energy use. In order to develop more efficient stimulation techniques, a clear understanding of the water-frac process is necessary.

Main hydraulic and seismic observations during hydro-fracs at the HDR/HFR test site Soultz and a conceptual model for the hydro-frac process as proposed by *Jung* and *Weidler* [4] have been reviewed. The conceptual model assumes the creation of a tensile artificial fracture within a natural fault zone or between major natural discontinuities. The fracture opening leads to irreversible shearing along the natural faults and a self-propping mechanism kept the fractures open. The conceptual model is in good qualitative agreement with the hydraulic observations at Soultz. However, the spatial distribution of micro-seismic events suggest a stimulated fracture system which is much more complicated. But the conceptual model seems to reflect the underlying mechanisms of hydraulic fracturing at Soultz.

Preliminary results from analytical and numerical model calculations indicate that the observed post-frac transient pressure behaviour can be reasonably explained by the proposed conceptual model.

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