Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

NUMERICAL SIMULATION OF THE WASABIZAWA GEOTHERMAL FIELD, AKITA PREFECTURE, JAPAN

Subir Sanyal[1], Minh Pham[1], Shun Iwata[2], Masaru Suzuki[2], Tsuneshi Inoue[2], Keiichi Yamada[3] and Masao Futagoishi[4]

[1]GeothermEx, Inc., 5221 Central Avenue, Suite 201, Richmond, California 94804-5829 USA
[2]Dowa Mining Co., Ltd., 1-8-2 Marunouchi, Chiyoda-Ku, Tokyo 100-8282, Japan
[3]Dowa Engineering Co., Ltd., 5-10-5 Shinbashi, Tokyo 105-0004, Japan
[4]New Energy and Industrial Technology Development Organization, 1-1-3 Higashi Ikebukuro, Toshima-ku, Tokyo 107, Japan

Key Words: initial state, well test, forecasting, deliverability, make-up well

ABSTRACT

A numerical simulation model of the Wasabizawa field was developed based on the conceptual model developed by Dowa Mining Company. The model covers a total area of 70 km2 and extends vertically from an elevation of 700m above sea level to 1,600m below sea level. The model has 2,185 grid blocks in 9 layers. The boundary conditions and distributions of horizontal and vertical permeabilities were arrived at by trial-and-error matching of the initial temperature and pressure distributions within the field. All other hydraulic and thermal properties of the field were known from exploration, drilling, well testing and core-analysis results. Observed and calculated temperature and pressure distributions were well-matched, confirming the validity of the conceptual model and providing the first stage of calibration of the numerical model. This effort yielded credible estimates of the locations and rates of fluid recharge and discharge in the initial state. In the second stage of calibration, long-term well test data and downhole pressure records from observation wells were matched by trial-and-error. In addition, the wellbore characteristics were calibrated against available data using wellbore simulation. This well test matching effort yielded excellent results, further confirming the model's validity and refining its calibration.

Forecasting shows that the field can easily sustain a power generation level of 30 MW with eight production and eight injection wells. Assuming that the productivity of new wells to be drilled lies between that observed in wells WZ-7 and WZ-9 (the two currently available production wells), a make-up well would be needed after 5.4 years, followed by one every six years. If the new wells were assumed to be closer in productivity to the more productive existing well, only one make-up well was needed at year 25 to maintain the required steam rate for a 30 MW plant. For a generation level of 40 MW, a total of 10 production and 10 injection wells are needed initially and one make-up well would be needed every 2.5 to 3 years.

1. INTRODUCTION

Wasabizawa geothermal field is located in Akita Prefecture on the island of Honshu in Japan. The field has been explored and drilled by Dowa Mining Company, Ltd. with support from NEDO (New Energy Development Organization). Several exploration wells and two production wells (WZ-7 and WZ-9) have been drilled to date. Based on a conceptual model developed by Dowa, a numerical model was developed in three stages: 1) initial-state modeling; 2) matching of the well test data; and 3) forecasting of reservoir behavior and make-up well requirements for generation levels of 30 and 40 MW. The simulation code TOUGH2, originally developed at Lawrence Berkeley National Laboratory and subsequently modified and improved by GeothermEx, was used for this effort. This simulator uses an integrated finite-difference (IFD) formulation and can handle transient and non-isothermal flow of water, steam and CO_2 gas in three dimensions.

2. INITIAL STATE MODELING

The simulation model for the Wasabizawa field (Figure 1) is oriented in a NW-SE direction, and includes a total area of 70 km2 (10 km in the NW - SE direction and 7 km in the SW - NE direction), which is much larger than the geothermal project area. The large area is required to ensure a reasonable representation of the overall geological framework of the geothermal system and to reduce the effects of the boundary conditions on the simulation model. Vertically, the model extends from an elevation of +700 m msl (mean sea level) to -1,600 m msl. The overall thickness of 2,300 m is subdivided into nine layers. The first two layers are each 300 m thick; the next five layers have uniform thickness of 200 m each; the next layer is 300 m thick; and the last layer has a thickness of 400 m. The number of gridblocks in each of the layers is not uniform. In areas where detailed reservoir information is available, the network of gridblocks is finer. Additionally, regions of higher potential productivity are modeled in more detail than non-productive areas. The total number of grid blocks in the model is 2,185.

In trial-and-error matching of the initial state, eighteen boundary blocks had to be added to define the heat and mass inflow and outflow from the model (Figure 1). These included: 1) a block attached to part of the SW edge of layers 2, 3 and 4 to represent subsurface discharge that ultimately gives rise to the Akinomiya hot springs; 2) a block attached to three blocks on the NE edge of layer 7 to allow deep discharge toward well YO-2; 3) a block attached to the SE corner of the bottom of layer 9 to supply heat and mass recharge; 4) nine blocks attached to the bottom of layer 9 to provide conductive heat transfer from below; 5) a block attached to the top of the southern part of layer 1 to allow heat dissipation to the cap rock at a constant temperature of 30°C; 6) a block attached to the top of the northern part of layer 1 to allow for heat dissipation to the rock at a temperature of 20°C; and 7) a block attached to the top of the model that allows for conductive heat loss to a constant atmospheric temperature of 10°C.

As shown in the example provided for layer 7 (Figure 2), the observed and calculated temperature distributions in each of the 9 layers of the model were matched satisfactorily by trial-and-error. The final permeabilities in the various parts of the reservoir ranged from 0.1x10-15 m^2 to 0.1x10-13 m^2. These values are consistent with the results from the analysis of well test data, which indicated that the intrinsic permeability of the Wasabizawa geothermal field is relatively low.

Using the heat and mass recharge sources and discharge sinks described above, it was found after many iterations that an inflow rate of 31.8 kg/s was required at the SE side of layer 9; the inflowing fluid is single-phase at a source temperature of 315°C. The subsurface discharge from the model is split among sinks located along the SW side of layers 2, 3 and 4. Deep subsurface discharge is also assumed to occur at layer 7 with the fluid going towards well YO-2 (Figure 1). The total rate of discharge from layers 2, 3, and 4 is 12.3 kg/s which is assumed to end up at the surface in the Akinomiya hot springs area. The remaining subsurface discharge of 19.5 kg/s is assumed to go toward the well YO-2 area.

3. WELL TEST DATA MATCHING

Initial state modeling allows the development of a mathematical model that represents the overall fluid and heat flow patterns in the geothermal system, establishing the general permeability distribution and locations and strengths of sources and sinks. The results from the initial-state modeling do not, however, provide detailed information on the local petrophysical parameters at and near the wells. These parameters are ascertained by matching the well test data, which is the next step in verifying and calibrating the numerical model. The well test data of most interest are enthalpy transients observed in the production wells during flow and downhole pressure response measured in the observation wells.

Before well test data matching, the production characteristics of the three production wells were defined and verified by numerical wellbore simulation. In modeling well WZ-9, a casing roughness value of 0.0056 e/d and a liner roughness value of 0.00008 e/d were used to match the temperature and pressure profiles taken in the wells under flowing condition. The low roughness value used for the liner is an indication that there may be some flow up the back side of the liner. Flow behind the liner would increase the effective diameter of this section of the wellbore, thereby reducing the pressure drop. Overall, an excellent match of the observed downhole flowing pressure and temperature data was obtained, as shown in Figure 3 for well WZ-9.

Pressure and temperature values indicate that two-phase conditions are present in the wellbore from the surface down through the main production zone (Figure 4). Wellbore modeling indicates that these two-phase conditions are also present in the near-wellbore area. Therefore, a non-linear inflow performance relationship was used to match the observed flow rate and wellhead data. The deliverability curve thus developed for WZ-9 is shown in Figure 5. At an average flow rate of 170 t/hr, the productivity index for this well is 3.74 (t/hr)/ksc. Similar analyses were conducted for the other two production wells.

To simulate the enthalpy transients due to production from wells WZ-6, WZ-7, and WZ-9, the total flow rate histories from these wells were input and the model was run for the duration of the test. The enthalpy transients obtained from the model were then compared to the observed enthalpy history. In addition to the enthalpy transients, pressure responses from the observation wells WZ-1, WZ-2, WZ-3, WZ-5, and the production wells WZ-6, WZ-7, and WZ-9 were also compared with the calculated responses from the numerical model.

Reasonable matches between the measured and calculated enthalpy histories were obtained, by trial-and-error, for production wells WZ-6 and WZ-9. The injection and production history of well WZ-7, however, was different from the other two producers. Near the end of May 1997, well WZ-7 was used as an injection well for about two months. Later on in August, well WZ-7 was flow tested at a production rate ranging from 45 to 100 t/h. To properly model the effect of the cool injection fluid on fluid enthalpy observed during the subsequent flow test, a special grid block arrangement has been devised for this well to match the complicated enthalpy transients (Figure 6).

A total of five concentric grid blocks, each containing matrix and fracture blocks, were created within the rectangular block. The matrix block is connected with two other neighboring matrix blocks while the fracture blocks are connected to two neighboring fracture blocks and one matrix block. This complicated arrangement, reflecting the impact of isolated, near-wellbore fractures on enthalpy transients, was necessary for the matching of the enthalpy trend in WZ-7. At the end of the injection period, the injection fluid has cooled the bottom hole of WZ-7, but the cooling effect is not uniform. As fluid moves through the fracture, the temperature of the fracture would approach the injection fluid temperature; however, the reservoir rock adjacent to the fracture has not been cooled as much. Consequently, when the well was flow tested, the fluid enthalpy rise was more rapid than would be expected for a homogenous reservoir due to the heating of the fluid by heat conduction from the reservoir rock matrix, which had not cooled as much as the fracture. The grid block arrangement shown in Figure 6 allows for such a process to be modeled.

In addition to the enthalpy trends, downhole pressure data from all the observation wells have been used to further calibrate the numerical model. Downhole pressure data are available for seven wells, including the three production wells. Very good agreement between calculated and measured pressure data was also achieved for all wells by trial-and-error; the matches for wells WZ-5, WZ-6, WZ-7, and WZ-9 are shown in Figure 7. The shape of the measured pressure trends has been closely matched for all the wells. The smoother appearance of the calculated pressure trends is due to the damping effects inherent in the discretized nature of numerical modeling.

The results from matching the flow test data from the Wasabizawa project area are considered to be very good. The model was able to accurately simulate the production enthalpies of the available production wells, WZ-6, WZ-7 and WZ-9, and the pressure response from all production and observation wells. The model was considered to be calibrated adequately, and suitable for forecasting reservoir behavior.

4. FORECASTING OF RESERVOIR BEHAVIOR

4.1 Forecasting Procedure Used

Forecasts were made under two basic scenarios of development: 30 MW - Scenario II; and 40 MW - Scenario III. Scenario I was abandoned in the early stages of this study. For each scenario, the required steam production rate was specified in conjunction with a specified deliverability curve for the average well defined based on well test data from WZ-7 and WZ-9. For Scenario IIA (30 MW), the initial deliverability curve for the average well was assumed to lie halfway between the curves for WZ-7 and WZ-9. For Scenarios IIB (30 MW) and III (40 MW), the initial deliverability curve for the average well was assumed to lie closer to that of WZ-9 than that of WZ-7 (Figure 9). From the selected deliverability curve and the average initial production enthalpy, the number of wells required to supply the plant was estimated. The proposed locations of the production and injection wells were then specified within the model; for example, Figure 8 shows the locations of production and injection wells (including make-up production and injection wells) in layer 7 for Scenario IIB. The predicted flowing bottomhole pressure and enthalpy decline trends for the individual wells were averaged to define field-wide enthalpy and pressure decline trends.

The results of forecasting show that the production enthalpy of an average well remains fairly constant over a 30-year project life. This implies that the total production rate required to supply a given steam rate to the plant would not change significantly with time; therefore, a short-cut approach could be used for forecasting make-up well requirement. A limiting deliverability curve was defined corresponding to the minimum required production rate per well for the given plant size and the minimum required wellhead pressure of 9 ksca. The latter allows up to 2 ksc pressure drop between the well and the turbine, which requires steam delivery at approximately 7 ksca. Then an estimate was made of the difference in the maximum discharge pressure (that is, wellhead pressure at zero flow rate) between the initial deliverability curve and the limiting deliverability curve. This difference is the amount of pressure decline allowable in the well block before the average well fails to supply the minimum required flow rate, and therefore, a make-up well needs to be drilled. The time needed for this amount of pressure decline is estimated from the pressure decline trend for the average well predicted from simulation.

Once the timing for the first make-up well is determined, the location of the make-up well and the average production rate for the wells (original and make-up) are specified again. The location of any make-up injection well and the average injection rate for the wells (original and make-up) are also specified. Then the forecast is re-run using the specified steam production rate. The above steps are repeated to estimate the timing of the second make-up well, and so throughout the life of the project.

For example, for scenario IIB, an average initial deliverability curve (lying between the deliverability curves for WZ-7 and WZ-9, but closer to the WZ-9 curve) was assumed (Figure 9). This curve indicates that each well is capable of producing approximately 155 t/h of total flow (steam plus water) at the minimum required wellhead pressure of 9 ksca. For a 30 MW plant, the required steam rate was estimated at 252 t/h. At the average initial enthalpy of the wells, this implies a total production rate of 900 t/h. As suggested by Dowa, 8 production wells were assumed for this scenario. The total production capacity of 8 wells at the average rate of 155 t/h was 1240 t/h, or 340 t/h higher than the required minimum rate of 900 t/h to run the 30 MW plant. Thus, eight initial production wells were more than adequate for 30 MW. To supply the required 900 t/h for the 30 MW plant, each of the 8 wells was assumed to produce 112.5 t/h.

The eight production wells and eight injection wells were then located as suggested by Dowa within the model. For example, Figure 8 shows the wells completed in layer 7. The model was run then under the specified steam production requirement and the pressure decline trend for the average well was calculated (Figure 10) from the pressure decline trends for individual wells. As field pressure declines due to production, the well deliverability curve also changes such that at any given wellhead pressure, the average well produces at a lower rate. Since each well must produce at least 112.5 t/h, the limiting deliverability curve must pass through the point in Figure 11 where the 9 ksca line intersects with the 112.5 t/h line. The limiting deliverability curve was drawn parallel to the initial deliverability curve and passing through this intersection point.

The difference between the maximum discharge pressures of the initial and limiting deliverability curves was estimated by approximately extending both curves to intersect the wellhead pressure axis; this difference (the maximum allowable pressure drop) was about 7.3 ksc in this case (Figure 11). To estimate the timing of the first make-up well, the maximum allowable pressure drop (7.3 ksc) was divided by the initial average pressure decline rate of wells for Scenario IIB (Figure 10). At the observed rate of pressure decline (about 0.56 ksc per year), a total pressure decline of 7.3 ksca would occur after 13 years from start-up. Therefore, the first make-up well was considered necessary after 13 years from start up.

The forecast under Scenario IIB was then re-run with the addition of a make-up production well, WB-6, and a make-up injection well, WH-4 (Figure 8), using the deliverability curve for the average well (including both the original wells and the make-up well) being as shown in Figure 9. The results of this new run provided the forecast of the individual well parameters, from which the field-wide average well parameters were calculated.

4.2 Forecast Results

The forecasting from simulation suggests that the Wasabizawa field can easily sustain a power generation level of 30 MW with the initial use of eight production wells and eight injection wells. If the wells are halfway between WZ-7 and WZ-9 in productivity, the first make-up well is needed at 5.4 years, followed by one every six years (Figure 12). If the wells are closer in productivity to WZ-9 than WZ-7 as shown in Figure 9, only one make-up well is needed at year 13 and another make-up well at year 25 to maintain the required steam rate for a 30 MW plant (Figure 10). For each make-up production well, the need for a make-up injection well is assumed. Table 1 summarizes the forecast results.

For a generation level of 40 MW, 10 production wells and 10 injection wells are initially required. If the wells are closer in deliverability to WZ-9 than WZ-7 (Figure 9), one make-up well is needed every 2.5 to 3 years to maintain the power production rate. Again, for each make-up production well, the need for a make-up injection well is assumed.

ACKNOWLEDGEMENTS

The authors thank Dowa Mining Company for permission to publish this paper and greatly appreciate the valuable help of Dowa in the course of this work. We also thank Dr. W.L. (Bill) Smith of Northern California Power Agency (NCPA) for providing a very useful review of this paper.

Table 1: Summary of Forecast Results

Scenario	Well Deliverability (t/h of total flow)	Initial Number of Production Wells	Initial Number of Injection Wells	Number of Make-Up Wells	Total Number of Wells During Project Life
IIA (30 MW)	125	8	8	6	22
IIB (30 MW)	155	8	8	4	20
III (40 MW)	155	10	10	22	42

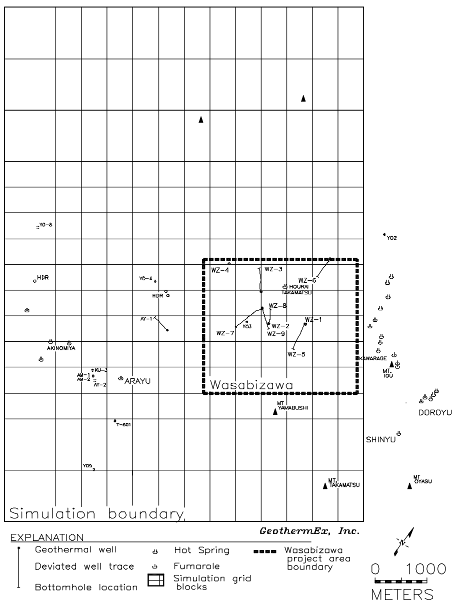

Figure 1. Well location map showing simulation grid

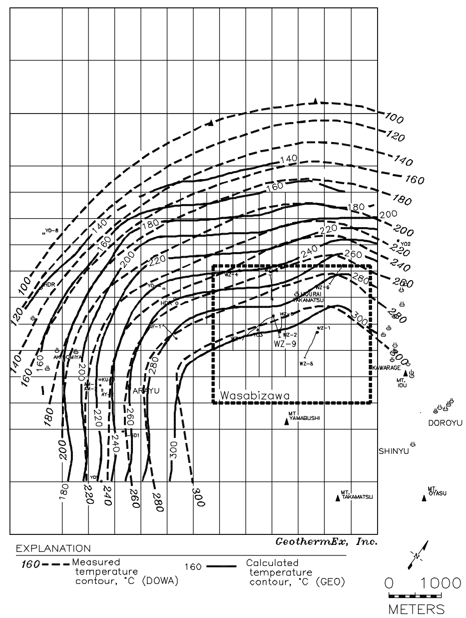

Figure 2. Measured and calculated temperature contours, layer 7, -500m (msl)

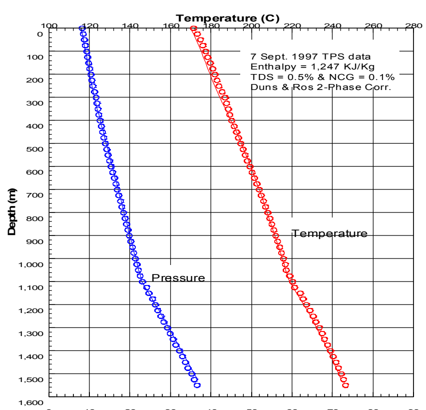

Figure 3. PTS matching of Wasabizawa well WZ-9

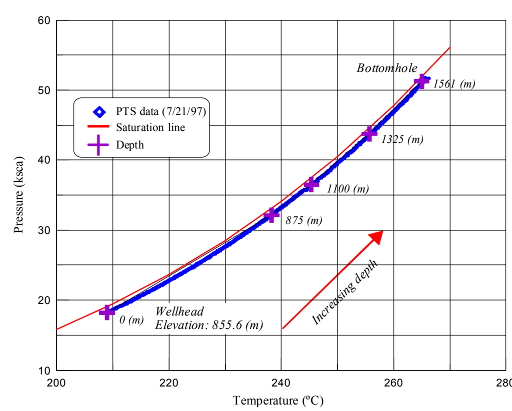

Figure 4. Steam condition along the wellbore from production PTS, well WZ-9

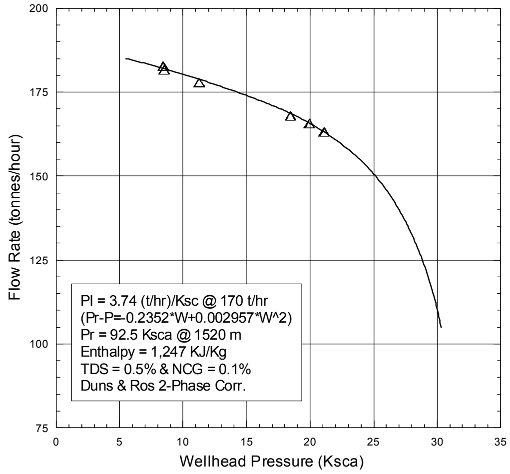

Figure 5. Deliverability matching using wellbore, simulation Wasabizawa well WZ-9

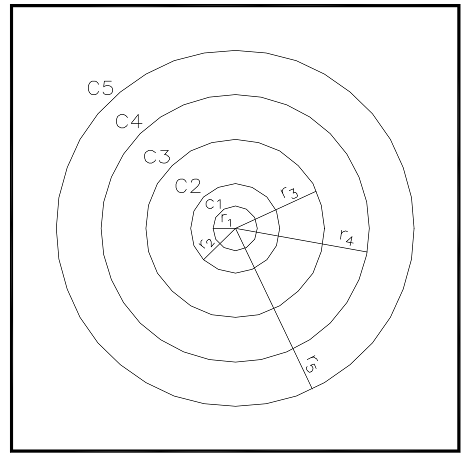

Figure 6. Special grid block arrangement for well WZ-7

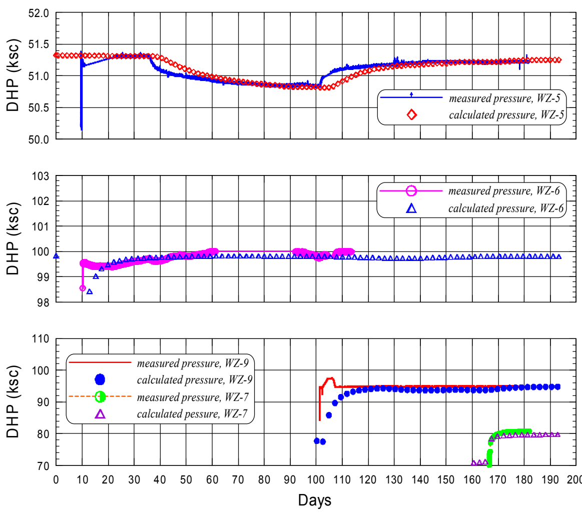

Figure 7. Observed well pressure data wells WZ-5, Wz-6, WZ-7, and WZ-9

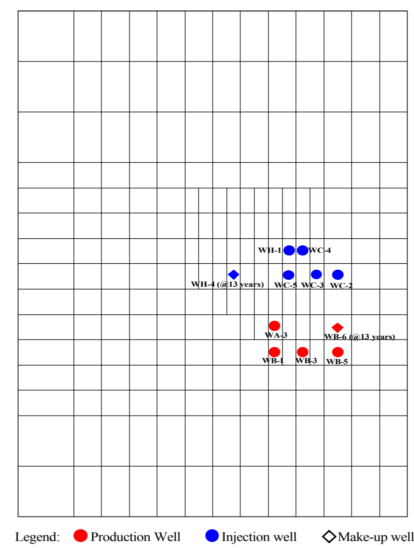

Figure 8. Placement of wells for scenario IIB at –800 m, msl, layer 7

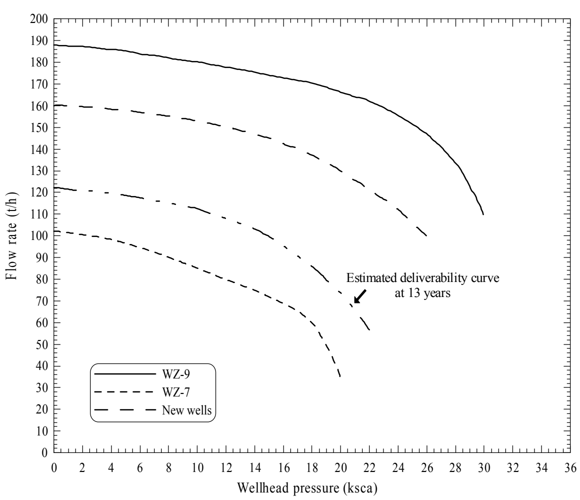

Figure 9: Deliverability curves used with 8 initial wells, scenario IIB

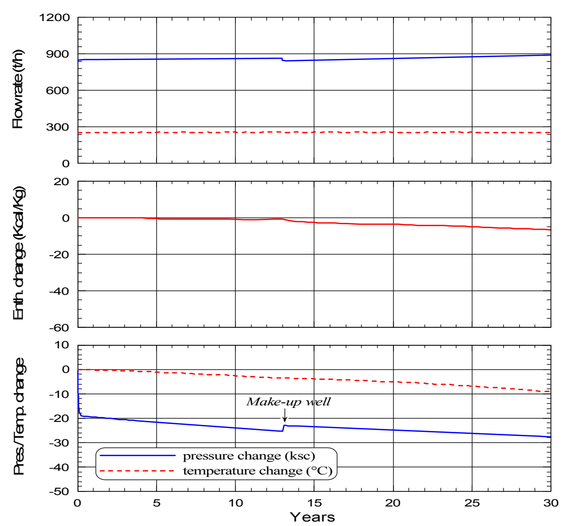

Figure 10: Fieldwide production parameters forecast, scenario IIB

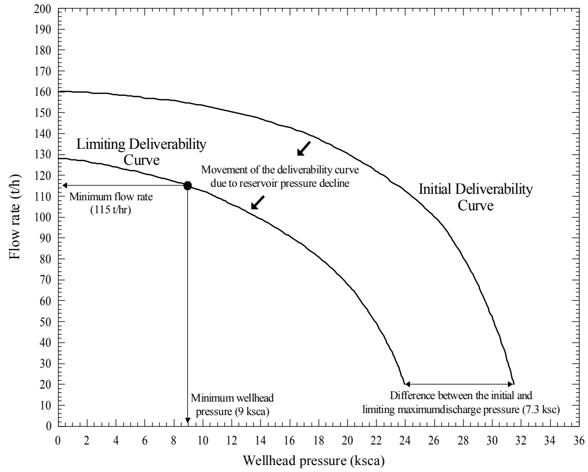

Figure 11: Illustration of concepts associated with the use of deliverability curves

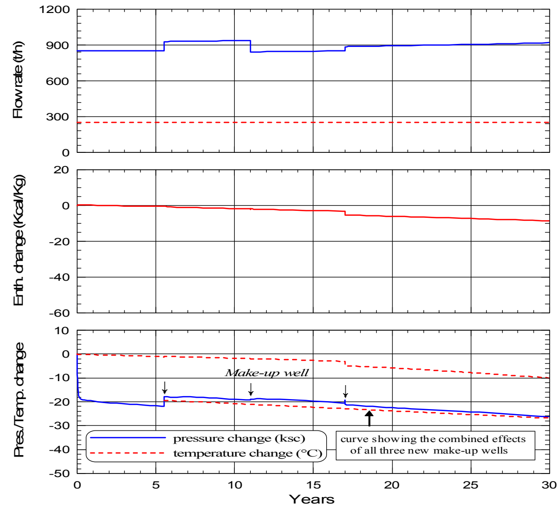

Figure 12: Fieldwide production parameters forecast, scenario IIA