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RESERVOIR PRESSURE ESTIMATION USING PTS DATA

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ABSTRACT

Big-hole production well Bulalo 100 is crossflowing while shut-in based on shut-in pressure, temperature, and spinner (PTS) survey results. The apparent crossflow is probably caused by a vertical upflow from the well's deep, less permeable and pressure supported feedzones into its shallow, more permeable and pressure depleted entry zone. Consequently, shut-in wellbore pressures at the entry zones do not represent true static reservoir pressures. Dynamic bottomhole pressures underestimate reservoir pressures at the deep producing zones and overestimate reservoir pressures at the shallow pressure depleted zones.

Crossflowing in Bulalo 100 would explain the large pressure decline rates observed in the field based on static pressure gradient surveys despite the field's uniformly low production decline rates. Reservoir pressures at the permeable zones of Bulalo 100 were then estimated using pressure, temperature and flow data obtained from shut-in and injecting PTS surveys. Linear flow equations that define flow at the well's entry zones at crossflowing and injecting conditions were solved simultaneously to estimate reservoir pressures.

BACKGROUND

Historical Bulalo reservoir pressures based on static pressure gradient surveys indicate large pressure decline rates greater than 50 psi/year that are difficult to reconcile conceptually and mathematically with the field's uniformly low production decline rates that are generally less than 4%/year.

To reconcile reservoir pressure and field production data, Strobel (1995) hypothesized that wells exhibiting large pressure decline rates are crossflowing while shut-in. This would imply that measured wellbore pressures during shut-in do not reflect true static reservoir pressures. The dynamic flowing pressures underestimate reservoir pressures at the producing zones and overestimate reservoir pressures at the pressure-depleted zones. Therefore, verifying the crossflow hypothesis through a shut-in PTS survey would explain the large pressure decline rates observed in the field and would provide a means of estimating reservoir pressures more accurately.

PTS surveys were then performed in Bulalo 100 while the well was shut-in to verify the crossflow hypothesis. Bulalo 100 is a big-hole two-phase steam producer situated in the center of the Bulalo field (Figure 1). The well was completed in August 1996 to a total drilled depth of 7328' MD (6409' bsl). The well produces about 200 kph steam with an enthalpy of 890 Btu/lb at a flowing wellhead pressure of about 200 psig.

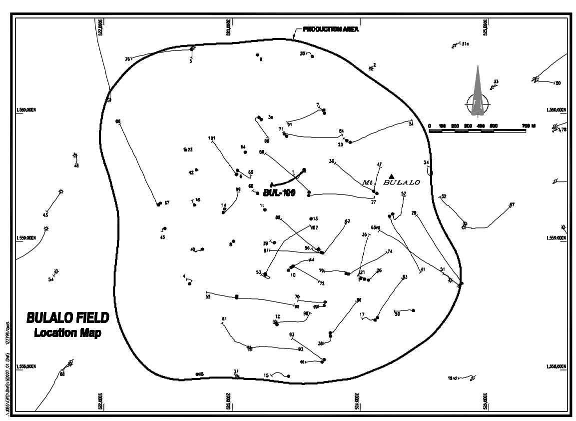

Figure 1. Bulalo Geothermal Field, Philippines.

The permeable zones of Bulalo 100 were determined based on results of injecting PTS surveys performed after well completion in September 1996 (Figures 2 and 3). Injection rate was varied at 9, 14 and 20 bpm. Three major permeable zones were identified at

2500'-3000' MD (1473'-1955' bsl), 4500'-5000' MD (3411'-3901' bsl) and 7000'-7300' MD (5898'-6197' bsl) (Aunzo 1996).

The temperature profile during injection (Figure 2) indicates an inflow of two-phase steam at the shallowest entry zone below the surface casing shoe. Injected water then flows out into the formation at the other two entry zones. Furthermore, the injecting spinner profile (Figure 3) suggests another possible permeable zone at 3200'-3400' MD (2175'-2367' bsl).

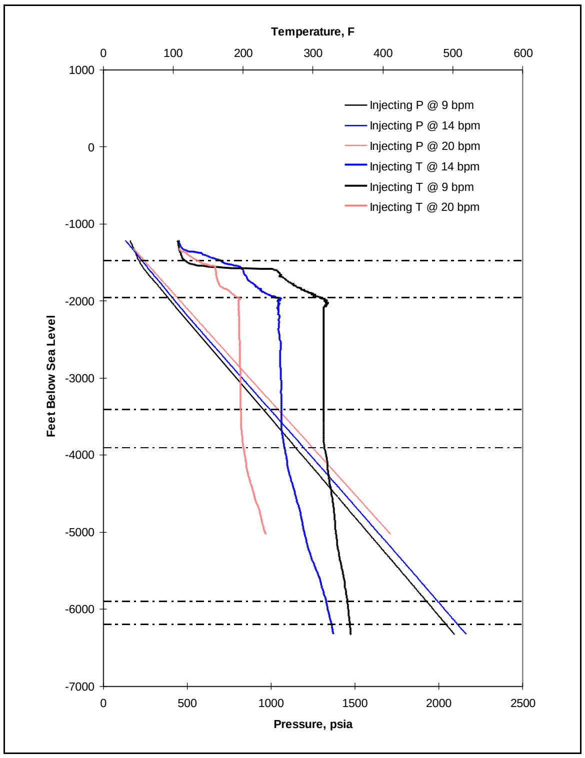

Figure 2. Bulalo 100 Pressure and Temperature Profiles during Water Injection.

RESULTS AND DISCUSSION

The shut-in PTS surveys in Bulalo 100 were conducted by Scientific Drilling International in April 1998. Spinner logs at a line speed of 80 fpm and stationary runs at selected depths were performed. Two spinner tools with 20° pitch three-bladed impellers were used during the survey. The first spinner tool was used during the down and up logs and was pulled out and replaced when the maximum operating temperature limit of the tool was reached. The stationary runs below 4650' MD (3559' bsl) were completed using the second tool.

Shut-in PTS survey results (Figures 4 and 5) indicate an apparent upward crossflow of two-phase steam along the wellbore while the well is shut-in. The deep permeable zone at about 6000' bsl and the intermediate zone at about

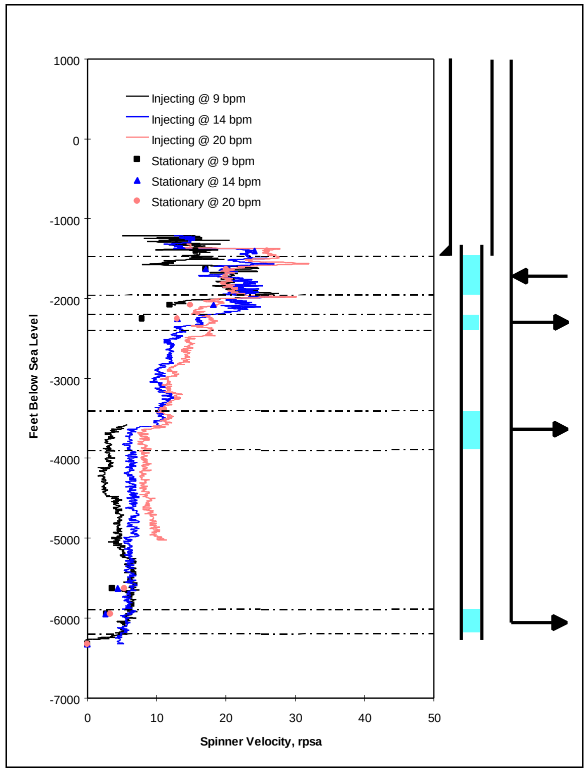

Figure 3. Bulalo 100 Spinner Velocity Profiles During Water Injection.

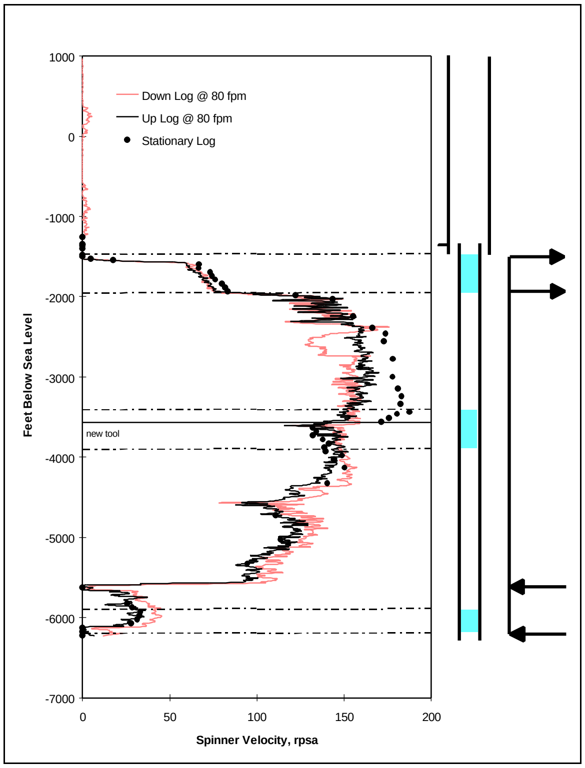

Figure 4. Bulalo 100 Shut-in Spinner Profiles.

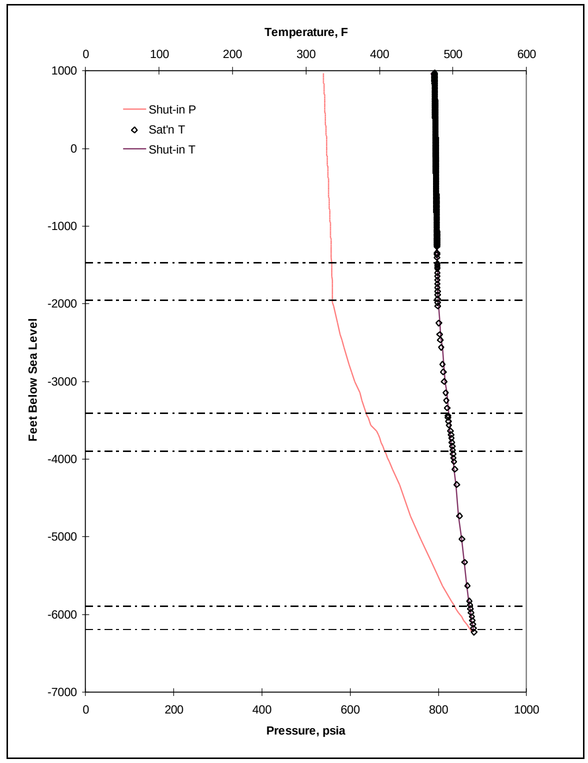

Figure 5. Bulalo 100 Shut-in Pressure and Temperature Profiles.

4000' bsl continue to produce two-phase reservoir steam even while the well is shut-in. Steam flows up the wellbore and flows out into the formation through the shallow feedzones below the surface casing shoe at about 1500'-2000' bsl. A static two-phase steam column extends above the shallow permeable zone up to the wellhead. The apparent upward crossflow is probably caused by a vertical upflow from the deep, less permeable and pressure supported feedzone into the shallow, more permeable and pressure depleted feedzone.

Reservoir pressures were then estimated by solving simultaneously equations involving the productivity and injectivity of the well's permeable zones using bottomhole pressures, temperatures and flow rates obtained from the shut-in and injecting PTS surveys.

At the shallow permeable zone, there is an inflow of two-phase steam during injection and an outflow of two-phase steam coming from the deeper zones during shut-in. The equations of productivity and injectivity defining this feedzone are given by Equations 1 to 4.

$$W_i = PI\left(P_{reservoir} - P_{w_i}\right) \quad (1)$$

$$PI = \frac{kh}{66{,}000}\left(\frac{s}{m}\right)_i \quad (2)$$

$$W_s = II\left(P_{reservoir} - P_{w_s}\right) \quad (3)$$

$$II = \frac{kh}{66{,}000}\left(\frac{s}{m}\right)_s \quad (4)$$

where W is the flow in kph, PI is the productivity index in kph/psi, II is the injectivity index in kph/psi, $P_{reservoir}$ is the reservoir pressure in psia, P_w is the wellbore pressure in psia, s is the specific gravity, and µ is the viscosity in cp. The subscripts i and s denote injecting and shut-in conditions.

At the deep and intermediate permeable zones, there is an outflow of injected water during injection and inflow of two-phase steam during shut-in. The equations of productivity and injectivity defining these zones are given by Equations 5 to 8.

$$W_i = II\left(P_{reservoir} - P_{w_i}\right) \tag{5}$$

$$II = \frac{kh}{66{,}000}\left(\frac{s}{m}\right)_i \tag{6}$$

$$W_s = PI\left(P_{reservoir} - P_{w_s}\right) \tag{7}$$

$$PI = \frac{kh}{66{,}000}\left(\frac{s}{m}\right)_s \tag{8}$$

where the variables and subscripts are defined above.

The rates of inflow and outflow at the permeable zones were estimated using the shut-in and injecting spinner velocity profiles. The inflow of two-phase steam at the shallow zone during injection was estimated by performing an energy balance around the feedzone.

Two-phase fluid properties were based on assumed reservoir pressures and reservoir fluid enthalpies and were estimated using Equations 9 to 11.

$$\frac{1}{r_t} = \frac{1}{H_{vl}}\left(\frac{H_t - H_l}{r_v} + \frac{H_v - H_t}{r_l}\right) \tag{9}$$

$$\frac{m_t}{r_t} = X\frac{m_v}{r_v} + (1 - X)\frac{m_l}{r_l} \tag{10}$$

$$X = \frac{H_t - H_l}{H_{vl}} \tag{11}$$

where H is the enthalpy, ρ is the density, μ is the viscosity and X is the steam quality. The subscripts t, l and v denote two-phase, liquid and vapor fluids.

The reservoir pressures and the productivity and injectivity indices were then calculated by solving Equations 1 to 8 simultaneously. The permeability thickness was assumed to remain constant with time. Furthermore, pressures were assumed to decline by about 20 psi per year at the shallow steam zone and by about 30 psi per year at the intermediate and deep feedzones.

The estimated reservoir pressures and the pressure profiles at shut-in, injecting and producing conditions are plotted in Figure 6. The pressure profile during production was simulated using *Wellsim* and Bulalo 100 production data.

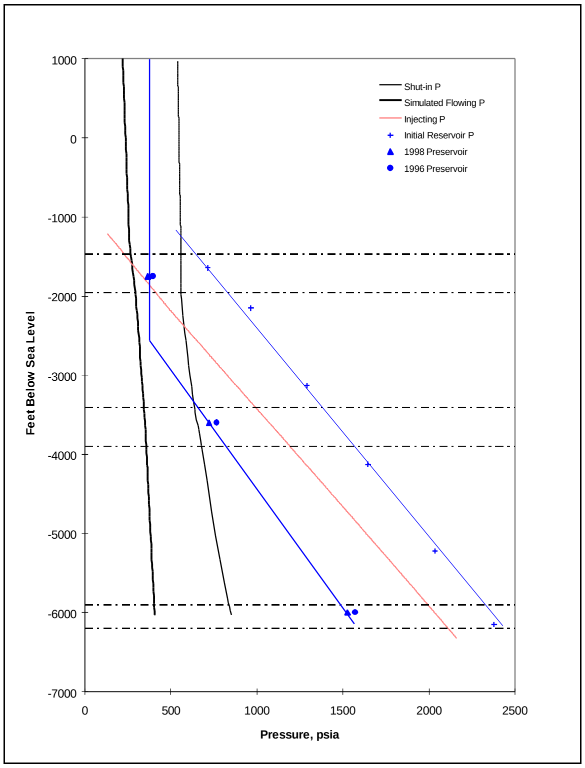

Figure 6. Bulalo 100 Pressure Profiles.

A coherent picture of Bulalo 100 during shut-in, injecting and flowing conditions is illustrated by the pressure profiles. The less permeable deep entry zones produce during shut-in and flowing conditions but accept water during injection. On the other hand, the more permeable shallow zone produces during injection and production but accepts upflow coming from the deep zone during shut-in (Figure 7).

The estimated current reservoir pressures are about 350 psig at 2000' bsl, 850 psig at 4000' bsl and 1510 psig at 6000' bsl. The shallow feedzone has an estimated permeability thickness of about 50,000 md-ft and the deep zone has only about 2,000 md-ft. Based on the calculation results, reservoir pressures in the steam zone have declined by about 400 psi at an average pressure decline rate of only about 20 psi/year since the start of field production. In the liquid zone, reservoir pressure drawdown is about 750-900 psi at an average decline rate of only about 30-35 psi/year. Table 1 summarizes Bulalo 100 wellbore and reservoir pressures as well as flow rates during shut-in and flowing conditions.

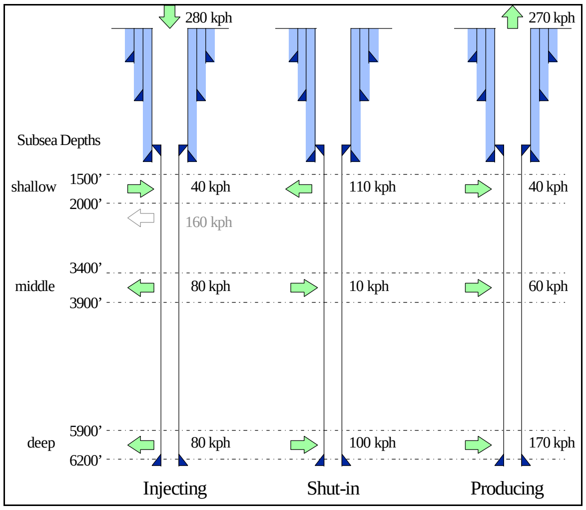

Figure 7. Bulalo 100 During Injection Shut-in and Production.

Table 1. Bulalo 100 Pressures and Flow Rates.

Entry zone	Subsea Depth feet	Initial $P_{reservoir}$ psi	Current $P_{reservoir}$ psi	Pressure Decline psi	Decline Rate psi/yr
shallow	1500-2000	750	365	400	20
middle	3400-3900	1450	725	750	30
deep	5900-6200	2400	1525	900	35

Entry zone	$P_{reservoir}$ psia	Shut-in Conditions			
		flow kph	PI kph/psi	P_{wf} psia	ΔP psi
shallow	365	110	0.58	560	195
middle	725	10	0.16	655	70
deep	1525	100	0.15	860	665

Entry zone	$P_{reservoir}$ psia	Flowing Conditions			
		flow kph	PI kph/psi	P_{wf} psia	ΔP psi
shallow	365	40	0.58	295	70
middle	725	60	0.16	350	375
deep	1525	170	0.15	405	1120

CONCLUSIONS

The apparent crossflowing in Bulalo 100 while it is shut-in would explain the large pressure decline rates observed in the Bulalo field despite the field's uniformly low production decline rates. Data obtained from PTS surveys performed during two different well conditions can be used to estimate reservoir pressures by solving flow equations simultaneously.

REFERENCES

Lee, John (1982). Well Testing. New York. Society of Petroleum Engineers of AIME.

Strobel, C. J. (1983), Initial State of the Bulalo Reservoir.

Strobel, C. J (1995). PGI Internal Memo to Phil Mogen and Zim Aunzo.

Bulalo 100 Injecting PTS Survey (September 1996), Scientific Drilling International.

Bulalo 100 Shut-in PTS Survey (April 1998), Scientific Drilling International.