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Evaluation on Productivity Index Distribution on Wayang Windu Geothermal Field to Identify Potential Production from Deep Brine Reservoir Section

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ABSTRACT

The successful development of geothermal fields requires a carefully integrated evaluation of all aspects affecting the decision on installed capacity (MW). For Wayang Windu field, there are three key resource aspects that need to be addressed to verify the opportunity of adding 60 MW of the installed capacity: 1) lateral extension of the reservoir toward the Northwest as indicated by the low resistivity anomaly profile from magneto telluric data; 2) vertical extension of commercial permeability to the deep brine reservoir section; and 3) long-term performance of the proven reservoir section represented in production decline rate.

A recent study to define the potential production from the deep brine reservoir to address the vertical extension of the commercial reservoir is completed. Despite significantly controlling production, in a mature field like Wayang Windu, the reservoir pressure and temperature are not considered as key uncertainties. The remaining key uncertainty that significantly affects the production performance, including the initial well production, belongs to the fracture permeability, especially with a low number of existing wells that have been drilled into the deep reservoir section. The distribution of fracture permeability is analyzed on a vertical scale with the goal to establish an empirical correlation between permeability as a function of depth. The study suggests the P50 of potential initial steam production gain from the well drilled to -200 m SL elevation is 16 kg/s with a potential upside of 28 kg/s (P90) and the chance of regret (non-productive reservoir) of 10%. The result of the study is used for planning a well that will be drilled to the brine reservoir section in 2019 in order to meet the production target and maximize the value of information.

1. INTRODUCTION

Currently, the performance of production wells in the Wayang Windu field is evaluated using wellbore hydraulic models that have been calibrated to match the production history of each well, using the WELLHIST application. The calibrated models should accurately represent well geometry, the location and productivity index (PI) of each permeable zone, and the historical evolution of pressure and enthalpy at each zone. The models are then used to forecast the deliverability of individual wells as reservoir conditions continue to evolve and are compared with actual well production. The deviation between actual production and the well deliverability profiles from the model is considered as a signpost to the presence of flow assurance issues in the wellbore such as scale development. In addition, the calibrated wellbore models were found to be accurate tools for identifying permeability distribution across the field. In the current study, the PI profile that represents the distribution of fracture permeability is analyzed on a vertical scale with the goal of defining potential production from the deep brine reservoir.

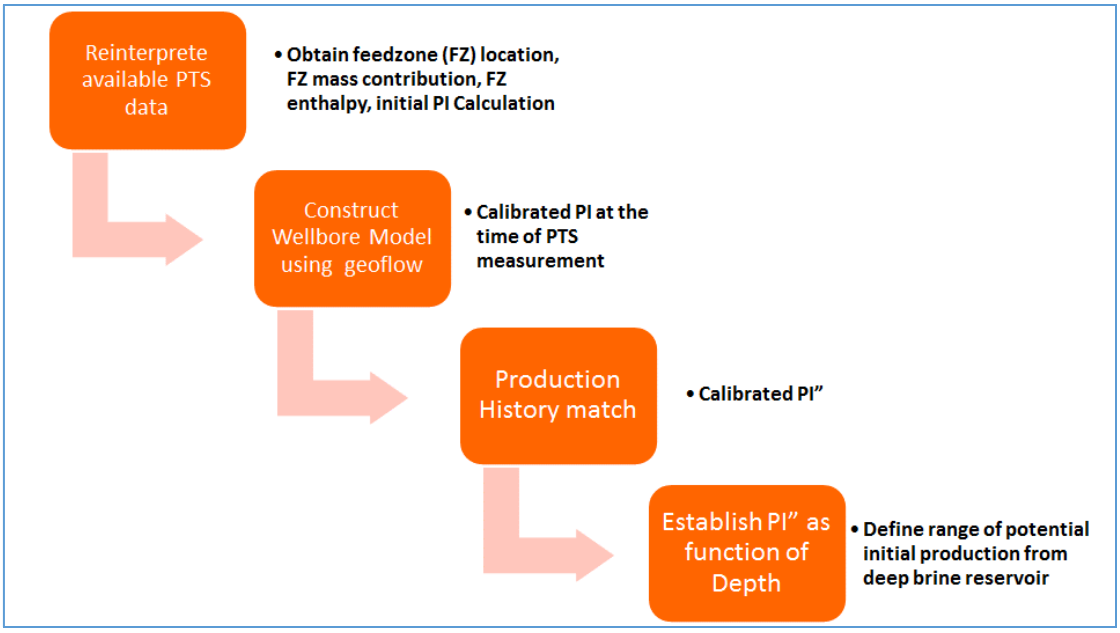


Figure 1: Workflow applied to study the permeability distribution on deep brine reservoir and its potential production

The WELLHIST program is a Star's in-house application for running a wellbore simulator as many times as required to produce a series of well deliverability calculations for different reservoir conditions. The first step of the process is to develop an initial wellbore hydraulic model for individual production using information of wellbore geometry and the pressure-temperature-spinner (PTS) data. Construction of the initial wellbore model is done by matching simulated wellbore fluid velocity, wellbore pressure, temperature and total mass flow rate to the measured data to identify the productivity index (PI) and enthalpy of each feed zone. In the second step, the wellbore hydraulic model is then calibrated by history matching its output to the historical data of wellhead steam mass flow rate and enthalpy. Some production wells in Wayang Windu are two-phase wells. The conventional inflow performance relationship (IPR), which is derived merely from a mass balance equation, is not applicable for this system (Pasikki, 2017). For a two-phase system, change in the pressure is not only related to the change in the mass flow rate but also to change in the enthalpy. To address this concern, the PI parameter used in the history matching process with WELLHIST is the mobility and enthalpy normalized PI (PI'). Besides PI', the other input for WELLHIST is the measured pressure and temperature history data at each feed zone obtained from the shut-in pressure and temperature surveys. During the calibration process, it is assumed that the permeability is unchanged throughout the entire period of well production. With this assumption, PI' distribution for a well with more than one feedzone remains constant. The calibrated wellbore hydraulic model mainly obtained by trial and error change of the PI' value until the calculated steam mass flow rate and enthalpy histories agree well with the measured data. The initial estimate of the PI value was obtained from PTS interpretation. As described on Figure-1, once the wellbore models are calibrated including the PI then we can establish correlation of the PI as a function of the depth and we are eventually able to define potential production from the deep brine reservoir section in Wayang Windu. The established correlation could be used as reference to determine minimum depth of the deep brine well that will be drilled in the 2019 drilling program. The correlation of the PI with the depth has been established on other Star Energy geothermal fields (Salak and Darajat).

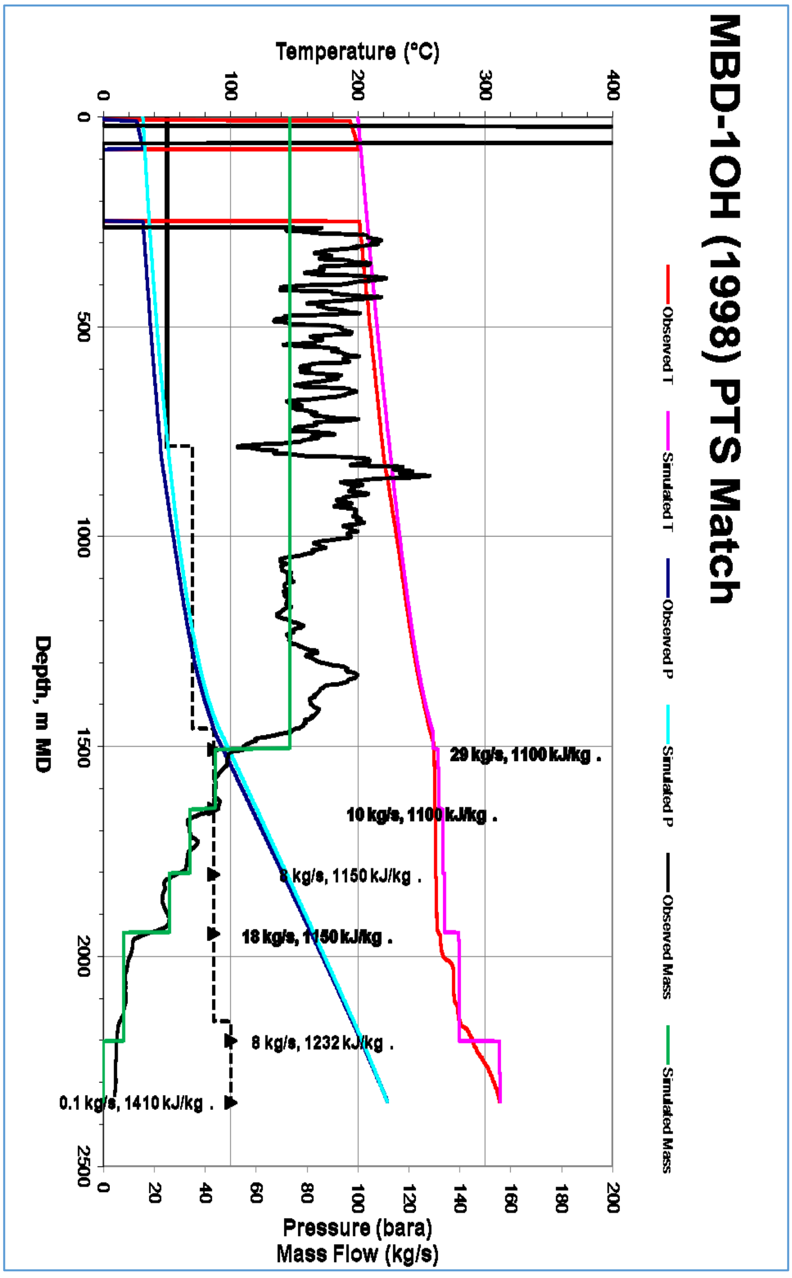


Figure 2: Wellbore simulation match of flowing pressure, temperature and fluid rate on MBD-1OH well

2. INTERPRETATION OF PRESSURE-TEMPERATURE-SPINNER (PTS) DATA

Pressure-temperature-spinner (PTS) surveys are a valuable surveillance tool for characterizing and diagnosing performance of geothermal wells and evaluating changes in reservoir conditions. Interpretation of a PTS survey relies heavily on the wellbore simulation. To match a model to observations, a trial and error procedure must be followed to determine the location and individual feed zone contribution both in terms of mass and enthalpy in the two-phase part of the well. The contribution of individual feed zones is usually seen as increases in the fluid velocity. An estimation of the feed zone enthalpy must be made in order to convert velocity changes to mass contributions. Inputs required to conduct PTS analysis using wellbore simulation include:

- Data (pressure, temperature, spinner) from logs (up runs, down runs, static) from different tool velocities
- Surface data (wellhead pressure, flow and discharge) enthalpy
- Well geometry

There are 36 raw PTS data from production wells (23 steam cap wells and 13 brine wells) in Wayang Windu that have been reanalyzed using Star's in-house application called PTS Analyzer. The main assumptions being used in this application is that the flow velocity is large enough so that there is no slip velocity (between steam and brine) so the flow is homogenous. The heart of PTS Analyzer is the Geoflow (an in-house thermal wellbore simulator) that solves steady-state conservation equation for mass and energy for wellbore and formation. Outputs from PTS analysis are the location, flow rate and enthalpy of feed zones in the well. Figure-2 shows an example of flowing wellbore model of MBD-01 well that was constructed by matching the simulated wellbore fluid velocity, pressure and temperature to the measured data. The missing mass flow and pressure profiles on the upper section of the wellbore were due to pressure and temperature tool problems when run at 100 – 250 m MD interval.

3. WELLBORE HYDRAULIC MODELS DEVELOPMENT WITH WELLHIST APPLICATION

WELLHIST runs a wellbore simulator as many times as required to produce a series of well deliverability calculations for different reservoir conditions. It is used to calculate the deliverability of wells as they evolve with changing reservoir conditions and compare it to measured historic records. The input deck for simulation with WELLHIST includes:

- Well geometry
- Elevation and PI's of the feed zones. In this study, the initial PI values for WELLHIST simulation are the ones from PTS analysis of the previous step.
- Pressure and enthalpy history of the feed zones
- Historic wellhead pressure

Output from the simulation would be the deliverability of the wells in terms of steam rate and discharge enthalpy. During the calibration of the well hydraulic model with historical data, the initial PI of the wells from PTS analysis have been adjusted to obtain an acceptable history match. The deliverability of geothermal wells is the product of the interaction of several variables such as reservoir pressure, fluid enthalpy and productivity index (PI) of the feed-zone. The relationship that reliably represents well response to changes in reservoir conditions is important. An Inflow Performance Relationship (IPR) as described in Equation 1 is an equation that predicts how a well flow rate varies with changes in flowing pressure. It consists of a constant PI that multiplies an effective pressure drawdawn. That effective drawdawn is a function of reservoir pressure and flowing bottomhole pressure. For geothermal production wells this type of equation is valid only for given moment in the life of the reservoir. Once reservoir properties other than pressure, such as fluid enthalpy, density, viscosity and relative permeability, change then the PI changes and consequently the IPR is no longer valid. Conventional IPR with fixed PI is not designed to evaluate deliverability changes when reservoir parameters evolve with time, which always occurs during the production time of a liquid-dominated geothermal reservoir. Therefore, despite maintaining the conventional inflow performance relationship IPR as per Equation 1, the PI parameter used in the history matching process with the WELLHIST simulator is PI" which the normalized PI with the mobility correction factor or v^{-1} and enthalpy correction factor or ECF. The work flow to construct and calibrate the individual wellbore hydraulic model is shown in Figure-3.

$$W = PI \times (P_{res} - P_{wf}) \dots (1)$$

where *W : Total Mass Rate (kg/s)*
PI : Productivity Index (kg/s/bar)
P_{res}: *reservoir or formation pressure*
P_{wf}: *wellbore pressure*

To satisfy the needs of constraining the model with sufficient data, we only include the wells with at least one (1) year of historical production data. There are totally 30 wells that meet the criterion -- 5 (five) of them are the brine wells while the remaining are shallow steam cap wells. Figure-4 shows examples of plots of model production profile from Wellhist simulation and historical production data at the wellhead for a steam well (MBD-4) and a two-phase well (WWQ-5).

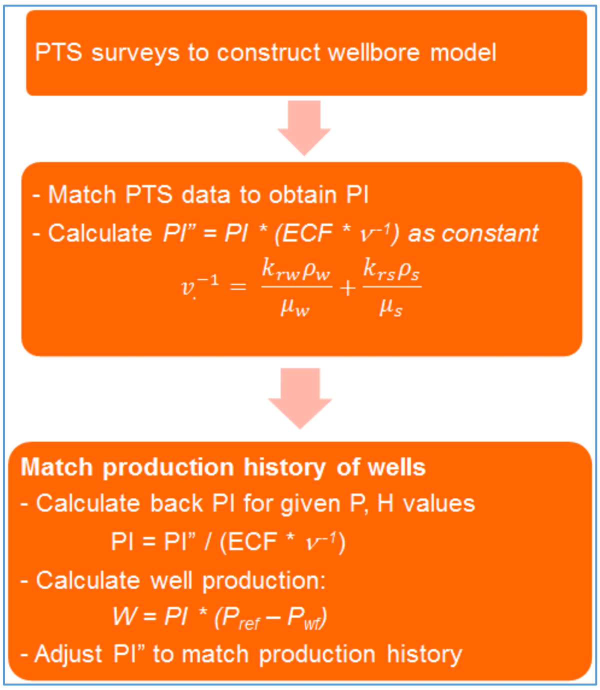


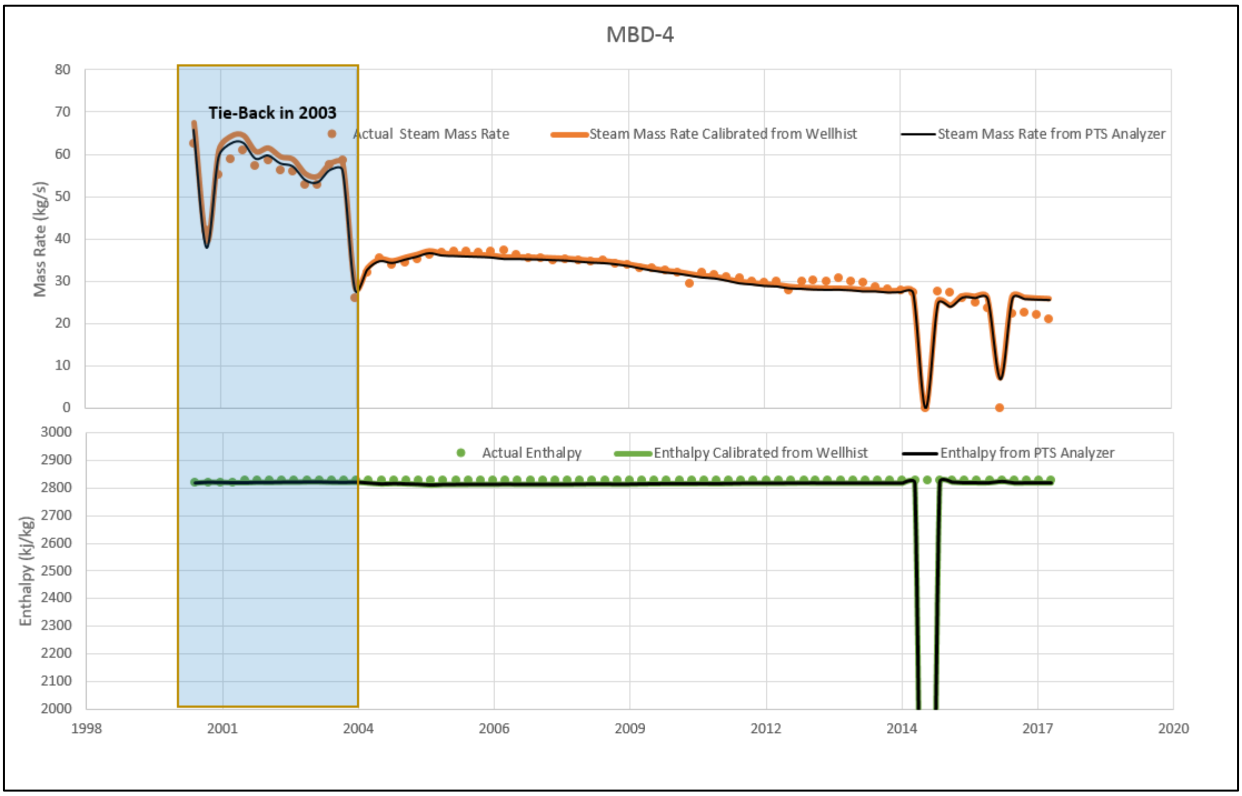
Figure 3: Workflow for construction and calibration of wellbore hydraulic models using Wellhist simulator

4. PI VS. DEPTH CORRELATION

Fracture permeability is a bulk property of the fractured medium. It is created by the combined action of fractures, each one with very different local permeability values. The permeability-thickness product (kh) of wells, typically obtained from a Pressure Transient Test, also is a property of the region close to the well. However, conducting Pressure Transient Tests on geothermal wells is somewhat challenging. Pressure response during a test in a geothermal well is not fully representation of the transmissivity feature of the formation because it is significantly affected by change of temperature. To address the concern of the absence of reliable pressure transient data, we have been using the PI's obtained from PTS and calibrated with Wellhist simulation of each well to determine the variation of permeability with depth. Figure-5 shows the raw plot of PI" versus elevation for all feedzones of the analyzed wells in Wayang Windu. In principle, PI's can be related to permeability and skin factor as explained in the following equation, so that the distribution of fracture permeability can be characterized by PI" distribution.

$$PI = \frac{2\pi}{\ln\left(\frac{r_e}{r_w}\right) + S} \frac{\rho_s}{\mu_s} kh \dots (2)$$

where PI : *Productivity Index (kg/s/bar)*
kh : *permeability thickness (milli-darcy ft or m3)*
ρ_s : *fluid density (kg/cu-m)*
μ_s : *viscoisty (cp)*
S : *skin factor*
r_e : *drainage radius (m)*
r_w : *wellbore radius (m)*



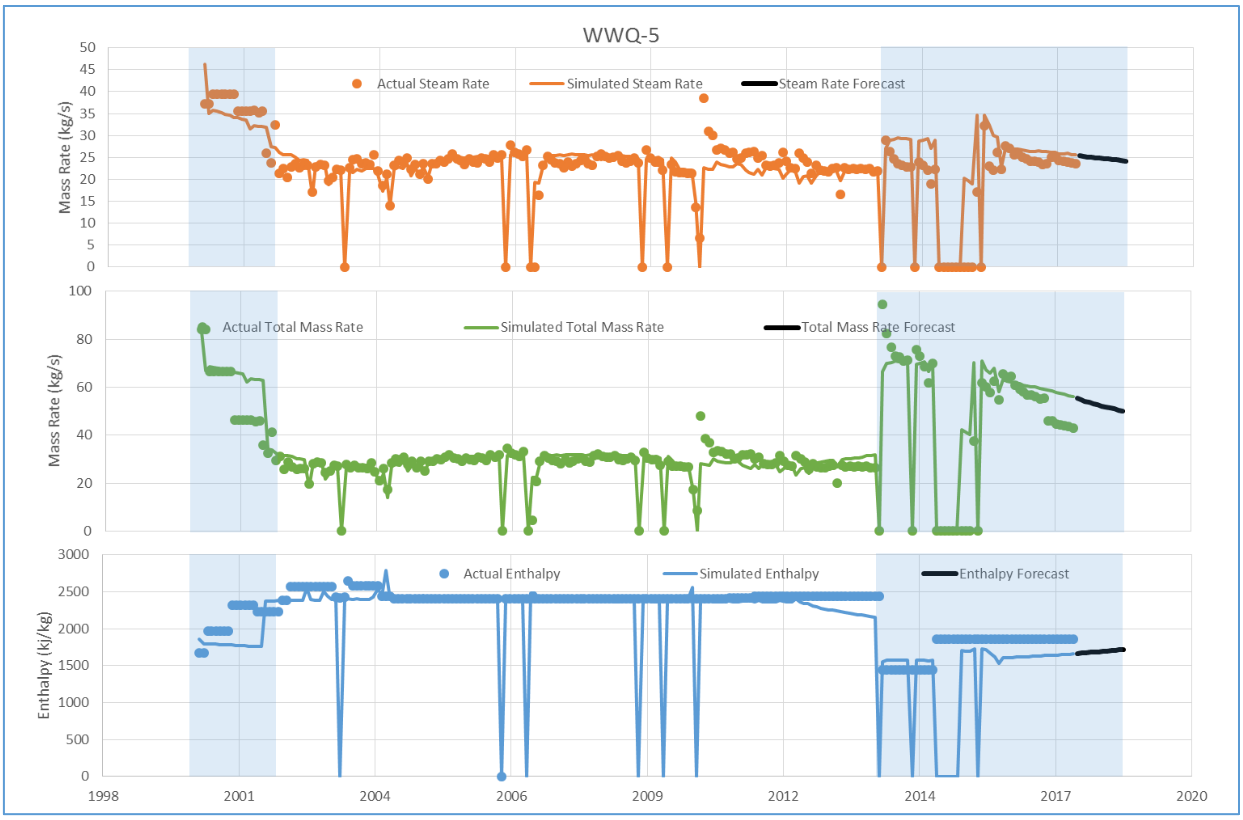


Figure 4: plot of model from Wellhist simulation and historical production data at the wellhead for steam well (MBD-4) and two-phase well (WWQ-5)

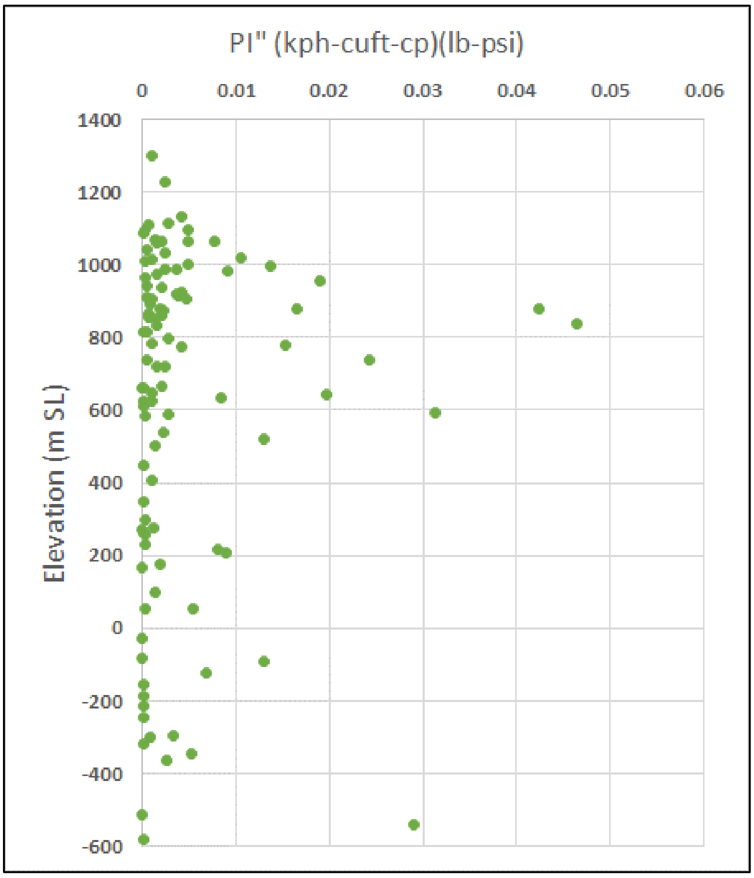


Figure 5: plot of PI” vs. Depth (elevation) for the all analyzed wells in Wayang Windu.

A well may not intercept all production horizons simply because the wellbore is a very small sample to characterize the fracture domain. To overcome this problem, all wells in Wayang-Windu field were normalized by assuming a total PI of 1 for each and then “adding up” the PI’s of zones that fall in the same vertical “bin” defined to be 200 m thick to coincide with the typical grid discretization in the reservoir model.

The result, which shows the vertical variation of PI is then corrected by the fraction of wells completed in each binning interval and is shown in Figure-6. Similar to what has been observed in Salak and Darajat fields, the study in Wayang Windu shows permeability decreases with depth. The actual variation can be fitted by the following exponential expression:

Fractional PI = exp ((Z- 1277.5)/419.3) ... (3)

Values for intervals below -600 m SL may not be too reliable. The exponential form assures that permeability will not go to zero at depth. The value of total PI can now be distributed vertically (n layers and bining every 200 m) using the following equation

$$PI = Total\ PI\ x \sum_{i=1}^{n} e^{((Z-1277.5)/419.3)} \ldots (4)$$

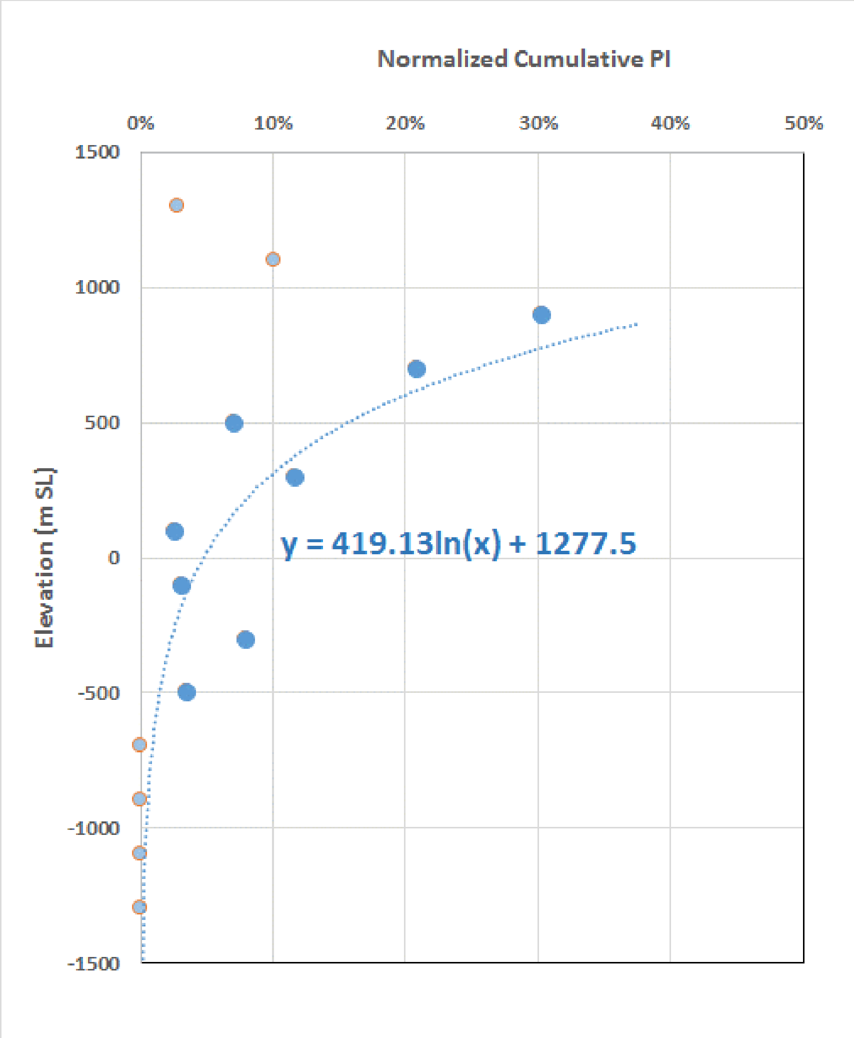


Figure 6: Result of Normalized Fractional PI versus elevation for all wells in Wayang Windu

5. POTENTIAL INCREMENTAL PRODUCTION FROM DEEP BRINE RESERVOIR SECTION

Reservoir parameters that control well deliverability are the reservoir pressure, fluid enthalpy and fracture permeability. The latter can be represented by PI. Combined with well geometry information, the well deliverability can be predicted using Star's 'in-house' geothermal wellbore simulator called Geoflow. An advanced version of Geoflow called Crystal-ball Geoflow that allows probabilistic wellbore simulation is also available. With capability to carry out probabilistic wellbore simulation, the Crystal-ball Geoflow could take the input value of reservoir parameters (pressure, enthalpy and PI) as the range of value instead of one deterministic value. Therefore for this study, the probabilistic approach is taken to define the potential incremental steam production from the deep brine reservoir section due to uncertainties on fluid enthalpy and the PI's. The distribution of total PI" is based on actual total PI magnitude of all production wells in Wayang Windu with P10, P50 and P90 values of 0.00131, 0.01164 and 0.03933 (kph-cuft-cp) (lb-psi) respectively. Because the study is aimed at defining the potential initial production from the deep reservoir, the actual total PI is normalized to the depth of -600 m SL. Average total depth (TD) of wells in Wayang Windu is +300 m SL. Based on Equation 3, the cumulative fractional PI on an interval depth of +300 to -600 is 18.3% and therefore the total PI is normalized by multiplying it with 1.183, and the P10, P50 and P90 after being normalized are 0.00160, 0.01425 and 0.04814 respectively. The PI range for each binning layer is then defined by multiplying the fractional PI calculated with the function described in Equation 3 with those normalized PI values. Table 1 shows the range of PI values for each layer resulting from the described calculation processes. In addition, the table also shows the range (P10, P50 and P90) of expected fluid enthalpy from the deep brine section. The range of enthalpy is defined based on recent temperature profiles from liquid wells in Wayang Windu as shown in Figure-7. Deterministic value of reservoir pressure for each layer is used considering low uncertainty and low impact to the calculation of steam production. Geological POS (possibility of success) is also assigned to each layer which represents the chance to successfully encounter permeability.

Table 1: Range of pressure, enthalpy and feedzone PI on deep reservoir section for probabilistic simulation

	UNIT	British									
PROBABILISTIC ANALYSIS											
NumZones			5		Liquid/Two-Phase/Superheat						
Feed Zones	Elevation (ft)	Fixed Pressure			Enthalpy			PI			POS
			FIXED VALUE		LOW	BASE	HIGH	LOW	BASE	HIGH	%
1	656	1319	1319	1319	467	532	578	0.00012	0.00109	0.003681	63%
2	0	1580	1580	1580	467	532	578	0.00008	0.00068	0.002284	22%
3	-656	1841	1841	1841	467	532	578	0.00005	0.00042	0.001417	55%
4	-1312	2102	2102	2102	467	532	578	0.00003	0.00026	0.00088	81%
5	-1968	2363	2363	2363	467	532	578	0.00002	0.00016	0.00055	50%

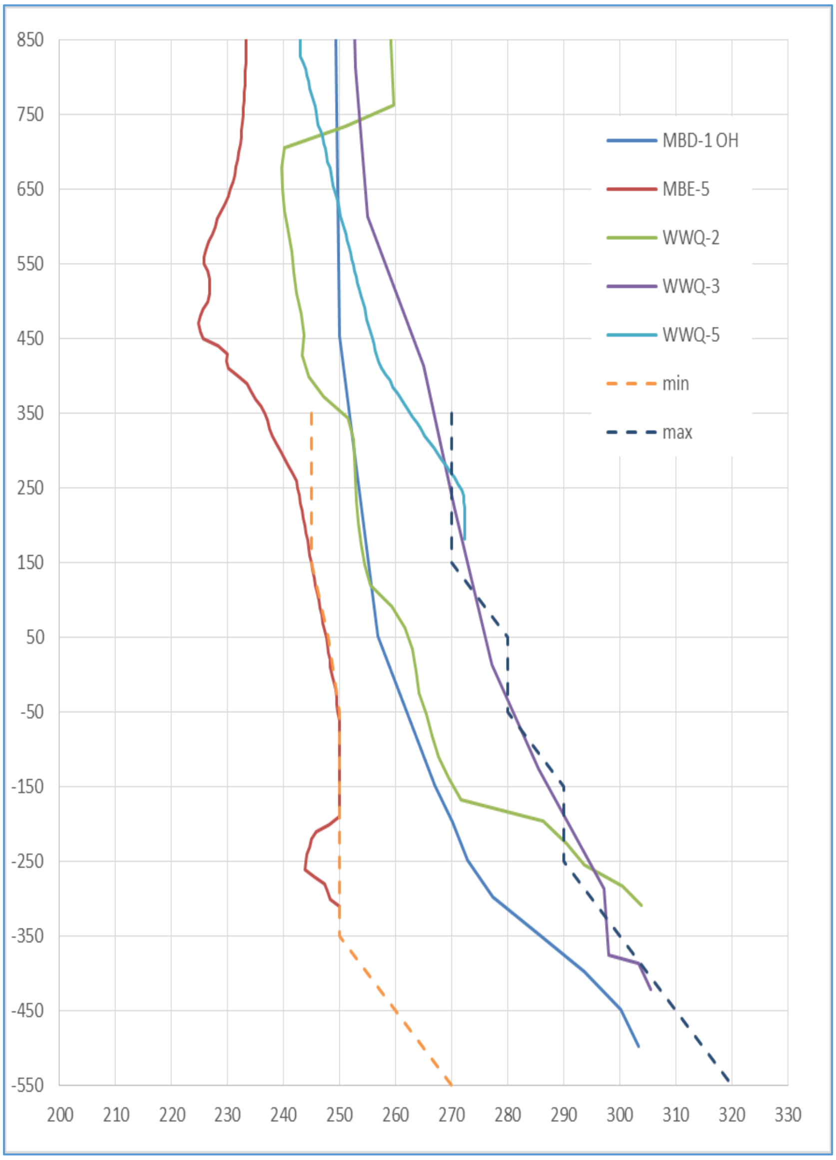


Figure 7: Measured Temperature from liquid wells in Wayang Windu to define range of enthalpy at deel reservoir section

Using information in Table-1 as inputs, the probabilistic wellbore simulations were carried out and the result is presented in Figure-8. Simulation results suggest that the incremental steam production from the brine reservoir resulting from drilling to -200 m SL depth would be 16 kg/s for the base (P50) case with potential upside (P90 case) of 28 kg/s and chance of regret (zero production) of 10%. Early economic analysis for growth opportunity in Wayang Windu suggests that the minimum production contribution from brine feedzones in a deep well would be 16 kg/s. Therefore, the next deep brine well to be drilled in the 2019 drilling program needs to target to -200 m SL or deeper.

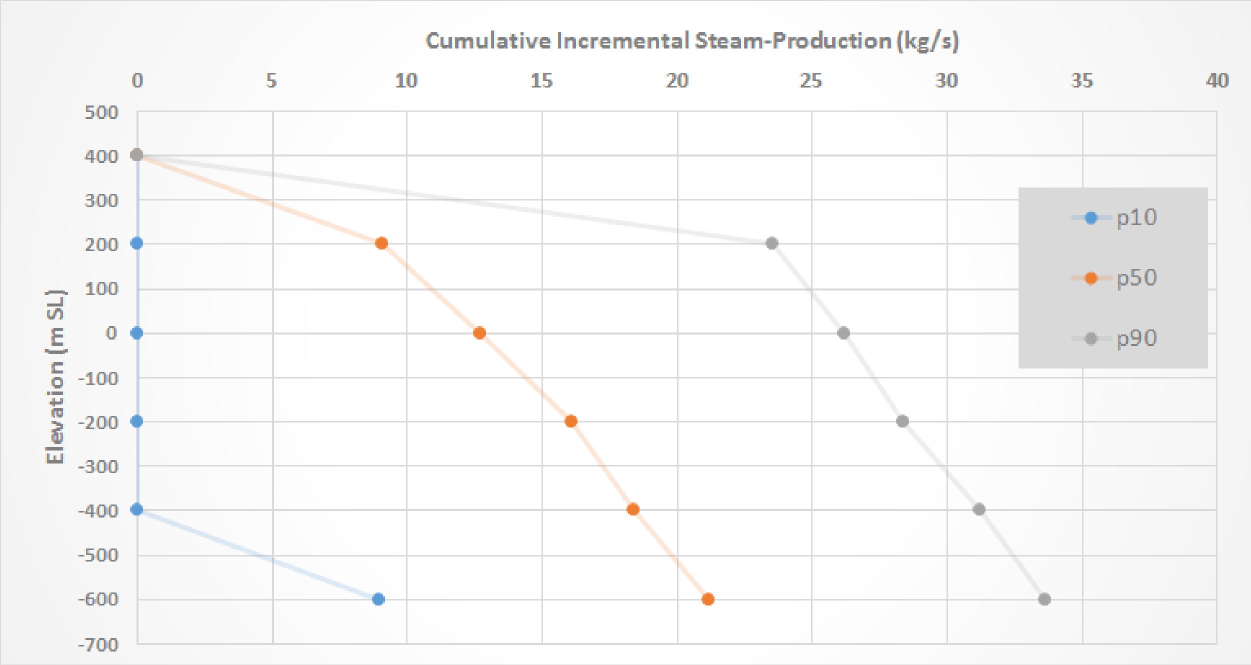


Figure 8: Range of cumulative incremental steam production as function of cumulative depth resulted from probablistic wellbore simulation.

CONCLUSIONS

We have available measured well PI's obtained from production (PTS) logs and calibrated with historical production data. PI distribution is then analyzed in vertical scale and corrected by the fraction of wells. Because PI can be related to the fracture permeability, PI distribution can be treated as the fracture permeability distribution. The vertical variation of PI shows permeability that decreases exponentially with depth. Once the vertical variation of permeability is obtained from all wells, permeability in the rest of Wayang Windu field can be interpolated and utilized as a constraint to the earth and reservoir models. In addition, the established PI vs. depth correlation can be used to determine the minimum target depth of the well that will be drilled to the deep brine reservoir section to achieve production target.

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