DEVELOPMENT STRATEGY FOR THE BULALO GEOTHERMAL FIELD, PHILIPPINES

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1. ABSTRACT

All of the brine and condensate produced in the Bulalo geothermal field has been injected since 1979, when the first two 55 MWe power plants came on-line. However, in 1989 the return of the cool injectate to the reservoir caused well productivity declines in the western part of the field. Between 1989 and early 1992, injection wells were drilled further from production wells to mitigate this problem. Numerical reservoir simulation validated this development strategy, and well productivity improved rapidly after injection was moved. Based on the predicted field performance, acceleration of production through capacity additions was shown to be feasible. In 1994, binary units comprising 16 MWe were installed, utilizing waste brine that was previously injected directly to the reservoir. Modular units consisting of 40 MWe baseload capacity and 40 W e standby capacity will begin operation in 1995-96. After the planned additions, Bulalo's installed capacity will be 426 MWe, making it the second largest liquid-dominated field in the world.

2. INTRODUCTION

Bulalo geothermal field is located about 70 km southeast of Manila on the island of Luzon (Figure 1, inset). The field is adjacent to Mt. Bulalo, a 0.5 Ma dacite dome on the SE flank of Mt. Makiling, a Quaternary volcanic center (Figure 1). The field was discovered by Philippine Geothermal, Inc (PGI), which is under contract to the National Power Corporation (NPC) of the Philippine government. The discovery well was drilled in 1974, and commercial production began in 1979 with an installed plant capacity of 110 MWe. This was increased to 220 MWe in 1980, and 330 MWe in 1984; binary units totaling 15.73 MWe were installed in early 1994. In 1993, the Bulalo power plants generated about 14% of the electricity demand of Luzon (Sussman et al., 1993).

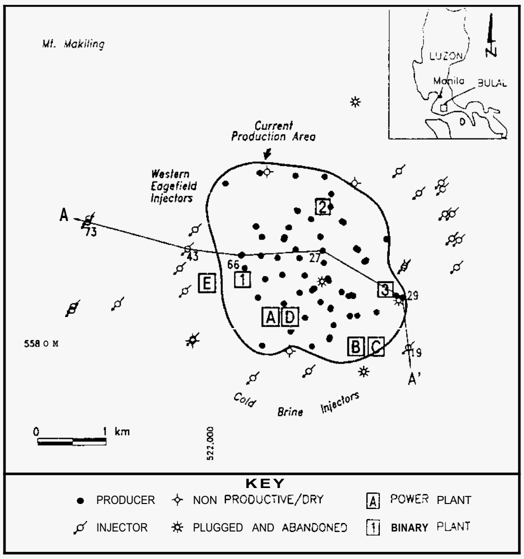

Figure 1. Map of Bulalo field showing production and injection wells. Inset shows field location. Power plants shown are A-C (existing), D-E (planned) and 1-3 (binary).

Commercial scale geothermal brine injection in the Philippines was pioneered at Bulalo. From the start of geothermal operations in 1974 (including the flowtests of the exploration wells) all of the produced brine has been injected back into the reservoir; about 60% of the total mass produced plus steam condensate from the power plants is currently injected. However, by 1988 the injection program was adversely affecting the productivity of certain wells. Thermal breakthrough caused rapid declines in steam production and increased brine production. It was clear that a new injection strategy was necessary.

3. RESERVOIR DESCRIPTION

The Bulalo reservoir is a liquid-dominated, fracture-controlled hydrothermal system. The productive reservoir is approximately 7 km^2 and is roughly circular in plan view. The reservoir is bounded by hot, low-permeability rocks to the east and south, and by lower temperature rocks to the west (Clemente and Villadolid-Abrigo, 1993). Partially open boundaries have been identified on the north and west; the undrilled northwestern boundary is not known. The top of the reservoir occurs between 100 m and 1250 m below sea level (bsl). It is shallowest near the center, deepens gradually to the west (Figure 2) and north, and deepens abruptly to the east and south. Upflow occurs in the central SE part of the reservoir. A porous volcanic tuff unit (Figure 2) provides an important fluid flowpath at the reservoir top; the bottom of the reservoir is unknown. The reservoir fluid is a neutral-pH sodium chloride liquid with low total dissolved solids and low gas content relative to other geothermal systems in the Philippines. The fluid salinity is also low, with an average Cl concentration of 2800 mg/kg. The average reservoir temperature is 280°C, and the maximum temperature is around 300°C in the southeast sector of the field.

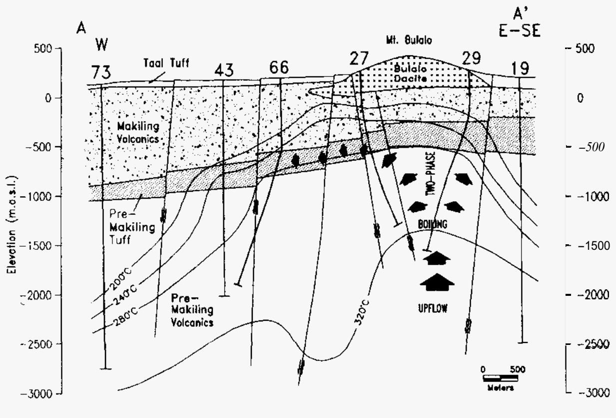

Figure 2. Cross-section A-A' through Bulalo reservoir showing isotherms and inferred fluid flow regime. Simplified lithologic units are also shown.

As of 1994, 97 wells have been drilled throughout the field. Of these, 65 are production wells, 23 are injection wells, and the remaining nine are either exploration, non-producing, or plugged and abandoned wells. The deepest well has a measured depth of 3,625 m while the shallowest is 655 m. The average well depth is 2,025 m.

In September, 1994 the average total mass flow rate was 1095 kg/s with an average steam fraction of 56% at 1.2 MPa separation pressure. Production wells produce two-phase fluids with discharge enthalpies ranging from 1,400 to 2,600 kJ/kg. The average steam production per well is about 16 kg/s at commercial wellhead pressures (typically 1.0 to 1.2 MPag). Some wells are capable of producing at rates greater than 25 kg/s steam. Since 1979, the well steam flow capacity has declined at about 3.5% per year (Strobel, 1993).

4. RESOURCE MANAGEMENT

4.1 Description of the Injection System

The injection system in Bulalo consists of two sub-systems, the hot and cold brine systems. The hot brine injection system disposes of 177°C flashed brine discharged from the separators (135°C downstream of the binary plants). The cold injection system handles mainly steam condensate and cooling tower blowdown. With the field now generating 346 MWe, the hot brine and steam condensate injection rates are about 2.5 million kg/h and 0.5 million kg/h, respectively.

The cold water injection wells are located along the south margin of the field (Figure 3). The formation penetrated by the wells in this area is hot but has low permeability. The initial injectivity of the wells was poor, but significant improvement has been observed through time. This phenomenon has been attributed to hydro-fracturing as the cold water interacts with the hot formation. Although the cold water injectors are located very near the production area (Figure 3), cold water injection has not been detrimental to production. This could be due to the lower injection rate in the southern injectors, or suggest that this area is hydrologically isolated from the reservoir. The hot brine injection wells are located west, east, and northeast of the field, generally within two kilometers of the reservoir. The injection pipeline system has a high degree of flexibility so that hot brine coming from any part of the field can be injected in any combination of the three areas.

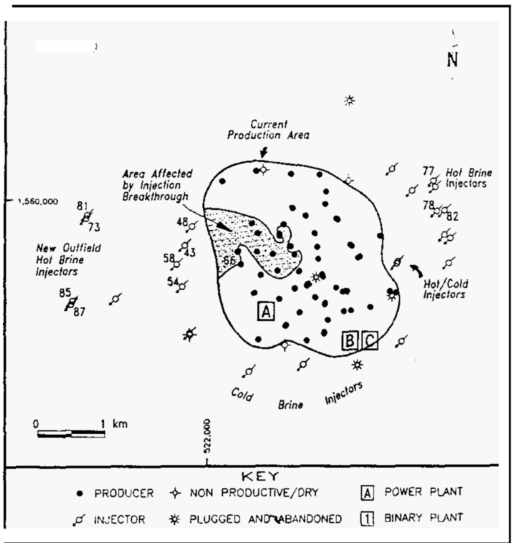

Figure 3. Extent of injection breakthrough in western Bulalo. The new western outfield and northeastern injectors are also shown.

4.2 Evolution of the Injection System

In the course of developing Bulalo, some exploration and delineation wells turned out to be poor producers. Several sub-commercial producers drilled on the periphery of the field were used for injection. In particular, four wells drilled near the western edge of the producing field between 1979 and 1980 were initially used for hot brine injection. These wells are Bul-43, -48, -54, and -58 (Figure 3); collectively they are called the "western edgefield injectors." These wells intersected the margin of the productive reservoir but were poor producers with sub-commercial wellhead pressures. As injectors, each well can accept more than 0.5 million kg/h of waste brine, and together these four wells are capable of accepting about two-thirds of the field's total hot brine production.

Eight years after the power plants were started, injected brine was detected during routine geochemical monitoring in seven production wells near the western boundary of the field This observation was verified by tracer tests, and the rapid decrease in productivity and enthalpy of the affected wells. Figure 3 shows the area affected by injection breakthrough. The first production well to show a significant response was Bul-66 (Figure 3). Chemical, thermal, and production changes in this well are shown in Figure 4, along with the injection history of the western edgefield injectors. Rapid increases in Cl concentration in Bul-66 were followed about six months later by thermal breakthrough and steam rate declines. Steam declines in the seven affected wells caused a maximum loss of 13 MWe starting in 1989.

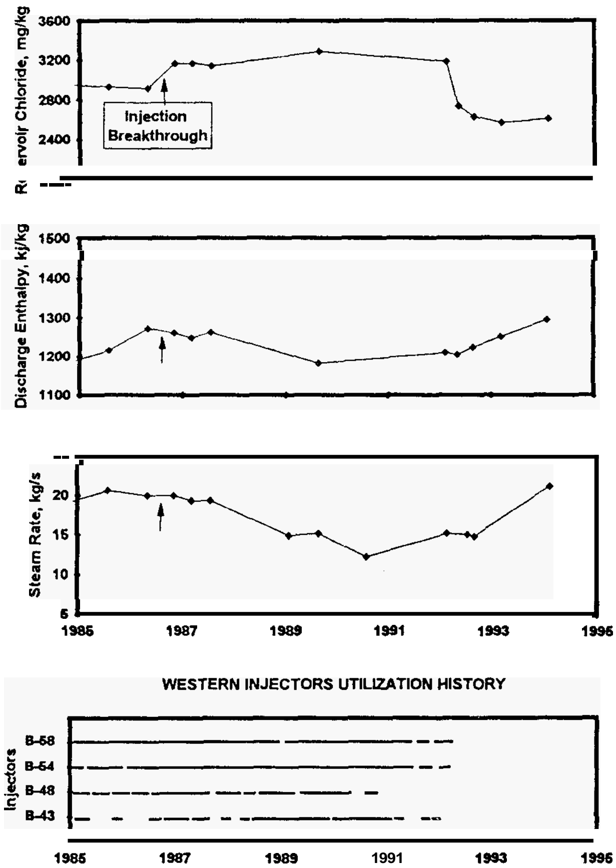

Figure 4. Chemical, thermal and production changes in **Bulalo-66.**

Injection breakthrough on a smaller scale also developed on the eastern side of the field (see Figure 6 in Villadolid, 1991). Two sub-commercial production wells used as hot brine injectors caused productivity declines of the neighboring wells. However, this problem was easily solved by promptly stopping injection into that area. The same is not true for the western edgefield injectors. In order to stop injecting the large volume of brine into the western edgefield injectors, about 2 million kg/h of new injection capacity had to be developed. PGI decided to drill four new, deeper injection wells further to the west (Bul-73,-81,-85, and -87), and three injectors northeast of the field (Bul-77, -78, and -82; Figure 3); seven outfield injectors were required to replace the four infield ones due to the lower permeability rocks encountered farther from the reservoir. As new injection capacity was developed, injection into the western edgefield wells was gradually reduced, and then terminated in 1992. Most of the affected production wells showed a rapid decline in chloride concentration after injection was terminated in Bul-43 and -48. Bul-66 demonstrated a dramatic thermal recovery and a steam rate increase of 80% about 18 months after shutting in those two injection wells (Figure 4).

4.3 Reservoir Simulation: Realized and Anticipated Benefits

A conceptual model of the Bulalo reservoir was established in 1989 (Strobel, 1991). This model was input to a numerical model to predict reservoir response to changes in development. Predictive runs were made for the following cases: 1) not relocating injection, and 2) relocating injection wells further from productive wells (Strobel, 1991). Simulation results showed that by relocating injection to western outfield areas and to the NE, fewer production and injection wells would be needed for full field development. To maintain a generation capacity of 330 MWe up to year 2015, 10 fewer production wells would be required than planned. The model showed that relocating injection would stabilize enthalpy, thereby reducing the waste brine by 2.5 million kg/h at the end of 20 years. This would eliminate the cost of 11 additional injection wells. A more immediate benefit was the productivity recovery of the wells previously affected by injection. The increased steam deliverability and enthalpy obviated the need for new production wells in 1993-94.

The predicted field performance also suggested it was feasible to accelerate production through capacity additions. The model and results were published by Strobel (1993).

4.3 Ongoing and Future Developments

In 1994, 15.73 MWe generating capacity from binary units were installed. The binary units extract additional heat from the flashed brine before it is injected. A pH modification system ensures that the injection system is safeguarded against silica scaling.

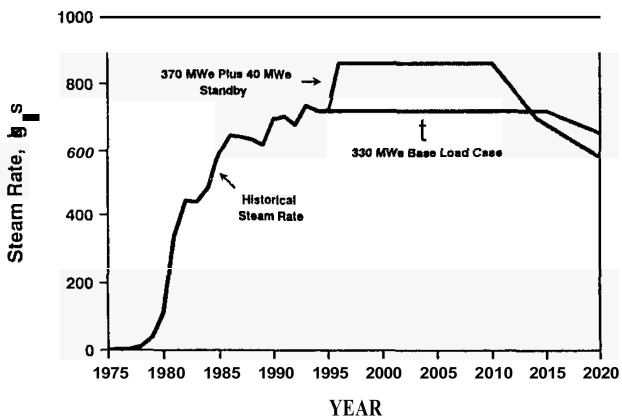

Figure 5. Bulalo steam supply prediction showing the expected production effects due to planned acceleration projects.

Additional generation capacity is planned based on the results of reservoir simulation, as discussed above. By 1995-96, modular power plants consisting of 2x20 MWe baseload and 2x20 MWe standby capacity will begin operation (Figure 1). These will raise the installed capacity of Bulalo field to 426 MWe. The 40 MWe standby plants will be operated whenever any one of the existing 55 MWe units is shut down for maintenance. Figure **5** illustrates how the proposed capacity additions will affect steam production rates through the year 2015.

5. CONCLUSIONS

PGI's experience in Bulalo has demonstrated that production and injection are closely linked and interdependent. An important key to successful reservoir management is to find an injection strategy that will preserve the resource and maximize its value. At Bulalo, moving injection has resulted in increasing value by reducing the number of required production and injection wells. Generation has been increased with the addition of binary units, and reservoir modeling supports a hrther expansion of field generation capacity.

6. ACKNOWLEDGEMENTS

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