

SIMULATION OF CIRCULATION TESTS AT THE HIJIORI HOT DRY ROCK WELLS

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ABSTRACT

The Hijiori hot dry rock test system was built with an injector and two producers which are connected by hydraulic fractures in two separate zones about 250 m apart in depth. Hydrothermal recovery tests were conducted by circulating water through the network for 15 days. Pressures, temperatures and rate changes were continuously measured at the wellheads, and production logs were run periodically through the tests.

In order to interpret the flow mechanism and to evaluate the efficiency of hydrothermal recovery in this system, simulation studies were conducted with a 3D model where hydraulic fractures were implemented by thin grids. Through matching the data, dynamic phenomena of the hydraulic fractures in the deep zone were necessarily simulated by a dynamic fracture growth/shrinkage option of the used simulator. For a reasonable match, areal propagation of the fractured zones was assumed in addition to linear propagation of the hydraulic fractures. Backflow through the wellbores and crossflow in formation need to be modeled appropriately for better matching of pressure behavior in the production wells.

INTRODUCTION

The Hijiori HDR field has an 11-years history of development and testing starting from 1986. A brief description of history is as follows (Previous papers are referred to for details, for instance Ikawa et al.): Well SKG-2 was fractured hydraulically at depth around 1800 m in 1986, and then well HDR-1 was drilled into the fractured zone. A water circulation test was conducted in 1988 between injector SKG-2 and producer HDR-1. After well HDR-2 was drilled into the fractured zone, the second circulation test was carried

out for 29 days in 1989 with SKG-2 as injector and HDR-1 and -2 as producers. The fourth well HDR-3 was drilled in 1990, and the third circulation test was conducted for 90 days in 1991 with SKG-2 as injector and the other 3 wells as producers. In 1992, HDR-1 was fractured hydraulically at deeper depths at around 2200 m. HDR-2 and HDR-3 were deepened (HDR-2 was side-tracked first) into the deeper fractured zone. The deeper fracture was tested for 25 days in 1995 by injecting from HDR-1 and producing from HDR-2, and -3.

The circulation test data have been analyzed by several groups. Kruger and Yamaguchi analyzed the 90-day circulation test by applying one-dimensional zonal sector models. In their simulation, cooldown behavior of bottom-hole temperatures was matched for three production wells by adjusting two major parameters, the reservoir volume and the mean fracture spacing.

Applying a model of resistance-capacitance circuit to the 90-day test system, Shiga et al. estimated the reservoir capacitance, defined as an incremental volume change in reservoir water per an incremental change in reservoir pressure, by calculating changes in reservoir storage volume caused by pressure changes. Hyodo et al. (1995, 1996) also introduced another method for calculating the reservoir fluid storage. The method is based on the best-fit exponential function for transient pressure data, from which the time constant, defined as product of capacitance and impedance (change in pressure per unit change in flow rate), is estimated.

Ikawa et al. reported in details on the 25-day circulation test conducted in 1995. Their estimation of the produced to injected volume ratio ranges from 30% to 55%, lower ratios of return at higher injection rates.

Yanagisawa et al. interpreted flow behavior during the first 4 hours of the 25-day test based on changes in water levels within the HDR-2 and -3 wellbores. They first inverted the water levels and wellhead pressures to downhole pressures at a reference depth of the shallow fracture zone, 1800 m. When HDR-2 started flowing after about 16 hours injection, downhole pressure at 800 m decreased rapidly as water temperature rose. At about 22 hours injection, downhole pressure in HDR-2 became lower than the initial reservoir pressure at 1800 m, while HDR-3 still showed higher pressure than the initial reservoir pressure. These pressure behaviors led Yanagisawa et al. to such an interpretation that water in the shallow fractured zone flowed from HDR-3 to HDR-2.

Yanagisawa and Sorimachi analyzed production logs run during the 25-day circulation test, and characterized the shallow and deep fractured zones. Their interpretation first identified 10 major fractures that are effective for flow in the shallow and deep zones, and then allocated mass flow rates to the individual fractures. They also showed that production from the deep zone increased with increasing bottom-hole pressure, while production from the shallow reservoir decreased as bottom-hole pressure increased.

In the present study, the 25-day circulation test in 1995 was analyzed by 3-dimensional hydrothermal flow models. The tested hot dry rock system consists of three deviated wells and two hydraulic fractures in different zones. 3-dimensional modeling reveals much insight into rock and fracture properties and on flow mechanism and hydrothermal recovery.

RESERVOIR DESCRIPTIONS AND TEST DATA

Wells

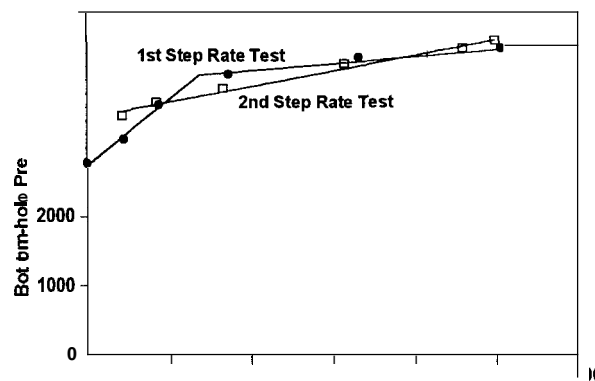
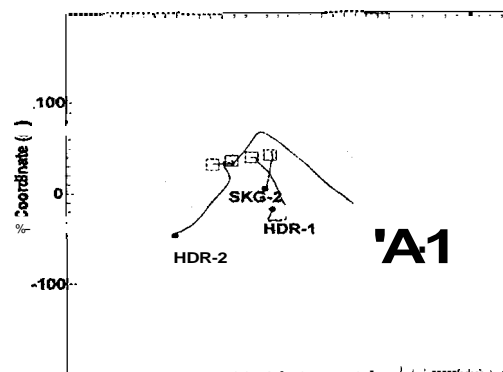
Fig. 1 shows a planview of the current geometry of the wells. The wells involved in the test, HDR-1, -2 and -3, are all deviated, as least deviated HDR-1 and most deviated HDR-3 below 1500 m. Total depths of these wells are 2205 m, 2303 m and 2303 m, respectively. HDR-1 is open-hole below 2151 m, while HDR-2 and -3 are open-hole below about 1500 m. The distances from HDR-1 to HDR-2 and to HDR-3 are about 100 m and 125 m, respectively, at depths of the deep fractured zone 2150 - 2200 m.

Hydraulic Fractures

First hydraulic fracturing was conducted for the interval 1788 m - 1802 m in SKG-2 well, and second

fracturing for the interval 2151 m - 2205 m in HDR-1. Based on well logging, oriented cores, and acoustic emissions, both fracture planes are interpreted to extend in the east-west direction, and to dip steeply (about 70 degrees) to the north.

In order to evaluate the hydraulic fracture in the deeper zone, two multiple step-rate tests were conducted, the first test on the first day and the second on the last day during the 25-day test period. Fig. 2 graphs bottom-hole pressures against injection rate. The plotted pressures are taken at the end of each rate hike. The first test shows clearly a fracture parting pressure, about 4100 psig, while the second test does not show any fracturing.



Pressure and Temperature Gradients

The pressure and temperature gradients at static conditions are estimated from well logging in HDR-1.

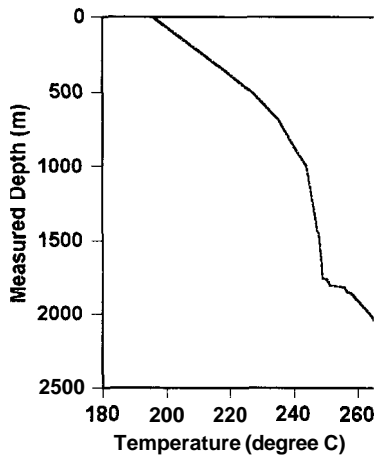


Fig. 3 Static temperature profile in HDR-1.

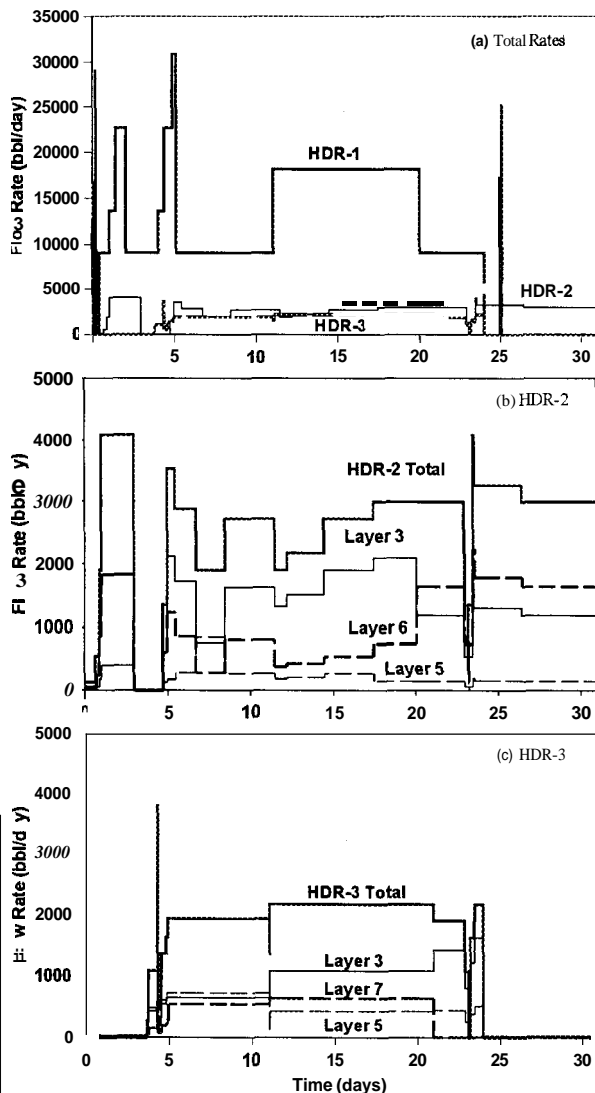


Fig. 4 Total injection and production rates, and production from the model Layers.

Static pressures follow a local hydrostatic gradient, while the temperature profile shows an anomalous increase at around 1750 m in depth as shown in Fig. 3.

Injection and Production

During 25 days of the circulation test, the injection rate was changed several times according to the test program. Step-rate tests were conducted at the beginning and end to evaluate fracture responses. The injection rate was raised up to 22600 bbl/day (41.6 kg/sec) and 30800 bbl/day (56.6 kg/sec) from a constant rate 9060 bbl/day (16.6 kg/sec) on the second and fourth days, respectively, to open up the fractures.

The constant rate was also doubled to 18100 bbl/day (33.3 kg/sec) for 9 days starting from 12th day. The total production rates of HDR-2 and -3 were maintained at the level of 3000 bbl/day (5.5 kg/sec) and 2100 bbl/day (4.5 kg/sec), respectively, but not stable most time. Fig. 4 shows the total injection and production rates of each well.

Pressures and Temperatures in Tests

Pressures and temperatures were measured at wellhead through the test. In addition, production logs were run 6 times each in HDR-2 and -3. Wellhead pressures of HDR-1 were converted to bottom-hole 2170 m by taking into account cooldown effects of formation. Bottom-hole pressures of HDR-2 and -3 were calculated by using liquid levels in wellbore measured at the beginning, and by interpolating the data obtained by production logging. Fig. 5 shows wellhead pressures and bottom-hole pressures for each well. Production logs also showed that bottom-hole temperatures of HDR-2 and -3 stayed almost constant at different depths, except at a feed point around 2170 m in HDR-2 where temperature gradually decreased from 260 °C to 220 °C (see Miyairi and Sorimachi).

SIMULATION

Model Descriptions

The reservoir was divided into 24x16x7 Cartesian grid blocks as shown in Fig. 6, where layers are numbered from bottom to top. The top depth was set to be 1486 m. Layers 3 and 6 are the deep and shallow fractured zones, respectively. The area within I=4, 21, and J=3,14 in the planview grid is the main part of the reservoir where the finest grid intervals are 10 m. HDR-1 is completed only in Layer 3, while both HDR-2 and -3 are open to formation at different grid blocks in Layers 2 through 7 as they are deviated.

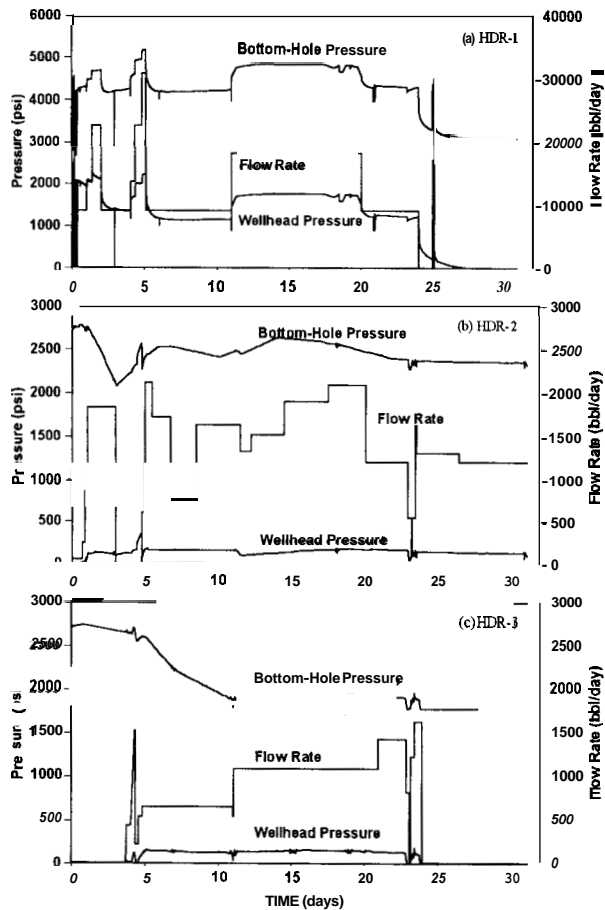


Fig. 5 The measured wellhead pressures and the converted bottom-hole pressures.

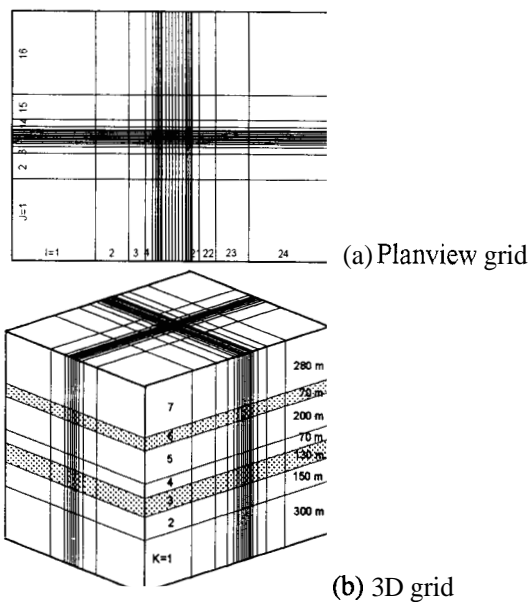


Fig. 6 3D grid for simulation studies.

Porosity is set to be 1 % for all the grid blocks. Permeability of reservoir matrix rock is set to be 0.4 md as the basic model. Hydraulic fractures in Layers 3 and 6 are modeled by the selected grid blocks of 10 m width connecting HDR-1, -2 and -3 as shown in Fig. 7 (a) and (b) where the well blocks are indicated by black. Effective permeability of the hydraulic fracture is fixed as 3000 md for the shallow zone Layer 6, while effective permeability of the fracture in the deep zone Layer 3 is treated as a matching parameter as described later. Initial values of pressure and temperature are assigned according to the pressure and temperature gradients.

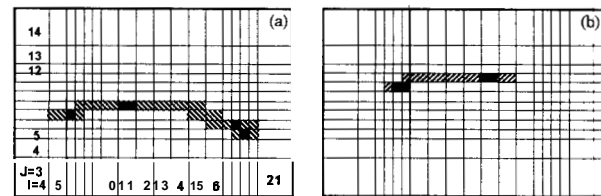


Fig. 7 Hydraulic fractures (shaded blocks) in the (a) deep and (b) shallow zones.

As HDR-1 is cased down to 2151 m, injected water flows into Layer 3 only. On the other hand, HDR-2 and -3 are open in Layers 2 through Layer 7, intersecting the shallow and deep fractured zones. The high injection pressures and the large completion intervals of the producers tend to create backflow through the wellbores. In order to effectively simulate backflow in HDR-2 and -3, the well blocks and the selected neighboring blocks were assumed highly permeable as 3000 md.

Effects of Fracture Permeabilities

Behaviors of bottom-hole pressure at HDR-1 were simulated first by assigning a fixed value to the hydraulic fracture region, as 1 md, 10 md, and 100 md. As seen in Fig. 8, bottom-hole pressures are quite sensitive to fracture permeability. The pressure responses are always lower than the measured pressures when the fracture permeability is 100 md or 10 md. When the fracture permeability is set as 1 md, the simulated pressures are lower at low injection rates, and higher at higher injection rates. These responses of the simulated pressure suggest that permeability of the fractured zone is to be lower than 1 md at lower injection rates, and to be higher than 1 md at higher rates.

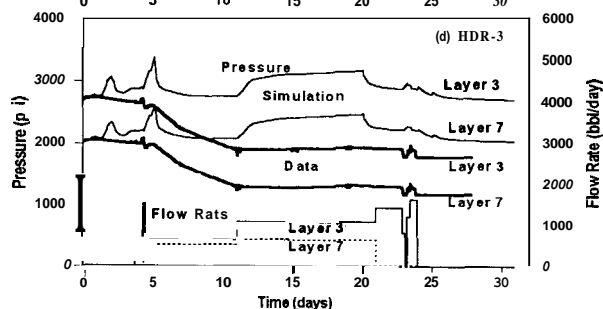
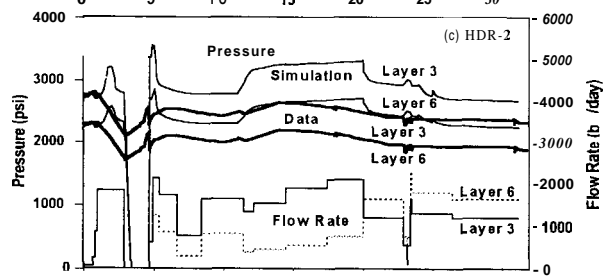
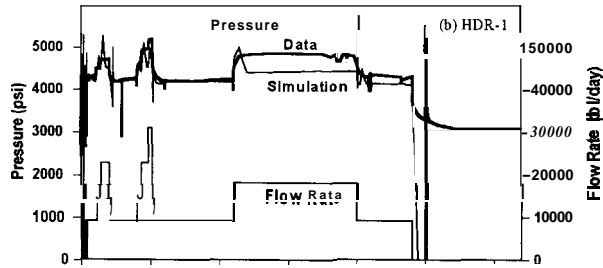
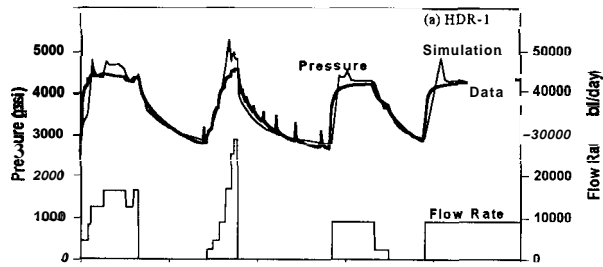
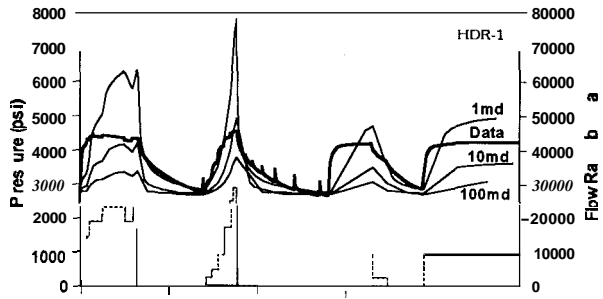


Fig. 9 Bottom-hole pressures simulated by dynamic fractures in Layer 3 as shown in Fig. 10.

Effects of Dynamic Fractures

Based on the simulation results obtained by static fracture permeability, hydraulic fractures were modeled by a dynamic fracture option of the used simulator. Permeability and porosity assignments were kept the same except for the deeper fractured zone (Layer 3). Input data for simulating dynamic behavior of hydraulic fractures are 1) a fracture opening pressure, 2) a pressure range over which fracture opens, 3) initial permeability and maximum transmissibility multiplier to be applied for fully open fracture, and 4) location of fracture. The fracture parting pressure and the pressure range are set as 3900 psig and 500 psi, respectively. The other parameters were adjusted while obtaining an acceptable match. Figs. 9 (a) and (b) show the simulated bottom-hole pressure of HDR-1 where pressures at higher rates are suppressed by opening fractures over 3900 psig within the region as shown in Fig. 10. The initial permeability was set to be 0.5 md for the innermost region connecting three wells. The permeability multiplication factor for the fractured region was 10000. Figs. 9 (c) and (d) are pressures of HDR-2 and -3, respectively, in Layers 3 and 5. Matching with the measured data is yet to be improved.

The extent of the fractured zone also affects on pressure behavior. When the hydraulic fractures are modeled by a narrow path of flow as shown in Fig. 11, bottom-hole pressures of HDR-1 tend to go up higher as seen in Fig. 12.

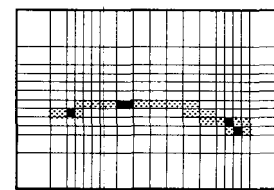
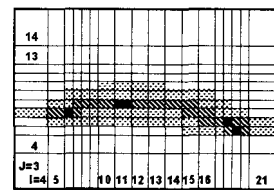


Fig. 10 Areal extension of hydraulic fractures.

Fig. 11 Linear extension of hydraulic fractures.

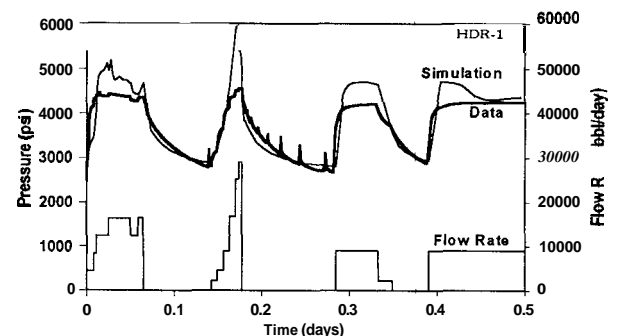


Fig. 12 Bottom-hole pressure of HDR-1 simulated by linear dynamic fractures as in Fig. 11.

Effects of Matrix Permeability

Permeability of matrix rock shows notable effects on bottom-hole pressures of both injection and production wells. If matrix permeability is increased from 0.4 md to 0.5 md, it affects on the rate of pressure rise and decline (pressure falloff) at HDR-1 as observed in Fig. 3. At the production wells, the higher matrix permeability is effective to lower steady-state pressures.

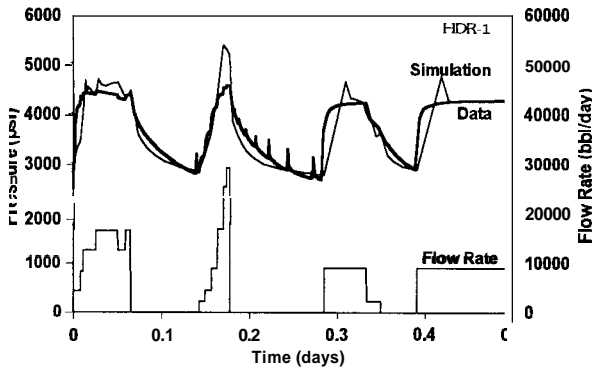


Fig. 13 Bottom-hole pressures of HDR-1 simulated by higher matrix permeability

Effects of Backflow through Wellbore

All the foregoing simulation runs were performed by models assuming conduits of high permeability along the producers. If these conduits are removed, pressures of HDR-2 and -3 in Layer 3 directly reflect high injection pressures of HDR-1 as seen in Fig. 14 (c) and (d), respectively. Pressure behavior of HDR-1 is not much affected as seen in Fig. 14 (a) and (b), though matching was changed slightly compared with Fig. 9 (a) and (b). These support existence of some effective commingle flow as backflow, though degree and mechanism of backflow through the wellbores and crossflow among layers are highly uncertain.

CONCLUSIONS

Effects of fracture permeability, dynamic fracture, matrix permeability, and backflow were evaluated through matching mainly bottom-hole pressures. Pressure behavior of the fractured well HDR-1 was effectively simulated by using a dynamic fracture option. The effective zone of the deep fractures was confirmed to extend areally. Matrix permeability affects on pressure falloff behavior of the injection well and steady-state pressures of the production wells.

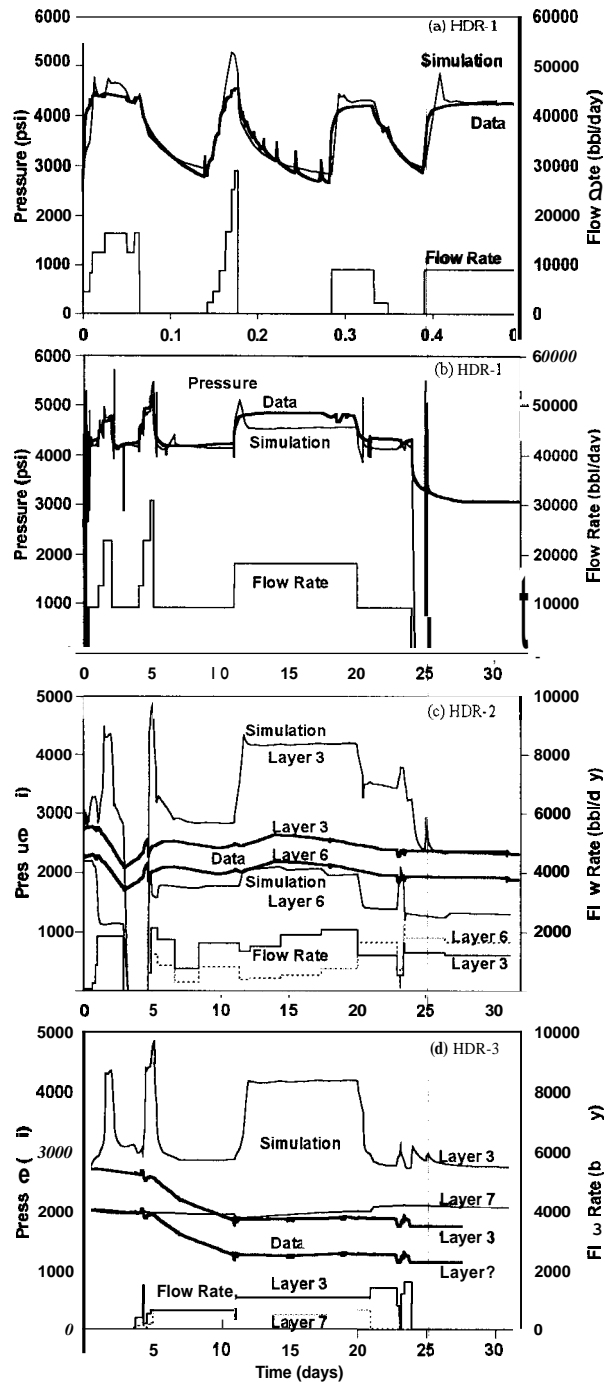


Fig. 14 Bottom-hole pressures simulated without high permeability conduit along the production wells.

The largest uncertainty is the degree of backflow through the wellbores and crossflow in formation. Backflow needs to be modeled more appropriately to attain acceptable matching of pressures of the production wells.

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