

Darajat Geothermal Field Expansion Performance- A Probabilistic Forecast

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ABSTRACT

Performance forecasts can either significantly overestimate or underestimate a subsurface resource capacity due to uncertainties associated with the collected data and the evaluation process. We applied a process developed around the Experiment Design methodology to capture relevant uncertainties existing in the Darajat's field static model construction, the dynamic simulation model building, calibration, and forecasting. This process systematically identifies, ranks, and quantifies key parameters affecting field performance. It generates a full range of probabilistic field generating capacity distributions that can provide a better platform for the economic evaluations, development planning, and decision making than relying on a single deterministic projection. The ranking of the reservoir and geologic parameters' uncertainty and the projected performance distribution provide a framework for the field operator to explore different expansion alternatives as well as to develop an effective risk management plan to mitigate the potential shortfalls.

1. INTRODUCTION

The vapor dominated Darajat geothermal field is located in the West Java province of Indonesia, about 150km southeast of Jakarta. The field is situated along a range of volcanic centers extending nearly 30km in lengths and is adjacent to the Kawah Kamojang and Wayang Windu geothermal fields. Surface topography and partially collapsed remnants of eruptive centers, with no obvious associated cones, highlight the field structure. As in the other adjacent geothermal fields, the movement of the Samudara Hindia Plate created south to north compression resulting in NE-SW and NW-SE trending faults in Darajat.

Geothermal evaluations at Darajat began in the early 1970's when surface scientific reconnaissance conducted in the area indicated the existence of a vapor dominated reservoir in a hydrological setting similar to the nearby Kamojang field. Three exploratory wells drilled in 1978-79 verified the geothermal field's existence. Wells drilled into the reservoirs encountered temperature and pressure gradients similar to that of static vapors. Ten years later, Amoseas Indonesia Inc. drilled four additional delineation wells and confirmed a commercial reserve. The first commercial unit has been generating 55 MW of electricity since October 1994. A second unit raised the field generating capacity to 150 MWe since June 2000. Figure 1 shows the field location on the Java Island.

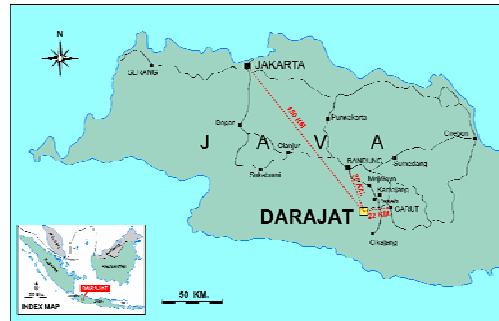


Figure 1: Darajat Geothermal Field location.

As the electricity demand out paces the current supply in Indonesia and the world's trend for using cleaner energy sources increases, Amoseas plans to add a third power plant unit that increases the current generating capacity by about 70%. The expansion decision depended on the field's ability to sustain the required production rate over the life of the contract remained a major uncertainty. Historically, performance predictions of a subsurface resource can greatly overestimate its performance or underestimate the risks associated with subsurface uncertainties. Gross overestimation or underestimation of the field performance can create severe economic consequences. The inherent uncertainty in the forecasts is the product of ambiguities in the measurements, interpretations, and representations of the reservoir and geologic parameters.

Engineers have used various methods, including field analogy, decline curve analysis, numerical simulation, etc., to predict a field response to the proposed changes. Each method has a different level of sophistication, limitations, and uses the available data in a different manner. Reservoir simulation is often the tool of choice for the performance forecasting because of its versatility. However, large uncertainties in major geologic and reservoir engineering parameters pose a considerable risk to the forecast.

A sensitivity study is normally conducted using extreme values for each uncertainty. This approach sets all parameters at fixed values, usually at mid range values (P50), and vary one parameter from low (P10) to high (P90). It uses a tornado diagram to evaluate the impact of these parameters' uncertainty on the results. This approach can have some drawbacks because it builds around an assumed P50 model and does not take the interactions between these parameters in the evaluation.

We applied a probabilistic process developed around the Design of Experiment methodology to capture relevant uncertainties that exist in major phases of a subsurface assessment. These phases include the geologic model construction, the dynamic model building and calibration, and the performance forecast. This process systematically identifies, ranks, and quantitatively assesses key parameters

affecting the field performance. Interactions between parameters are included as part of the evaluation. The process generates a whole range of probabilistic performance forecast distributions for economic evaluations.

2. FIELD PERFORMANCE

At present, there are 14 producers feeding steam to the two power plants generating 150 MWe at Darajat. Most of the deep wells exhibited high capacity, averaging about 15 MWe. A number of wells drilled during later periods to supply steam for the second unit can deliver over 30 MWe. Darajat producers discharge dry steam at the wellheads. Monitoring pressures of production wells showed a low decline, about 3% per year or less. The nearby Kawah Kamojang geothermal field showed a slightly higher pressure decline for a smaller generating capacity of 140 MWe. Darajat observation wells located outside of the current production zone and near the reservoir peripheral showed no or very little changes in the pressures. This suggests that boiling has not taken place extensively all over the reservoir, but rather locally around the producers. In addition, adding the second power unit apparently has not significantly accelerated the decline.

3. RESERVOIR GENERATING CAPACITY ESTIMATION METHODOLOGY

For the Darajat expansion evaluation, we define the reservoir generating capacity as its ability to sustain the required vapor production rate with a fixed number of wells, subject to certain minimum flowing wellhead pressures. Specifically, it is the production plateau length that the reservoir can sustain with the specified constraints. Darajat's reservoir ability to deliver water vapor depends on many geologic and reservoir parameters that have inherent uncertainty. We used the probabilistic forecast approach in order to properly estimate the range of reservoir generating capacity, to identify major uncertainties, and to quantify the risks associated with the proposed expansion. We employed the reservoir simulation as the main method for the performance forecasts using ChevronTexaco's CHEARS® reservoir simulator.

We applied the following process for the probabilistic reservoir performance forecast:

1. Define the reservoir performance dependent variable and perform screening to identify pertinent geologic and fluid flow parameter's uncertainties.
2. Use the Design of Experimental methodology to create a series of dynamic reservoir simulation models capturing the full range of reservoir performance.
3. Calibrate and validate these various models by matching with the natural state conditions and with production data.
4. Create the response surface for the reservoir performance using multiple variable regression analysis.
5. Apply the Monte Carlo simulation approach to generate the full probabilistic performance distribution. And, derive the P10, P50, and P90 performance forecasts from the S-curve.

6. Construct the P10, P50, and P90 reservoir simulation models, based on the Monte Carlo parameter combinations, and verify the Monte Carlo simulation results.

7. Use the P10, P50, and P90 reservoir simulation models to evaluate development alternatives; e.g., plant size and economics.

The flow chart in Figure 2 summarizes the work process that we applied to assess Darajat Geothermal field uncertainties and to obtain a probabilistic forecast for the field expansion performance.

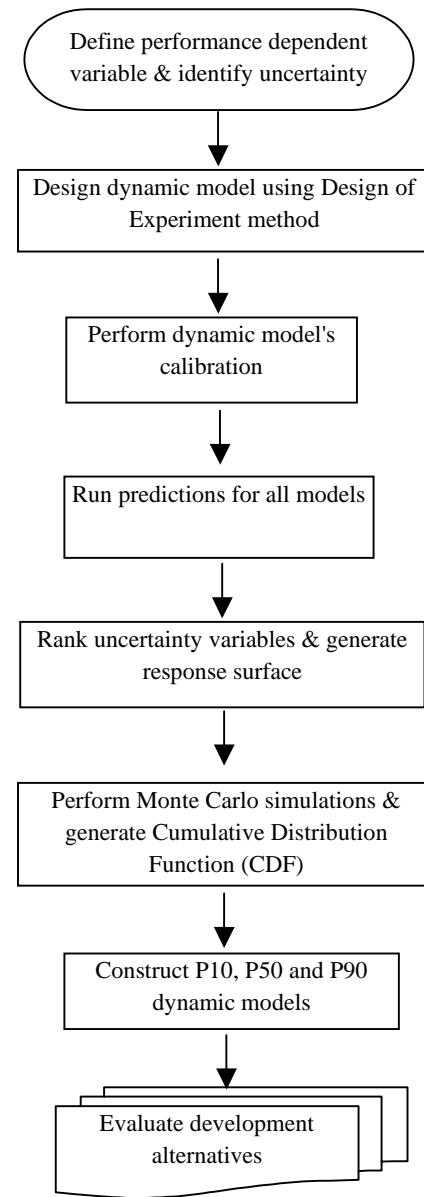


Figure 2: Probabilistic performance Forecast work process.

4. DARAJAT SUBSURFACE UNCERTAINTIES

One of the most important parameters affecting the long-term generating capacity of a vapor-dominated reservoir is the amount of initial liquid in place. In a reservoir, the initial liquid volume is proportional to the pore volume and the initial liquid saturation. The static models' construction

and evaluation indicated that the reservoir pore volume, the product of bulk volume and porosity, is the most important parameter affecting the initial fluid in place. The potential values for pore volume vary over a wide range due to the uncertainties in the top of reservoir location and the porosity distribution. Location of the top of the reservoir, beyond the well controlled region, can affect the bulk volume significantly.

Uncertainty in the facies and lithotype distribution in the reservoir resulted in a number of possible porosity realizations. We carried three realizations of the static models into the uncertainty analysis. These three realizations represent the low, mid, and high cases based on the pore volume distribution. In addition, the bottom of the reservoir poses another uncertainty. Micro seismic information suggests that the lower boundary of the Darajat reservoir can extend deeper than 3km below the current deepest production interval. To assess effects of the lower boundary location on the reservoir performance, we vary the reservoir depth from 1km to 3 km below the bottom of the current production interval. Some combinations of pore volume and reservoir depth can make a huge difference in the fluid in place and, hence, reservoir performance.

Over the years, Amoseas collected and analyzed several fluid samples and used various methods, from geochemistry to heat balance, to estimate the reservoir average liquid saturation (Swc). However, the results vary over a wide range, from a low of 20% to nearly 90%. Although a number of investigators have addressed the irreducible liquid saturation in vapor-dominated geothermal reservoirs, it is still not definite. Previously, Grant (1979) and Strauss and Schubert (1981) suggested that the irreducible liquid saturation should be near the 30% range. Pruess and Narasimhan (1982) pointed out that the earlier speculations were incorrect and the irreducible liquid level can be much higher. In fact, Pruess (1985) indicated that the irreducible liquid saturation in a vapor-dominated reservoir could be of the order of 90% or higher. In the absence of any definite value for the field irreducible, and therefore the initial, liquid saturation, we tested a range of values between 30% and 90% in the uncertainty analysis.

We also investigated effects of natural recharge in the uncertainty analysis because it may have significant impacts on the long-term deliverability of the reservoir. Surface measurements at Darajat estimated a natural heat discharge of about 70 MWt corresponding to a discharge rate of 24.5 kg/s of vapor. The uncertainty range of the natural recharge varies from 0% to 100% of the natural discharge.

The water liquid-vapor relative permeability is a subject of on going research. Previous studies have used different expressions for modeling two-phase flow in geothermal reservoirs (Grant, 1982). There is considerable doubt as to whether any available relative permeability expression can truly represent the two-phase flow in geothermal reservoirs. In many cases, in order to obtain a reasonable match to the field data, investigators adjusted or “pseudorized” the relative permeability curves as in the oil and gas reservoir simulations. We investigated effects of relative permeability on the field performance by using the power law correlations and they cover a wide range, from Corey correlation, to the linear model, and to that of a very wide range of pore size formation.

Table 1 lists the uncertainty variables and their possible value ranges.

Table 1: Uncertainty ranges for Darajat reservoir main variables investigated in the Design of Experiment methodology

Variable	Low Value (-)	Mid Value (0)	High Value (+)
Swc (%)	30	60	90
PorVol (10^9 m^3)	3.9	4.9	6.2
Rech/Disch Ratio	0	0.5	1
Rel Perm Power law exponential (n)	4	1	0.5
Res. Depth (km ASL)	-2	-3	-4

5. SIMULATION MODEL DESIGN

We used the Plackett Burman (PB) Design of Experiment approach, or Fractional Factorial method, to incorporate the uncertainty of the identified subsurface parameters in the dynamic model building. The PB design is a two-level design, high and low, that efficiently estimates main (or linear) effects of all variables being investigated. In this design, geologic and reservoir parameters vary simultaneously instead of the relative inefficient one variable at a time approach. It can capture the non-linear variable interactions in the simulation forecasts, resulting in a more objective selection of the P10, P50, P90 scenarios (Friedmann, et al., 2001.) In many cases, the two-level design is sufficient to analyze the main effects of variable uncertainties. If variable interactions are strongly present, then a three-level factorial design should be used to model effects of the variables on the response.

As the results of the PB design, we generated a series of nine dynamic reservoir models with different combinations of the parameters to quantify effects of the subsurface uncertainties on the reservoir performance. These models represent a wide spectrum of mass (water liquid and vapor phases) in place. The initial liquid volume of the largest model is more than nine times that of the smallest model. Table 2 shows the parameter combinations for the nine reservoir simulation models evaluated. The center-point (CP) model has all uncertainty variables at or near their mid range values. Table 2 shows the model design.

Table 2: Dynamic model design using Plackett Burman screening method. 9 models with different variable combinations capture the full range of variable uncertainties.

Model	Swc	PorVol	Rech/Disch	Rel Perm powr law exp. (n)	Res. Depth
1	+	-	-	-	-
2	+	+	-	+	-
3	+	+	+	+	+
4	-	+	+	-	+
5	+	-	+	-	+
6	-	+	-	-	-
7	-	-	+	+	+
8	-	-	-	+	-
CP	0	0	0	0	0

6. SIMULATION MODELS

6.1 Model Description

We scaled up a geologic model using the flow-base technique to reduce the number of cells to a more manageable level (Durlofsky, et al., 1996). The scale-up technique employed preserves the main characteristics of the geologic models and adequately mimics the flow performance of the original fine grid. As the result, we reduced the model from over 9.3 million cells to less than 200,000 cells for the simulation model. We constructed the Darajat reservoir simulation model as a single porosity model and used a range of pseudo relative permeability to mimic the vapor and liquid water flows in the fracture networks. In selecting the single porosity model, we emphasized on the long-term reservoir performance responding to the depletion exploitation of the field. We further assumed that effects of about 1%wt CO₂ on the fluid behaviors is relatively small and modeled the Darajat fluids as pure water.

The lateral boundaries of the reservoir model are impermeable to fluid flow. The model upper boundary represents a tight cap rock. A series of artificial wells completed near the top layer of the model represent the surface manifestations. We imposed a constant pressure and constant saturation boundary at the bottom layer of the model. Previous works of Pruess, K. (1985), McGuinness, et al, (1993), O'Sullivan., et al, (2001) discussed more in detail the required bottom boundary conditions for a stable natural state vapor-dominated system. In addition, we applied a limited fluid recharge in the layer above the model bottom layer, away from the current production interval, to simulate the natural recharge. The recharge magnitude is an uncertainty variable and has different values in different models in the uncertainty analysis. In no case does the magnitude of the recharge exceed the surface discharge. We also imposed a very low transmissibility value to restrict the fluid recharge from the bottom boundary layer into the reservoir.

In order to speed up the natural state equilibrium, we initialized the model by filling all the cells with two-phase fluids, water liquid and vapor, at a temperature of 245° C_±. The initial liquid saturation (s_{swc}) was near the irreducible levels (s_{wir}) and varied from 0.30 to 0.90 in various models we used in the uncertainty analysis. We modified the end points of the relative permeability curves used in the

models accordingly dependent upon the liquid water irreducible values.

6.2. Model Calibration

The first step in the Darajat dynamic model calibration process was to simulate the natural state and refine the model to match the model output with the measured pressure and temperature gradients. We ran the model up to a few thousand years or until the pressure, temperature, and saturation profiles reached a pseudo steady state (dynamic equilibrium). We achieved the match by adjusting the model global permeability, vertical to lateral permeability ratio, and heat flux from the bottom.

Figure 3 shows a plot comparing the simulated natural state pressure profiles with the measured pressures obtained from nine deep wells. These measured pressures were the shut-in pressures taken at individual wells' main feed zone at various locations of the field.

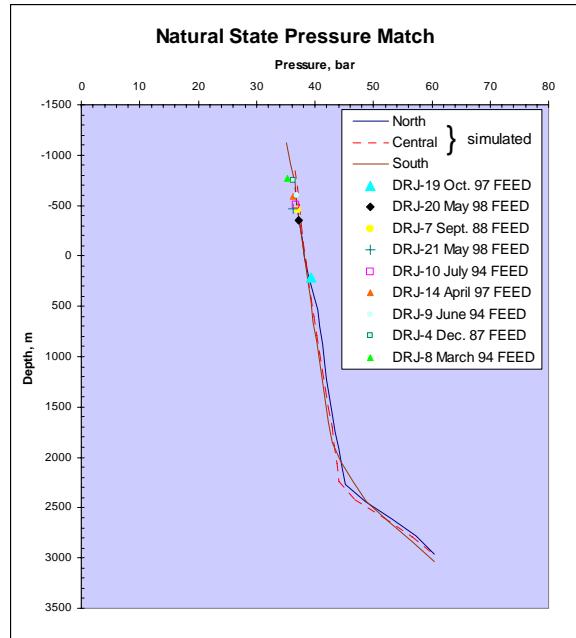


Figure 3: Comparison of simulated (lines) and measured pressure gradients (points) for Model CP natural state.

We were able to obtain reasonable matches for most of the wells between the simulated and production data for all of the 9 dynamic models.

Figure 4 shows comparisons between the simulated and measured pressures for the CP model for some typical flowing and observation wells. Figure 5 compares the simulated pressure distributions with the measured pressure contours at two points in time, years 2000 and 2003. The overall good agreement between the simulated and measured data at individual wells and the field wide levels validates these dynamic models and provides confidence for the performance projections.

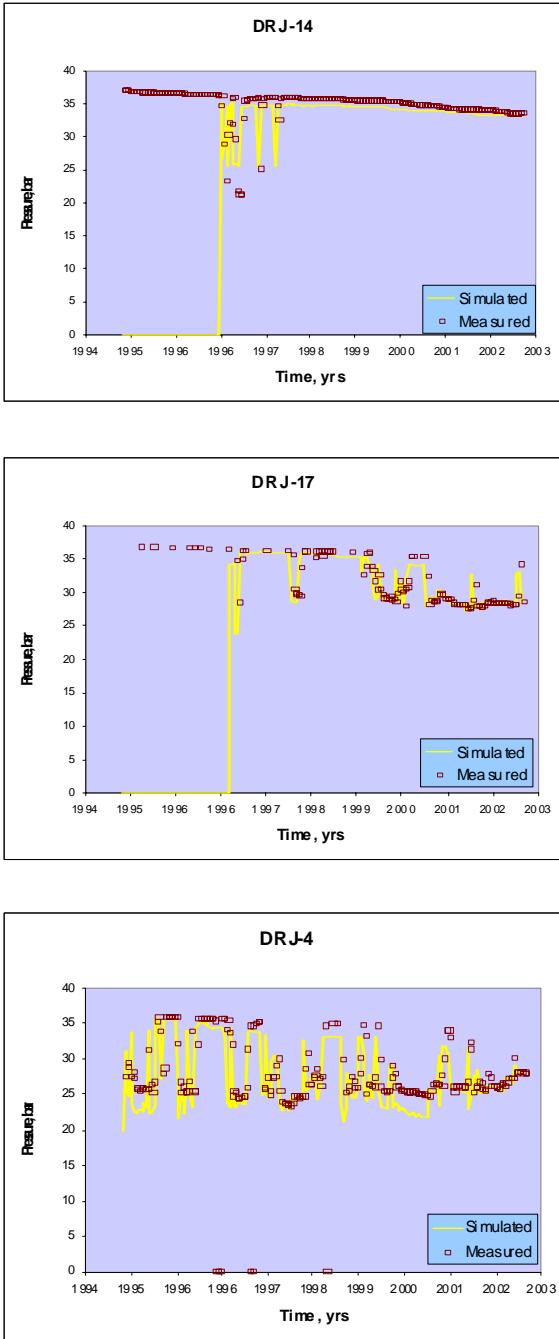


Figure 4: History matching of typical producers and observation wells for Model CP calibration.

6.3 Model Prediction

The calibrated models provide the basis for predicting the reservoir performance in response to the planned expansion. We obtained the production plateau lengths for all nine models using the base case expansion scenario. In the predictions, we assigned specific groups of wells to individual power plant units. These well groups consist of both the existing and future in-fill wells. Each unit has a minimum steam rate target. During a prediction simulation run, if the combined production rates feeding to a plant unit falls below the target then a future in-fill well assigned to that unit will be automatically put on-line to make up for the short fall. We assumed a maximum of 14 in-fill wells

for the three units during the life of new power plant contract.

Figure 6 compares the production plateau predicted by the nine models. The production plateau varies from 18 for Model 8 and up to 98 years for Model 3. The wide range of the predicted performance reflects the parameter uncertainty as well as the non-unique nature of reservoir simulation.

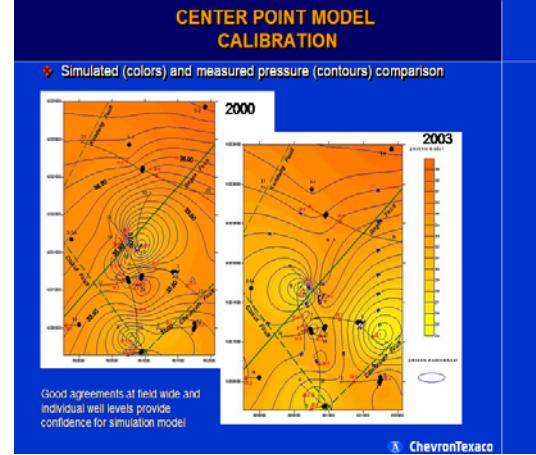


Figure 5: Pressure distribution comparison, simulated (colors) vs. measured (contours) for Model CP calibration.

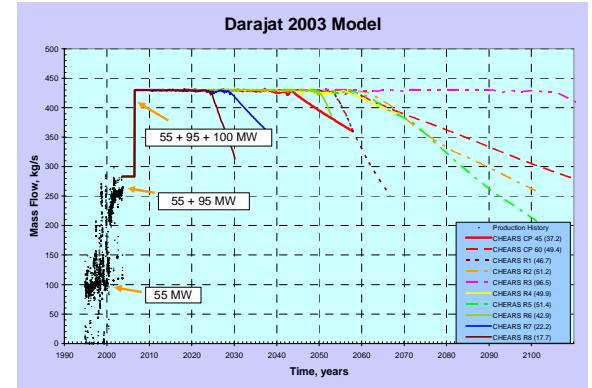


Figure 6: Predicted production plateau potentially can vary from 18 to 98 years.

7. UNCERTAINTY VARIABLE RANKING AND RESPONSE SURFACE GENERATION

The standard statistical analysis of variance and the t-test allow us to calculate and rank effects of the uncertainty variables. We used the standardized Pareto chart to display the results in Figure 7. The Pareto chart ranks the linear effects of each uncertainty variable on the production plateau in decreasing order and uses the Analysis of Variance to evaluate the degree of significance. A variable has a statistically significant effect on the production plateau, with 90% confidence in this case, if it crosses the vertical limitation line on the Pareto chart.

The ranking results indicate that, for a given development scenario, the initial water liquid saturation and the reservoir pore volume would have the greatest influences on the production plateau length. The shape of the fluid relative permeability would have a very small impact on the

reservoir performance. In addition, the relatively small effects of the curvature on the performance indicate that the 2-level Plackett-Burman screening design is sufficient to evaluate the effects of uncertainties. It also implies that the interactions between these uncertainty variables are not very strong and the plateau length varies somewhat linearly with these parameters.

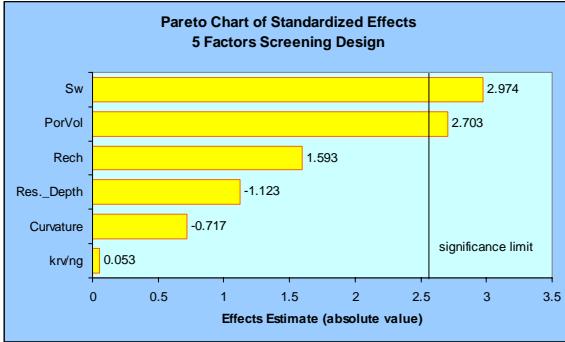


Figure 7: Reservoir performance is most sensitive to the initial liquid saturation and pore volume.

We used the multivariate regression analysis to fit a linear model through the data that relates the production plateau with the variables. We could develop a model using only the top two variables. However, for this case, adding more variables in the model provides a better fit and more flexibility in selecting parameter combinations for P10, P50, and P90 reservoir simulation model constructions. If we chose the first four parameters in the order of significance, the following model is derived from the regression analysis:

$$\text{Plateau Length} = -28.785 + 47.125 * \text{Swc} + 1.109e-08 * (\text{Pore Volume}) - 5.387 * (\text{Res. Depth}) + 15.375 * (\text{Rech/Dis Ratio}) \quad (1)$$

$$R^2 = 0.91$$

The model provides a better way to understand the relationship between the variable and the reservoir response. It also acts as a proxy model for rapid Monte Carlo simulations.

8. RESERVOIR PERFORMANCE PROBABILISTIC DISTRIBUTION

We used the proxy model, Equation 1, to evaluate the probability distribution for the response plateau length by performing Monte Carlo simulations (5000 simulations.) Results of the Monte Carlo simulations provided the cumulative distribution function (S-curve) for the uncertainty as shown in Figure 8.

The performance S-curve indicates that the plateau lengths for the P10, P50, and P90 cases for the 100 MW expansion developments are around 38 years, 53 years, and 68 years respectively.

9. P10, P50, AND P90 RESERVOIR SIMULATION MODEL PREDICTIONS

The Monte Carlo simulation results provide multiple combinations of the subsurface parameters for the construction of the P10, P50, and P90 reservoir simulation models. We selected three parameter combinations for these base models having a wide range of initial liquid water saturation and reservoir pore volume, the two most important uncertainty parameters. The out comes of the

three predictive simulation models are then compared with the Monte Carlo P10, P50 and P90 values (Fig. 8). Good agreements of the results generated by the two methods provide higher confidence for the predictions.

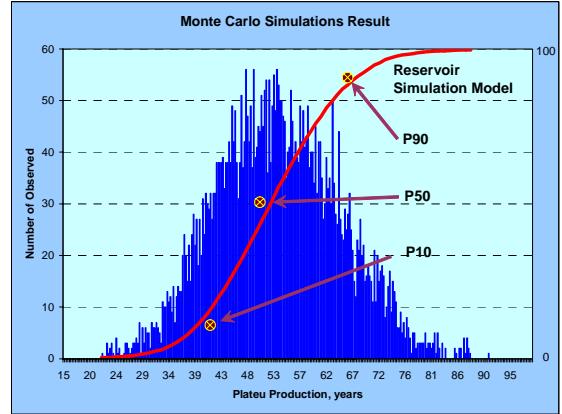


Figure 8: Reservoir simulation P10, P50, and P90 models provide similar results as Monte Carlo P10, P50, and P90.

These three predictive simulation models yield statistically valid estimates of the P10, P50, and P90 reservoir production plateaus. They provide an effective probabilistic forecast means for various development alternatives assessment. The P50 model results are often used for economic evaluations of different development alternatives. The P10 and P90 models, on the other hand, can offer insight for downside mitigation and upside potential capturing options.

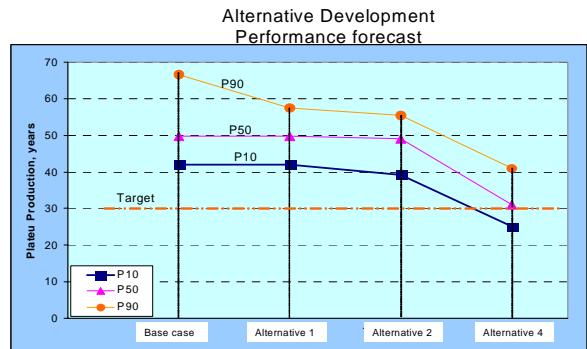


Figure 9: Expansion alternative assessment.

We used the, P10, P50, and P90 simulation models to project the reservoir performance for four different expansion development scenarios for Darajat. These development scenarios require different field total vapor production rates at various turbine inlet pressures. Figure 9 shows the performance forecasts for the four expansion scenarios.

The results indicate that, if the required production plateau is 30 years and P50 model forecast is used, then the reservoir has a reasonable probability to support all four expansion alternatives. Of course, the risk taking mind-set and other factors can change the development alternative selection. If one wishes to take a risk adverse approach, using a P40 or P30, then Alternative 3 for development would be eliminated from the selection. On other hand, if one prefers a more optimistic approach then Alternative 3

can be selected. Detailed results of the predictive models then can provide pertinent information for the uncertainty reduction and risk management plan development.

12. CONCLUSIONS

The statistical evaluation process developed can effectively capture and assess key subsurface uncertainties affecting a geothermal field performance forecasts. The probabilistic performance forecasts provide a useful tool for selecting development alternatives as well as for reservoir risk management. The results of the forecast indicate that the Darajat field has very high probability to support many of the development alternatives considered.

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