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STIMULATING A HIGH ENTHALPY WELL BY THERMAL CRACKING

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ABSTRACT

Well BO-4 is situated in the geothermal area of Bouillante, Guadeloupe. The well was drilled in the 70's to a depth of 2500 m. When electrical production started from a nearby power plant in 1988, it was not considered economical to connect the well due to low steam output. The actual stimulation took place between August 10 and 27 1998, with production tests before and after to evaluate the results of the stimulation. Up to 25 l/s of sea water, mixed with inhibitors to prevent anhydrite scaling, were injected into the well in periods of up to 72 h. The wellhead pressure and the downhole pressure at 600 m were monitored throughout the whole stimulation. The wellhead pressure decreased gradually during the injection and was close to zero for maximum injection at the end of the program. The pressure behavior at 600 m depth showed similar decrease which indicated thermally induced fracturing. After each injection period the pressure falloff was recorded at 600 m depth. The injectivity of the well increased by 50% and the skin effect decreased substantially. The production test after the injection period was not successful due to equipment failures. By simulating the dynamic pressure and temperature logs for the well flow a backpressure curve was obtained, that showed increase in productivity. The well produced about 40 – 60 t/h total flow at high wellhead pressure, during the production test, which corresponds to about 1 MW_e. A year later a short production test confirmed the characteristic curve, which shows a 50% improvement. If the well can sustain this production it will be economical to connect it to the power plant.

1. INTRODUCTION

The Bouillante geothermal field is situated on the island of Guadeloupe, Lesser Antilles. It is located near the seaside of the western coast of Basse-Terre (Figure 1). Around the small town of Bouillante, there were numerous surface manifestations like hot springs, fumaroles and steaming ground which led to the selection of this site as a potential candidate for geothermal energy production. Initial exploration of the Bouillante geothermal field was carried out in the years 1965-70, including a survey of surface manifestations, geology, geochemistry of the thermal springs, temperature gradient measurements in shallow wells, resistivity profiles and seismic reflection profiling.

Four production wells were drilled into the Bouillante geothermal field in the 70's. They all revealed high temperature conditions (240 -250°C), but only one BO-2 was productive enough for utilization. It produces about 30 t/h of steam from a permeable fracture zone at the bottom of the well at 340 m depth. Wells BO-1 and BO-3 were later plugged, but in 1998 well BO-4 was stimulated in the hope that it would be possible to connect that well to the existing geothermal plant. Well BO-4 is 2500 m deep, with maximum recorded temperature of 253°C. An initial production test, carried out after the drilling of the well, indicated about 10 t/h steam production at a 4 bar-g separation pressure. The low productivity of well BO-4 was believed to be due to unfavorable permeability conditions between the well and the geothermal reservoir. By stimulating the well, to improve the near well permeability, the heat extraction from the field could be increased.

A reassessment of the geothermal potential of the Bouillante geothermal field and adjacent areas was carried out by the French company BRGM in the years 1983-87, with additional geological mapping, fluid geochemistry, geophysical exploration (magneto-telluric method, natural microseismicity), radon and mercury surveys in the soils (BRGM, 1984). A preliminary geological model was proposed. The development of the geothermal field appears to be related to the recent volcanic episode called the "Bouillante Chain" (0.8 to 0.2 M.Y. old) which built several small monogenic volcanic centers (maars, seamounts) delivering differentiated magmas (Gadalia et al., 1988). The location of these volcanic centers is controlled by a major regional tectonic lineament oriented NW-SE (the Montserrat-Marie Galant Fault) which was evidenced only recently (Bouysse et al., 1988; Polyak et al., 1992). It crossed Basse Terre Island, and Bouillants is located on a segment of this fault. The recorded seismic activity probably develops secondary fracture permeability sustaining the development of the hydrothermal system.

Since 1995, the Research Division of BRGM has had an ongoing research program focused on the geological background of Bouillante, the origin of the geothermal fluids and the flow model. Tracer tests have been done between the wells BO-4 and BO-2 by using injection of chemical tracers and monitoring of wellhead pressure, natural microseismicity, temperature profiles and downhole fluid sampling in well BO-4. The data collected was used to refine the knowledge of the geothermal reservoir and was useful for the design and conduction of the stimulation experiment.

In 1997 Companie Francaise de Geothermie (CFG), the owner of the power plant, applied to the European Committee for a grant to stimulate well BO-4 by cold water injection. BRGM and Orkustofnun were in cooperation with CFG on this project and finished it by a report to the EC describing the project and the results in detail (Correia et al., 1999)

2. OBJECTIVES

A problem frequently observed in the exploration of high enthalpy geothermal reservoirs, is the poor hydraulic connection between the production wells and the geothermal reservoir. These circumstances restrict considerably the possibilities to extract the geothermal energy through the production wells. In cases where some wells are productive, but others are not, or less, it is considered to be because of different permeability conditions between the wells and the reservoir fracture network. By using low cost stimulation methods to improve the hydraulic connection between the "dry" wells and the reservoir fracture network, the economical condition of the geothermal area can be improved and drilling cost reduced.

3. WELL BO-4

Well BO-4 is located at 84 m a.s.l. and about 600 m east of well BO-2 and the power plant. It was drilled in two parts, first in 1974 to a depth of 1200 m, then deepened to 2505 m in 1977. It is completed with a 9 5/8" cemented casing from 0 to 558 m, a 7" slotted liner from 541 m to 1199 m (perforated intervals; 645-690 m, 730-770 m and 855-1075 m) and a 4 1/2" slotted liner from 1184–2504 m depth. Several mud losses were observed during drilling, the main ones at 1050 m depth. Other losses were at 560–610 m depth, around 650 m depth between 740 and 760 m depth, and 850 – 880 m. Continuous losses were observed during the drilling of the deeper part, possibly due to the feed zones in the upper part.

The lithology is plotted in Figure 2 along with inferred and measured temperatures. The main rock units, the well penetrates below the casing, are tuff and massive lavas with some coarse-grained tuff in between. The longest continuous temperature profile was recorded in 1996, between 400 and 1800 m depths (Herbrich, 1996). It indicates a cap-rock horizon with an elevated thermal gradient (300°C/km) between 400 and 500 m depths which corresponds to a 100 m thick lava horizon. Below, the temperature increases slightly from 242°C to 248°C, then stays rather constant down to 1100 m depth. This 600 m zone roughly corresponds to the interval of mud losses during drilling. Below 1100 m depth, the temperature profile shows a reverse gradient as the temperature decreases to about 230°C at 1800 m depth.

During the discharge test performed at the end of the deepening of well BO-4, intermittent eruptions of a mixture composed of water, steam and rock fragments were recorded. After some time the flow stabilized at a well head pressure of 3.6 bar-g. A long term production test was carried out by the French drilling company EURAFREP between July 1978 and June 1979, using a separator. Data acquisition was limited to flow rate measurements by lip pressure method and enthalpy by the calorimetric method. The following values were obtained; wellhead pressure 4.2 bar-g, separation pressure 4 bar, steam production 10.5 t/h and water production 50 t/h (Correia, 1999).

Interference tests were carried out between wells BO-2 and BO-4 in order to check for hydrological connection between the wells (Herbrich, 1996, Sanjuan and Brach, 1997, Sanjuan et al., 1998). In all the tests, tracers were injected into well BO-4, while well BO-2 and thermal springs were monitored. No tracers were recovered neither in well BO-2 nor at the thermal springs, which suggests the absence of a direct hydraulic connection between wells BO-2 and BO-4 and the springs. This is consistent with a fracture network striking N100-120° that may act as a permeability barrier between the two wells.

4. STIMULATION

4.1 Water supply

The local freshwater supplier could not guarantee sufficient flow rate of fresh water for the injection. Therefore, it was necessary to use seawater. Before implementing the injection an extensive study was made in order to prevent anhydrite scaling in the well due to the salinity of the seawater. An inhibitor was found that ensured this and it was mixed with the seawater before it was pumped into the well. The sea water was pumped from a pumping station at the seaside close to well BO-2 and the power plant, through a 650 m long pipeline at a maximum rate of 25 l/s, with initial wellhead pressure of 25 bar-g.

4.2 Reference production test

The first step of the stimulation program was to make a reference production test to evaluate the initial production characteristics of well BO-4. It would act as a reference to evaluate the benefits of the stimulation regarding the production performances. Because of some problems with the lip/weir test loop this reference test became limited to one flow rate at high wellhead pressure.

Before discharging the well, a static temperature logging was performed down to 540 m, where an obstruction was encountered. The obstruction prevented gauges to go deeper into the borehole. During the injection, the obstuction moved down the well. This static temperature profile indicated that the well was colder in the uppermost 500 m, compared to the measurement done in 1996 (Figure 2).

In order to avoid backflow through the silencer collecting pipe, well BO-4 was discharged with a limited opening of the 6" throttling valve installed in the horizontal discharge line. The final phase of the production test was carried out with 4 cm opening of the throttling valve. The wellhead pressure (WHP) for these conditions was 20 bar-g which was near the maximum pressure obtained when the well was shut-in. This means that the production data obtained corresponds to the minimum flow output of BO-4. The flow rates measured were identical to those of EURAFREP (1974, 1977) during a three month long production test. The main difference between the two mentioned tests is that the WHP for EURAFREP was about 4.5 bar-g for maximum flow, but this time it was about 20 bar-g for a minimum flow.

The dynamic pressure and temperature profiles taken during the reference test are shown in Figure 3. Also shown in the figure is a calculated match to the profiles. The match indicates flashing in the wellbore near 386 m depth. The pressure profile should be correct in the upper part of the well as it compares to the wellhead conditions during the measurement. However, it is unclear what causes the pressure lowering between 350-450 m, as no caliper logging or probing with baskets were done to obtain the inside diameter of the well. The clock in the temperature gauge stopped early during the measurement so the readings are not reliable.

The relevant features observed during the reference production test are:

- For the last setting of the throttling valve at 4 cm, the WHP reached 20.5 bar-g and was still rising.

- The flow was unstable (strong pulsation in the lip pressure) oscillating between a “dry” and “wet” regime; these features can be either a result of the flow restrictions imposed by the obstruction or indicative of a well with two feed zones of different thermodynamic conditions.
- The WHP was unstable in the beginning of production, but stabilized on the last day.
- Significant production of solid material (sand and clay sizes) accumulated in the weir box.

4.3 BO-4 stimulation

The aim of the BO-4 stimulation by injection of cold seawater, was to enhance the secondary permeability (and consequently enhance the production) through thermal cracking. The activities related to the stimulation of BO-4 started on August 10 1998 and finished on August 27 1998, with a short waterloss test and where then followed by four days of logging.

The injection pumping system was composed of a centrifugal pump at the sea shore, a high pressure centrifugal pump for testing purpose, a inhibitor injection system, an injection pump and a 650 m water line. The flow rates injected, were established in terms of strokes/min where the volume of each stroke was 28.2 liters. The maximum flow rate delivered by the injection pump was 26 l/s. The flow rates injected were monitored continuously through an ultrasonic flow meter connected to a data acquisition system (DAS) with acquisition frequency of 5 min. The anhydrite scaling inhibitor added to the intake of the injection pump was IDOS 130 and dosed at 10% of the seawater flow rate.

Pressure monitoring during injection was performed at the wellhead through two electronic pressure sensors, connected to the DAS. A bourdon pressure gauge was also available. Pressure was also monitored at 600 m depth with a Kuster pressure gauge.

The injection history is shown in Figure 4 and a sample of the wellhead DAS-record for one injection step in Figure 5. After the long injection period from August 15^{th} to 18^{th}, the DAS worked only sporadically and the data was not useable.

The main feature during the stimulation was the continuous decrease of the wellhead injection pressure for all the injection flow rates.

Several temperature and pressure profiles were measured before, during and after the stimulation operation. The obstruction observed at the start of the operation at 540 m depth was in later measurements encountered at continuously increasing depths. The pressure profile measured 11 days after the reference production test indicates that the pressure has recovered to its initial stage. At the end of the stimulation operation a water loss profile was measured inferring a loss zone around 720 m depth. The last profiles measured show that the well has not fully recovered after the stimulation operation. No pivot point is seen in the pressure profiles in the measured interval (<800 m) and the profiles indicate that the pivot point would be much deeper in the well.
The pressure response was monitored at 600 m depth during the stimulation operation. Pressure was measured both during the injection steps and for some time after each injection was stopped. The pressure falloffs in the beginning of the stimulation operation show higher pressure in the well and they tend to stabilize at higher pressure than those measured later. Furthermore, in the early stage the thermal recovery in the well influences the falloffs after 70-80 minutes while it influences the later falloffs after only 20-30 minutes.

Each falloff was normalized by dividing the flow rate before shut-in into the pressure change to simplify the comparison between all the falloffs. The normalized pressure (unit pressure change) is shown in Figure 6. From the figure it can be seen how the injectivity of the well changes between injection steps during the stimulation operation. The first two falloffs from August 10 and 12, indicate the initial injectivity of well BO-4, then on August 13, the injectivity has decreased. After that the injectivity increases in steps. It has increased on August 19, and again on August 23, but after that it stays about the same. Initially, the injectivity is about 0.9 l/s per bar increasing to about 1.4 l/s per bar at the end of the stimulation operation. This increase in injectivity is supported by the behavior observed in most of the injection steps which show declining pressures during injection. Such behavior infers thermally induced fracturing as fractures are opened due to contractions when formations accepting the injection fluid are cooled.

Horner plot for the pressure falloffs shows similarly the changes during the stimulation operation. Average pressure prevailing at 600 m depth during the operation can be estimated from the Horner plot to be around 44.9 bar (44 kg/cm^2). All the injection and falloff steps are strongly influenced by thermal changes in and around the wellbore as well as thermal fracturing. Therefore, it is difficult to obtain estimates for transmissivity, storage and skin from them. An interpretation was tried for two injection steps from August 13 and 14, which appear to have the longest undisturbed pressure response. A match to Theis model infers low transmissivity around $(0.5\text{-}0.7)*10^{-8}$ m^3/Pas, a skin factor about –2.6 and formation storage in the range $(1\text{-}5)*10^{-8}$ m/Pa. These values are only approximates as both the injection steps and the falloffs are not well behaved. Furthermore, there is a dependancy between the estimated transmissivity and the skin. Nevertheless, the results give low transmissivity for this well while other parameters are around average values for a productive high enthalpy geothermal well.

To better evaluate the changes in injectivity the pressures measured at 600 m depth at the end of each injection step are plotted for the different flow rates in Figure 7. The figure clearly demonstrates how the pressure decreased as the stimulation progressed and the injectivity improves.

4.4 Evaluation production test

Thirty eight days after the end of the stimulation operations, well BO-4 was discharged again to assess the benefits of the stimulation as regards production. The time length of this test was only eight days instead of the fourteen days scheduled. The duration of the discharge was shortened mainly due to complaints from the residents in the vicinity of the well site, of noise, especially during the nights.

Even after the modifications introduced to the surface equipment, backflow of separated water through the silencer collector pipe was again experienced. During the production evaluation test, the opening of the 6” throttling valve was restricted to be in the range of 4 to 4.7 cm, as for the reference production test. The flow data obtained corresponded again to minimum well output (40-60 t/h).

An attempt was made to get higher flow rates than was possible to measure with this separator by disconnecting the horizontal discharge line from it and discharging directly to the atmosphere. The 4” lip pipe was replaced by a 5” lip and the throttling valve was opened to 5 cm. Under those new conditions the WHP dropped to 19 bar-g resulting in the highest flow rate measured during that testing period, or around 80 t/h. However, a strong vibration in the discharge line was noticed. Therefore, it was not advisable for safety reasons to proceed with further opening of the throttling valve. After this short attempt the lip/weir loop was connected again and kept like that until the end of the test period with the 5” lip pipe.

The relevant features observed during the evaluation test were:

- This time the WHP was stable (no fluctuation) at each discharge step and presented a slight increase compared to the reference test. The WHP range during the test was from 20 to 21.5 bar-g.
- The flow was stable over the whole testing range; the strong oscillation noticed in the reference test disappeared.
- The quantity of solid materials accumulated in the weir box, composed mainly of sand, decreased significantly.

Good dynamic pressure and temperature profiles were obtained during the evaluation production test. The temperature profile agreed with the conditions measured at wellhead during the logging, but the pressure profile gave slightly lower pressure values in the two phase section of the well than was expected from the wellhead pressure. The same wellbore conditions are used to match the pressure profiles measured during the reference and the evaluation production tests except that an assumed obstruction at about 530 m depth was mostly removed for the later match. As limited information were available on the thermal gradients in the area and conductivity of the formations, only an approximate match was made for the temperature profile, but the difference is normally within 2°C. A satisfactory match was obtained indicating the flashing level in the wellbore to be near 323 m depth. As in many of the earlier measurements some disturbance is recorded at around 350 m depth.

Results from both the reference and the evaluation tests are presented in Figure 8 along with the calculated characteristic curves for each test. Also shown on the figure is the highest flow rate obtained during the evaluation test inferring that the calculated curves are representative for the conditions of well BO-4. Results from a short discharge test performed a year later are also presented in Figure 8, but they confirm the findings of the evaluation test.

5. DISCUSSIONS AND CONCLUSIONS

Pressure measured during the injection steps in well BO-4 showed that pressure decreases with time, sometimes gradually and in some cases in steps. That kind of pressure response can be interpreted as an effect of thermally induced fracturing. That is further supported by the falloff pressure responses, all indicating increasing injectivity. During the stimulation operation the injectivity of well BO-4 is estimated to have increased from about 0.9 l/s per bar to 1.4 l/s per bar or about 50%. Furthermore, the obstacle first encountered in the well at 540 m depth had been reduced or removed. Obstacles found deeper in the wellbore have also been reduced. All this comfirms that the stimulation was successful. Caliper logs made in the well in 1999 confirm the removal of most of these obstacles. The increase in injectivity cannot be directly translated to productivity for a high enthalpy well due to the different thermal conditions prevailing in the well and the reservoir for those two situations. However, the short discharge tests made after the stimulation indicate that similar increase in productivity can be expected.

Due to problems encountered with the production equipment it was not possible to measure a well characteristic curve during the reference and evaluation production tests. However, the well characteristic curves were calculated using the matching parameters to the measured dynamic pressure and temperature profiles. The calculated curves are only indicative of the well performance before and after the stimulation operation. The calculations indicate that the flashing level in the well changes considerably with increased flow rate from about 300 m depth down to the feeding zone assumed at about 720 m depth. Calculation was stopped when flashing reached the feeding zone, because then mobility in the reservoir is changed and that will affect the output from the well. The calculated well characteristic curves indicate that the maximum flow rate for the reference production test is about 80 t/h (22 kg/s) and the maximum flow rate has increased after the stimulation to possibly about 140 t/h. Some measurements were available that confirm the second characteristic curve upto 80 t/h.

During a short discharge test in July 1999 discharge rates up to 135 t/h were obtained (Sigurdsson, 1999), but there were indications that higher rates could be obtained The lip/weir box method with 4” lip pipe was used for flow rate measurements. The equipment used then performed well and the results are shown in Figure 8. They confirm the calculated characteristic curve for the evaluation production test. Overall the measurements confirm the success of the stimulation operation, indicating an output increase of 50% for well BO-4 around.

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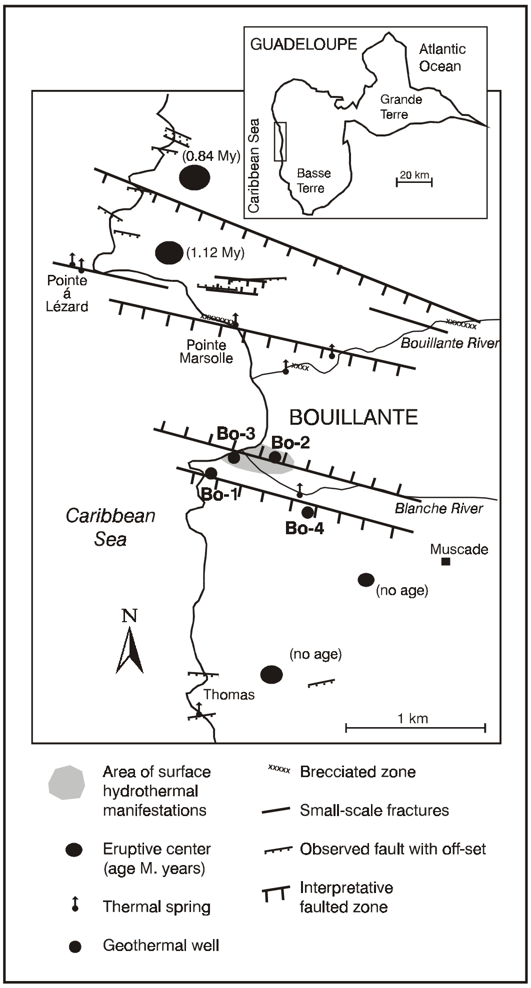

Figure 1. The Bouillant geothermal field in Guadeloupe.

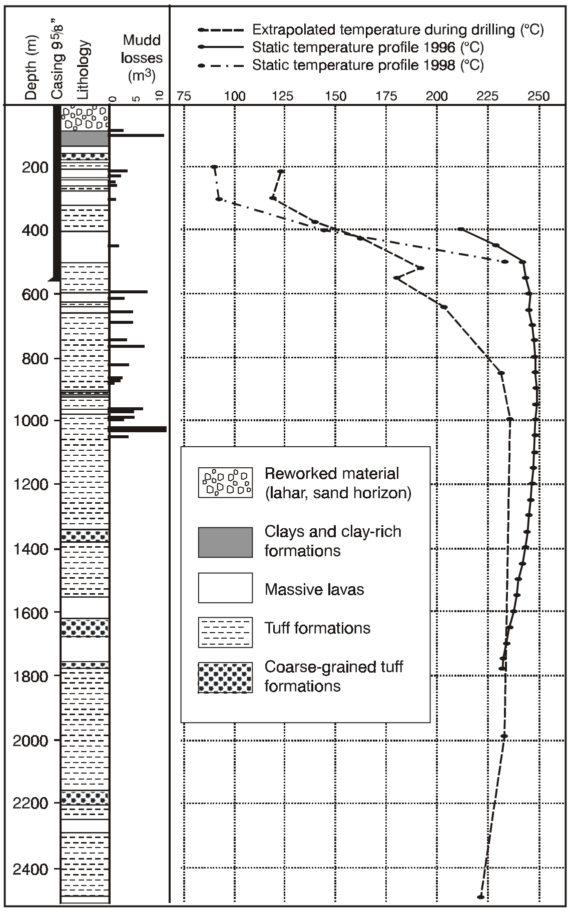

Figure 2. Simplified geologic log and static temperature for well BO-4.

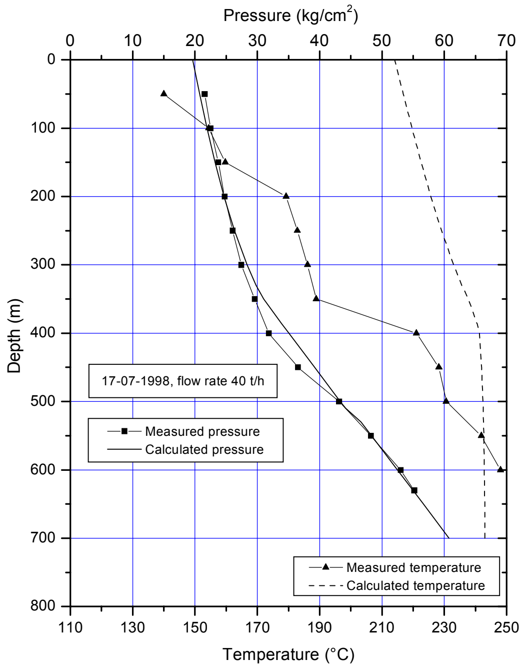

Figure 3. Dynamic pressure and temperature profiles during reference production test in BO-4.

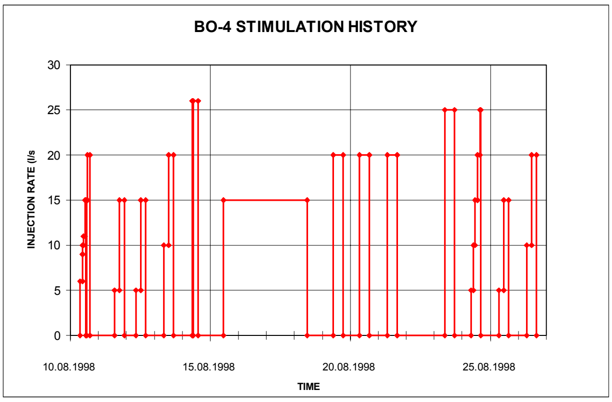

Figure 4. Injection rates during the stimulation period.

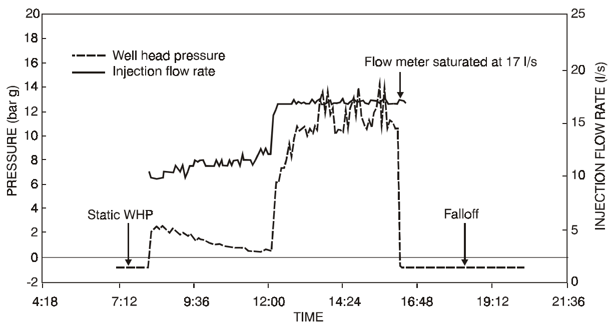

Figure 5. Sample of wellhead measurements during the injection step on August 13, 1998.

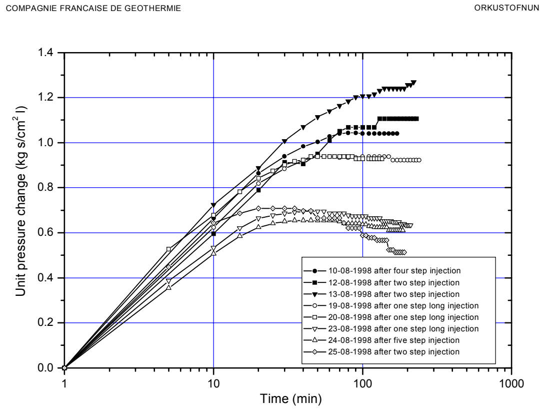

Figure 6. Unit pressure changes during pressure falloff tests at 600 m depth. The tests were made after most of the injection steps during the stimulation.

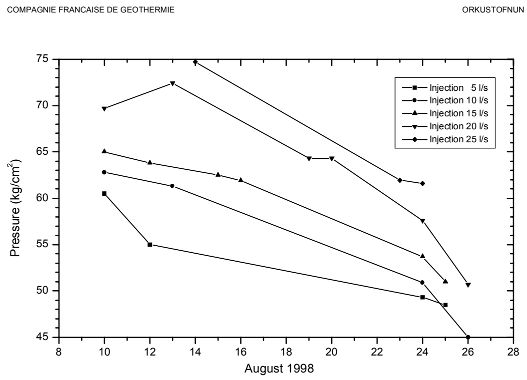

Figure 7. Pressure measured at 600 m depth at the end of the injection steps.

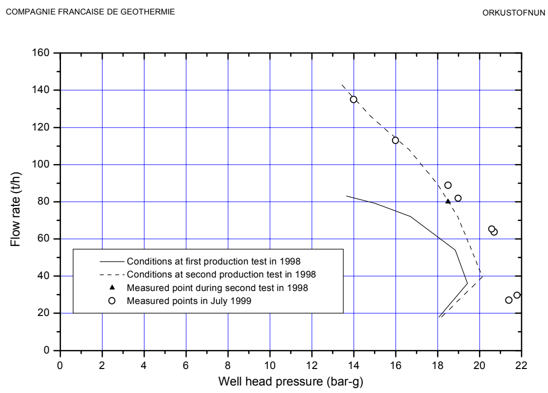

Figure 8. Calculated well characteristic curves for well BO-4 along with measured data.